# Advances in time-domain induced polarization monitoring with application on chlorinated solvents contamination

## Towards scalable real-time geophysical monitoring

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2023

*Citation for published version (APA):*
Nivorlis, A. (2023). *Advances in time-domain induced polarization monitoring with application on chlorinated solvents contamination: Towards scalable real-time geophysical monitoring*. Engineering Geology, Lund University.

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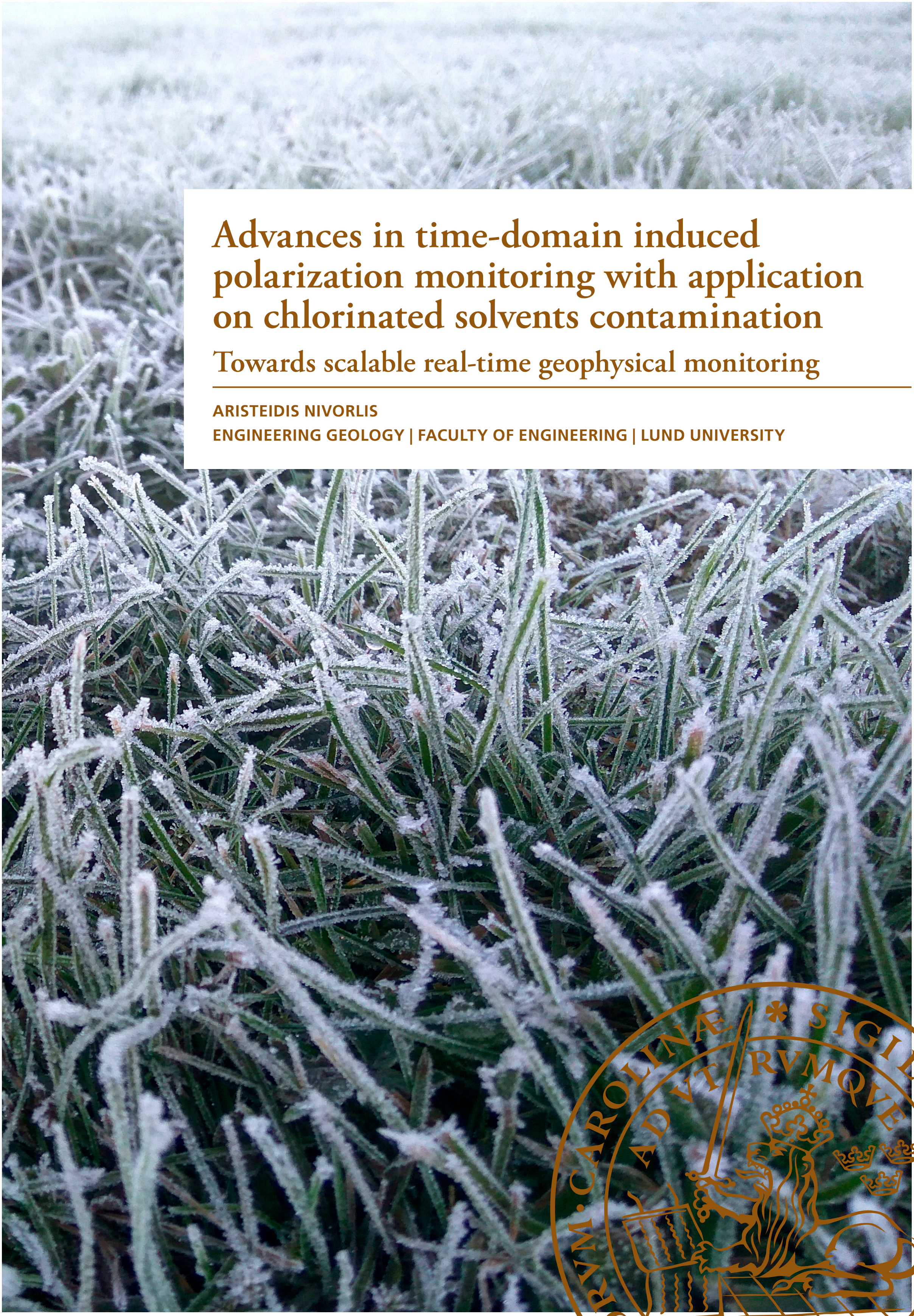

# Advances in time-domain induced polarization monitoring with application on chlorinated solvents contamination: Towards scalable real-time geophysical monitoring

# Advances in time-domain induced polarization monitoring with application on chlorinated solvents contamination

## Towards scalable real-time geophysical monitoring

Aristeidis Nivorlis

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DOCTORAL DISSERTATION

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To be publicly defended at V-Huset, John Ericssons väg 1, Lund, Sweden,
Lecture Hall V:D, on June 16, 2023, at 9.15.

*Faculty opponent*
Prof. Frederic Nguyen, Université de Liège, ArGEnCo, Belgium

**Organization:** LUND UNIVERSITY

**Document name: D**octoral dissertation **Date of issue** 2023-06-16

**Author(s):** Aristeidis Nivorlis **Sponsoring organization:**

**Title and subtitle:** Advances in time-domain induced polarization monitoring with application on chlorinated solvents contamination – Towards scalable real-time geophysical monitoring

**Abstract:**

Environmental pollution is a significant concern for scientists, practitioners, authorities and the society. Among the various pollutants, chlorinated solvents pose a considerable risk to our groundwater resources. These hazardous chemicals, often used in industrial processes, can contaminate soil and water, posing a threat to both human health and ecosystems. Detecting and tracking the spread of these contaminants is crucial to prevent further damage and facilitate remediation efforts.

The research focuses on developing and refining a technique called direct current resistivity and time-domain induced polarization (DCIP) monitoring, which is a geophysical method to measure the electrical properties of subsurface materials. The method can provide images of the subsurface, like medical imaging, showing the change of the electrical properties over time. By tracking those changes researchers can monitor dynamic processes in the ground. The focus of the study is to use the methodology to follow changes that happen in the ground following an in-situ bioremediation treatment of a site contaminated with chlorinated solvents.

The research shows that the joint use of geophysical and hydrochemical data enhances the overall understanding of in-situ remediation processes and indicates that the ongoing remediation is successfully reducing the concentration of contaminants in the ground. While geophysical imaging can potentially provide qualitative answers in areas where it is challenging to collect water samples, follow-up mostly relies on groundwater sampling to delineate information regarding the concentration of contaminants. Furthermore, the study highlights the importance of considering seasonal variations in data interpretation, as well as the need for consistent water sampling during the same period. Geophysical imaging offers insights into the spreading of injected fluids, while groundwater chemistry data is crucial for a qualitative analysis of contaminants in the water. Together, these methods complement each other to better understand the changes occurring during in-situ remediation experiments. Also, the study demonstrates the importance of using a multimethod geophysical approach together with auxiliary data to update existing geological models and improve the understanding regarding the subsurface conditions prior to a monitoring experiment.

In the rapidly evolving field of geoelectrical monitoring, managing and interpreting large volumes of data is a constant challenge. The research study presents an efficient methodology that simplifies the process of collecting, processing, and displaying geoelectrical monitoring data, making it more accessible and user-friendly for experts and stakeholders alike.

One of the most interesting aspects of this research is its scalability. The newly developed methods can be readily applied to small- and large-scale monitoring projects, making it a cost-effective and practical solution for environmental protection agencies and industries alike. With the ability to track in-situ bioremediation experiments in real-time, authorities can respond more quickly to mitigate the spread of pollutants, saving precious time and resources in the process. Furthermore, the research shows great potential in other geophysical monitoring applications.

**Key words:**

**Classification system and/or index terms (if any)** **Supplementary bibliographical information**

**Language** **ISSN and key title**:

**ISBN:** 978-91-8039-723-0

**Recipient's notes** **Number of pages**: 182

**Price** **Security classification**

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Coverphoto by Aristeidis Nivorlis

Faculty of Engineering
Division of Engineering Geology

ISBN: 978-91-8039-723-0 (print)
ISBN: 978-91-8039-724-7 (pdf)
ISRN: LUTVDG/(TVTG-1045)/(1-182)/(2023)

Printed in Sweden by Media-Tryck, Lund University
Lund 2023

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# Preface

The work of this thesis has been carried out at the Division of Engineering Geology, Lund University in Sweden.

I want to thank my main supervisor Torleif Dahlin and my assisting supervisors Matteo Rossi and Alfredo Mendoza for excellent support, help and guidance throughout my work. I would also like to thank my assisting supervisors Gianluca Fiandaca and Panagiotis Tsourlos for providing valuable comments on my work. Furthermore, I would like to thank my colleagues within the MIRACHL group for their fruitful discussions and suggestions during the planning of the fieldwork and the analysis of the results and my colleagues at the Division of Engineering Geology for a friendly and supportive working environment. Finally, I would like to thank my family for their love and support.

This work has been carried out within the MIRACHL project (http://mirachl.com/). Funding which made this work possible was provided by the Swedish Research Council Formas—The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (ref. 2016-20099), SBUF—The Development Fund of the Swedish Construction Industry (ref. 13336), ÅForsk (ref. 14-332), SGU—Swedish Geological Survey, Sven Tyréns stiftelse, Västra Götalandsregionen, InfraSweden/Vinnova (project 2018 00649), Swedish Energy Agency (project 48411-1), SVC (Svenskt centrum för hållbar vattenkraft) - Swedish Centre for Sustainable Hydropower (project VKU32020) and Lund University.

Aristeidis Nivorlis

Lund, March 2023

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# Popular science summary

Environmental pollution is a significant concern for scientists, practitioners, authorities and the society. Among the various pollutants, chlorinated solvents pose a considerable risk to our groundwater resources. These hazardous chemicals, often used in industrial processes, can contaminate soil and water, posing a threat to both human health and ecosystems. Detecting and tracking the spread of these contaminants is crucial to prevent further damage and facilitate remediation efforts.

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One of the most interesting aspects of this research is its scalability. The newly developed methods can be readily applied to small- and large-scale monitoring projects, making it a cost-effective and practical solution for environmental protection agencies and industries alike. With the ability to track in-situ bioremediation experiments in real-time, authorities can respond more quickly to mitigate the spread of pollutants, saving precious time and resources in the process. Furthermore, the research shows great potential in other geophysical monitoring applications.

# Populärvetenskaplig sammanfattning

Miljöföroreningar är en viktig angelägenhet för forskare, företag, myndigheter och samhället. Bland de olika föroreningarna utgör klorerade lösningsmedel en avsevärd risk för våra grundvattenresurser. Dessa farliga kemikalier, som ofta används i industriella processer, kan förorena jord och vatten, vilket utgör ett hot mot både människors hälsa och ekosystem. Att upptäcka och spåra spridningen av dessa föroreningar är avgörande för att förhindra ytterligare skador och underlätta saneringsinsatser.

Denna forskning fokuserar på att utveckla och förfina övervakning med resistivitetstomografi kombinerad med inducerad polarisation (förkortat DCIP efter den engelska benämningen), vilket är en geofysisk metod som mäter de elektriska egenskaperna i marken. Metoden kan ge bilder av underjorden, liknande medicinsk avbildning, som vid upprepad undersökning visar förändringen av de elektriska egenskaperna över tid. Genom att spåra dessa förändringar kan man övervaka dynamiska processer i marken. Fokus för studien är att använda metodiken för att följa förändringar som sker i marken efter en sanering på plats genom stimulerad biologisk nedbrytning i mark som är förorenad med klorerade lösningsmedel.

Forskningen visar att den kombinerade användningen av geofysiska och hydrokemiska data förbättrar den övergripande förståelsen av saneringsprocessen och indikerar att den pågående saneringen framgångsrikt minskar koncentrationen av föroreningar i marken. Även om geofysisk avbildning potentiellt kan ge kvalitativa svar i områden där det är utmanande att ta representativa vattenprover, förlitar man sig ofta på grundvattenprovtagning för att få information om föroreningarnas koncentration. Vidare betonar studien vikten av att beakta säsongsvariationer vid tolkning av data, samt behovet av konsekvent vattenprovtagning under samma period. Geofysisk avbildning ger insikter i spridningen av injicerade vätskor, medan grundvattenkemidata är avgörande för en kvalitativ analys av föroreningar i vattnet. Tillsammans kompletterar dessa metoder varandra för att bättre förstå förändringarna som sker under sanering på plats. Dessutom visar studien vikten av att använda en multimetod-geofysisk strategi tillsammans med kompletterande data för att uppdatera befintliga geologiska modeller och förbättra förståelsen av de geologiska förutsättningarna före ett övervakningsexperiment.

Inom geoelektrisk övervakning, som utvecklas snabbt, är hantering och tolkning av stora datavolymer en ständig utmaning. Forskningsstudien presenterar en effektiv metodik som förenklar processen att samla in, bearbeta och visa geoelektriska övervakningsdata, vilket gör det mer tillgängligt och användarvänligt för både experter och intressenter.

En av de mest intressanta aspekterna av resultaten av detta arbete är dess skalbarhet. De nyligen utvecklade metoderna kan enkelt tillämpas i både små och stora övervakningsprojekt, vilket kan göra det till en kostnadseffektiv och praktisk lösning för både miljöskyddsmyndigheter och industri. Med förmågan att spåra föroreningsspridning eller saneringsprocesser i realtid öppnas möjligheter för att reagera snabbare för att begränsa spridningen av föroreningar, vilket sparar värdefull tid och resurser i processen. Det finns vidare stor potential inom andra övervakningstillämpningar.

# List of Papers

*Paper I*

Nivorlis, A., Dahlin, T., Rossi, M., Höglund, N., & Sparrenbom, C. (2019). Multidisciplinary characterization of chlorinated solvents contamination and in-situ remediation with the use of the direct current resistivity and time-domain induced polarization tomography. Geosciences (Switzerland), 9(12). Scopus. https://doi.org/10.3390/geosciences9120487

*Paper II*

Nivorlis, A., Rossi, M., & Dahlin, T. (2022). Temporal filtering and time-lapse inversion of geoelectrical data for long-term monitoring with application to a chlorinated hydrocarbon contaminated site. Geophysical Journal International, 228(3), 1648–1664. https://doi.org/10.1093/gji/ggab422

*Paper III*

Nivorlis, A., Sparrenbom, C. J., Rossi, M., Åkesson, S., & Dahlin, T. (2023). Multidisciplinary monitoring of an in-situ remediation test of chlorinated solvents. Science of The Total Environment (in review)

*Paper IV*

Nivorlis, A. Dahlin, T. & Hedblom, P. (2023). Advancements in geoelectrical monitoring; an open-source suite for deployment of automated geoelectrical monitoring systems aiming for real-time monitoring applications. Manuscript for submission to Computers & Geosciences

# Author's contribution to the papers

*Paper I*

The thesis author conceptualized the paper. He performed the necessary fieldwork to collect the data, analysed and visualised the data that are presented in the paper. As the main author he wrote the original draft, and he has been leading the revision and submission process.

*Paper II*

The thesis author conceptualised the paper. He performed the necessary fieldwork to collect the data, analysed and visualised the data that are presented in the paper. He also introduced the synthetic experiment part to strengthen the paper during the peer-review process. As the main author he wrote the original draft, and he has been leading the revision and submission process. He was not involved in the collection of the hydrochemistry data.

*Paper III*

The thesis author conceptualized the paper. He performed the necessary fieldwork to collect the data, analysed and visualised the data that are presented in the paper. As the main author he wrote the original draft, and he has been leading the revision and submission process. He was not involved in the collection of the hydrochemistry data.

*Paper IV*

The thesis author conceptualized the paper. He wrote and tested the code. He analysed the data and produced the figures presented in the paper. As the main author he wrote the original draft, and he has been leading the revision and submission process.

# Abbreviations

| | |
|---|---|
| DCIP | direct current resistivity and time-domain induced polarization |
| ERT | electrical resistivity tomography |
| SRT | seismic refraction tomography |
| MIP | membrane interface probe |
| IP | Induced Polarization |
| ZVI | Zero-Valent Iron |
| DNAPL | Dense Non-Aqueous Phase Liquid |
| PCE | tetrachloroethene |
| TCE | trichloroethylene |
| DC | dichloroethane |
| VC | vinyl chloride |

# 1 Introduction

Urban environments are dynamic, complex systems that are influenced by human actions, natural processes, and environmental factors. Understanding the subsurface conditions and dynamics of urban environments is essential for numerous applications, such as infrastructure development, environmental protection, and hazard mitigation. The subsurface of urban environments can be characterized in a non-invasive and economical manner through geophysical investigations. Geophysical methods involve the measurement of subsurface physical properties such as electrical resistivity, magnetic susceptibility, and seismic wave velocity. By analysing these measurements, geophysicists can infer the geologic structure of the subsurface, soil characteristics, groundwater conditions, and potential dangers. This thesis focuses on the use and development of direct current resistivity and time-domain induced polarization method (DCIP) with application in monitoring remediation of chlorinated solvents.

Due to its ability to detect subsurface structures based on variations in electrical conductivity and chargeability, the DCIP (Direct Current Induced Polarization) method has a broad range of applications in geophysical investigations. Commonly employed in mineral exploration to identify prospective mineralization zones based on the presence of conductive and charged materials. The DCIP method is used to determine the distribution and movement of groundwater in hydrogeological investigations by identifying subsurface variations in conductivity and chargeability. It is utilized in environmental assessments to detect and delineate contaminated sites and groundwater emissions. In addition, the technique is employed in engineering studies to identify subsurface structures, such as faults, cavities, and fractures, that may impact the stability of infrastructure. The DCIP method is an essential tool for subsurface investigations in a variety of disciplines due to its adaptability. However, the accuracy of the results is contingent upon the complexity of subsurface conditions and the quality of data collection and processing.

## 1.1 Background

The increasing global demand for sustainable development and efficient resource management has pushed academics to develop more innovative and efficient environmental monitoring techniques. The widespread poisoning of natural resources by manmade contaminants, especially chlorinated solvents, is one of the most significant concerns facing modern society. The widespread use of these compounds in numerous industries, including dry cleaning, degreasing, and the production of solvents and pesticides, has led to severe groundwater contamination. The detrimental effects of chlorinated solvents on human health and the environment have sparked concern among policymakers, scientists, and the general public, necessitating the development of sophisticated monitoring tools to detect and minimize their impact. Non-invasive and cost-effective geophysical technologies have emerged as potent instruments for assessing and monitoring subsurface contamination. Among these approaches, DCIP has demonstrated large potential for identifying and characterizing pollutants in subsurface environments. DCIP measures the electrical response of the subsurface to an injected current, yielding useful information about the materials and pollutants. Despite its potential, DCIP monitoring for chlorinated solvent pollution is not straightforward due to the complexity of the environment and the processes that take place.

## 1.2 Aim and Objectives

The main aim of this work is to monitor the progress of an in-situ bioremediation experiment using geophysics, namely the DCIP method. Understanding the changes that occur in the subsurface after an in-situ treatment is challenging and often relies on labor-intensive field campaigns to collect soil and water samples.

The main objective therefore is to investigate to what extent an automated DCIP monitoring system can be successfully deployed and be used to provide reliable data that can assist in understanding the underground conditions during an initiated bioremediation treatment. The main objective can be broken down into three specific objectives:

i. To design and implement an automated DCIP surveying system that allows continuous monitoring of the subsurface processes.

ii. To use geophysics and complementary data (geotechnical, hydrochemical) to develop or improve geological conceptual models for contaminated sites.

iii. To follow the changes due to an in-situ bioremediation experiment using a multidisciplinary approach based on geophysical and hydrochemical data.

Furthermore, to validate and evaluate the proposed methodology and steps above.

## 1.3 Limitations

DCIP gives a thorough representation of the subsurface in space and time and has significant potential for extrapolating time-step point information from conventional sampling techniques. The generated DCIP monitoring models require additional calibration and interpretation in conjunction with water and soil sampling. The suggested processing and inversion method is developed using data from the Alingås site. Furthermore, it has been deployed and tested on three different sites, but the findings are not included as part of this doctoral thesis.

The investigation of complex environments often requires the fusion of different methodologies, to obtain data that can provide a more holistic description of the underlying conditions in the subsurface. Hydrochemical modelling can then be used to validate the suggested models that derive from geophysics or to constrain the otherwise ill-posed geophysical problem. The work conducted in this thesis does not use hydrochemical modelling and only rely on the hydrochemistry, as it was measured from water samples.

Additionally, the suggested algorithms for data processing and inversion are proven to be robust for monitoring slowly occurring processes. However, it is likely that the complexity of other time-lapse experiments would require the fine-tuning or the development of additional routines.

# 2 Chlorinated solvents

Chlorinated solvents are a class of organic compounds that contain one or more chlorine atoms and are extensively used in various industrial processes as solvents, degreasers, and cleaning agents. Commonly used in the production of plastics, textiles, pharmaceuticals, and electronics, chlorinated solvents are highly effective at dissolving and removing a wide range of organic materials. However, it is also known that chlorinated solvents are persistent, toxic, and potentially carcinogenic, and that they can have significant negative effects on human health and the environment.

Trichloroethylene (TCE), perchloroethylene (PCE), methylene chloride, and carbon tetrachloride are typical chlorinated solvents. As a solvent and degreaser, TCE is a clear, colourless liquid with widespread application. PCE, also known as tetrachloroethylene, is a colourless liquid utilized in dry cleaning, metal degreasing, and various industrial processes. The colourless, volatile liquid methylene chloride is used as a solvent in paint removers and as a blowing agent in polyurethane foams. The colourless, heavy liquid carbon tetrachloride is used as a solvent, degreaser, and precursor to refrigerants. Due to their potential impact on human health and the environment, the use of chlorinated solvents is, today, highly regulated worldwide.

The behaviour of chlorinated solvents in the subsurface is complex and influenced by numerous variables, including their physicochemical properties, environmental conditions, and subsurface characteristics. Understanding the behaviour of chlorinated solvents in the subsurface is necessary for the effective management and clean-up of contaminated sites.

## 2.1 Behaviour in the subsurface

PCE is characterized as a Dense Non-Aqua Phase Liquid (DNAPL), which means that it is denser than water, is hydrophobic and can occur as free phase (e.g. Fletcher et al., 2011). In cases of spills, the compound moves through the subsurface by gravity (Gerhard et al., 2007), adsorbs to the ground matrix, remains as residual free phase globules/residual saturation (Huling and Weaver, 1991), partly dissolves in water and when reaching the groundwater zone, contaminant plumes are formed

(Pearce et al., 1994; Yan et al., 1994). Figure 1 shows how such plumes can be formed after a spill.

The chemicals degrades naturally into trichloroethylene (TCE), dichloroethane (DCE), vinyl chloride (VC) and finally ethene (Yu et al., 2020). Natural degradation of PCE often takes many years, decades and possibly centuries (He et al., 2003; Wiedemeier et al., 1999) and as PCE, and it's first three degradation products, are hazardous and known or suspected to be carcinogenic (Rusyn et al., 2014; IARC, 2014, 2012), it is a high priority to treat the sites to mitigate further impact to the environment, the groundwater, and humans. The natural degradation and remediation treatment techniques, with emphasis on in-situ bioremediation, are described in more detail in the next sections.

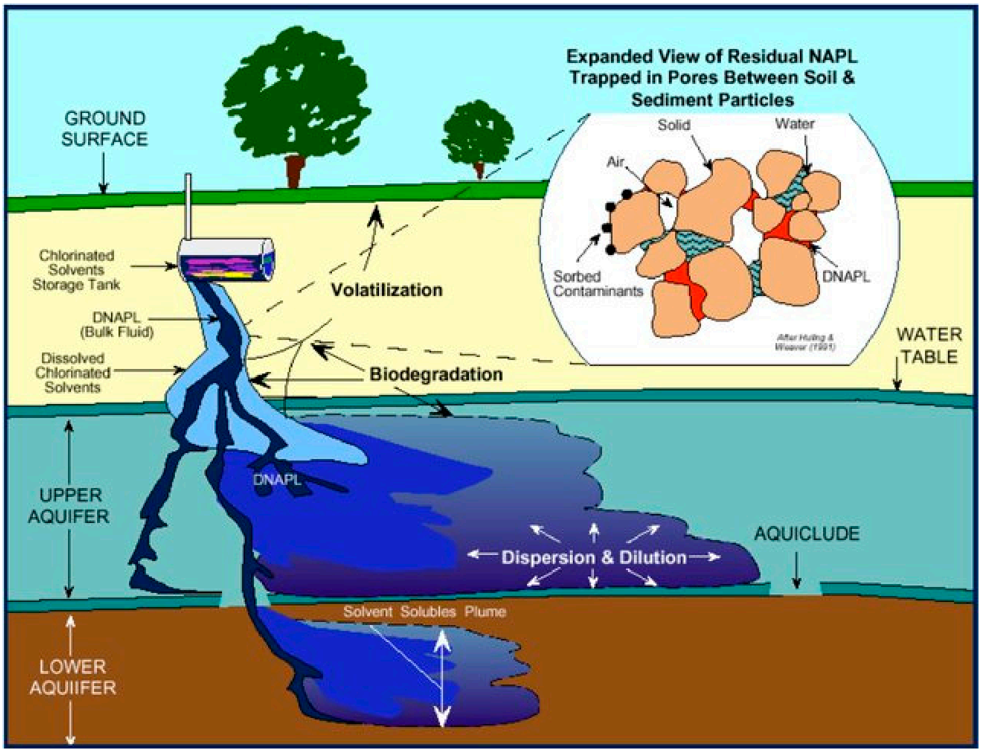


**Figure 1.**Schematic of chlorinated solvent pollution as dense non-aqueous phase liquids migrating downward in an aquifer and serving as a source for a solvent soluble plume. Also shown are natural attenuation processes (U.S. EPA, 1999).

## 2.2 Natural degradation

The natural degradation of perchloroethylene (PCE) can occur through various processes, including chemical and biological mechanisms.

Chemical degradation can occur through reactions with hydroxyl radicals, which are highly reactive species that are formed in the atmosphere by the action of sunlight on air pollutants. Hydroxyl radicals can react with PCE molecules to form trichloroethylene (TCE), which is less toxic than PCE but still considered a hazardous substance (Watts and Teel, 2019).

Biological degradation can occur through the action of microorganisms, which can break down PCE molecules into simpler compounds. This can occur under aerobic (Gaza et al., 2019; Varzaghani et al., 2021) or anaerobic conditions (Liang et al., 2019; Prakash and Gupta, 2000), depending on the type of microorganisms involved. Under aerobic conditions, PCE can be broken down through aerobic biodegradation, which involves the use of oxygen to break down PCE molecules into carbon dioxide and water. This process is carried out by a variety of microorganisms, including bacteria, fungi, and yeast. Under anaerobic conditions, PCE can be broken down through reductive dechlorination. This process involves the action of bacteria such as Dehalococcoides, which remove chlorine atoms from PCE molecules to produce a series of intermediate compounds, ultimately resulting in the formation of non-toxic ethene (**Figure 2**).

The natural degradation of PCE can occur over a period of years or even decade, depending on the environmental conditions and the availability of suitable microorganisms (Pierri, 2021). In addition, the effectiveness of natural degradation can be influenced by various factors, including the concentration of PCE, the presence of other contaminants, and the pH and temperature of the environment. While natural degradation can be an effective method for reducing PCE contamination in some situations, it may not be sufficient for complete remediation of highly contaminated sites. In such cases, other remediation methods, such as reductive dechlorination or chemical oxidation, may be necessary to achieve complete removal of the contaminant.

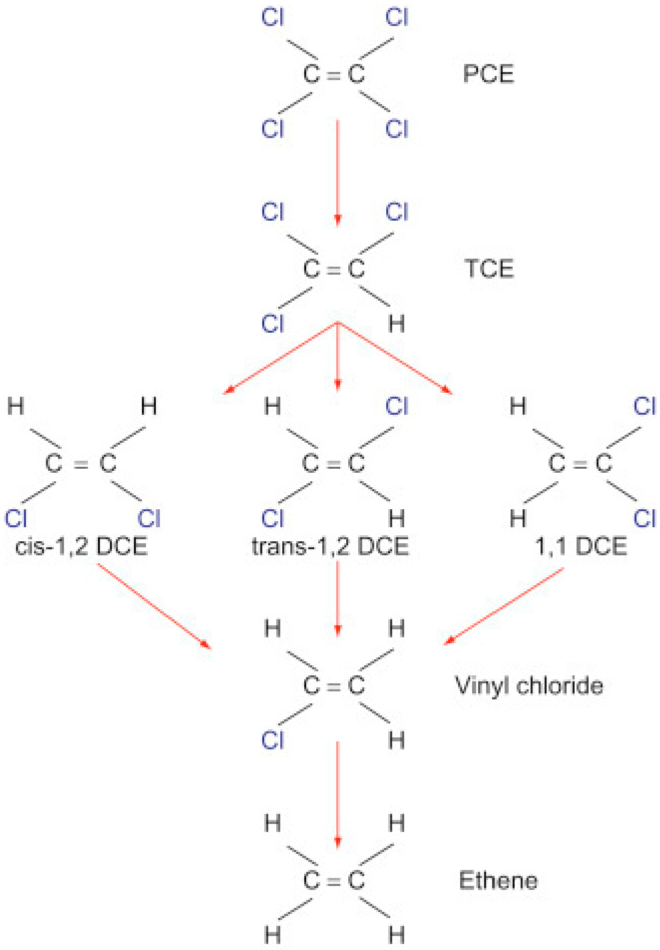


**Figure 2.** Reductive dechlorination of PCE (Popek, 2018).

## 2.3 Remediation

A common method to treat contaminated sites is excavation and deposition, which is a quick process that removes the entire contaminated volume. Even though the method can in some cases effectively remove the entire contaminated volume, it introduces risks due to secondary exposure to the contaminants. Furthermore, the problem of treating the soil is not solved, as the contaminated mass still needs to be treated elsewhere. Also, often those former industrial sites are near urban areas and therefore the excavation might not be an appealing option and could potentially be very costly or impossible if the contaminated mass is located at large depths.

In contrast, in-situ remediation is treatment of the contaminated volume in place. That is typically achieved by increasing the natural degradation of the contaminants either by e.g. injecting substances into the ground (chemical oxidation or reduction), injecting or stimulating microorganisms (bioremediation) (Liang et al., 2019), heating up the ground (thermal remediation) (Murray et al., 2019) or by creating reactive barriers (Bortone et al., 2021). In this case there is no need to remove the contaminated mass, as the contaminated volume is treated in place which provides a modern cost-efficient and effective solution to the problem; the reduction of the total concentration of the contaminants and prevention for further spreading. The Swedish Environmental Protection Agency (SEPA) suggests that in-situ remediation shall be used instead of traditional excavation as a more sustainable approach to remediate contaminated sites (SEPA, 2014). There is, however, a need to develop tools to monitor the effectiveness of in-situ remediation experiments, both in terms of the successful injection of the remediation fluids but also the treatment, i.e., degree of degradation/removal of the contaminants and possible metabolites.

The work presented in this thesis is used to monitor an initiated in-situ bioremediation experiment, using enhanced reductive dechlorination.

Reductive dechlorination is a process by which bacteria remove chlorine atoms from molecules of the chlorinated solvent perchloroethylene (PCE), ultimately transforming them into non-toxic ethene (Dror and Schlautman, 2004; Popek, 2018). This process occurs under anaerobic conditions, meaning that oxygen is absent or present only in low concentrations. Reductive dechlorination of PCE is carried out by a group of bacteria known as Dehalococcoides, which produce enzymes called dehalogenases. These enzymes catalyse the removal of chlorine atoms from PCE molecules, leading to the formation of a series of intermediate compounds, such as trichloroethylene (TCE), cis-1,2-dichloroethylene (cis-DCE), and vinyl chloride (VC). Each successive dechlorination step removes one or more chlorine atoms, until the final product of ethene is produced. The process of reductive dechlorination can occur naturally in certain environments, such as groundwater aquifers, where Dehalococcoides bacteria are present. However, it can also be stimulated by introducing specific types of electron donor compounds, such as lactate, into the contaminated area. These compounds provide the necessary energy and carbon sources for the bacteria to carry out the dechlorination reactions. Reductive dechlorination is an important process in the bioremediation of PCE-contaminated sites, as it offers the potential for complete removal of the contaminant. In addition, it is a relatively low-cost and sustainable method of remediation, as it harnesses the natural processes of microbial metabolism to break down the contaminant. However, reductive dechlorination can be a slow process, and it is dependent on the presence of suitable bacteria and electron donors, as well as favourable environmental conditions.

# 3 Methods and material

## 3.1 Geoelectrical

Direct Current resistivity and time-domain Induced Polarization tomography (DCIP) method was the primary method used in this thesis work; therefore, it is described in some detail. The SRT, MIP, temperature monitoring and hydrochemical sampling methods used as complementary methods to the DCIP will be introduced briefly to obtain a clear overview of the overall methodology used in this work.

### 3.1.1 Direct Current resistivity and time-domain IP

The Direct Current resistivity and time-domain Induced Polarization (DCIP) method includes the use of the traditional resistivity method and its extension, the induced polarization method. The former measures the distribution of the electrical resistivity where the latter measures the capacity of the ground to store charges. Recent advances in the past years, both in terms of hardware and software, made it possible to measure both quantities simultaneously making the acquisition faster and more accurate therefore increasing the popularity of the method significantly. The essential theory of the DCIP method, which is required to follow the thesis work, is described in this chapter.

*Resistivity method*

The electrical resistivity, ρ (Ω·m) is a fundamental property that quantifies the opposition of a material, the ground in our case, to the flow of electrical currents. For a single resistivity measurement four electrodes are employed, two electrodes are used to inject the current (A and B) and two electrodes (M and N) are used to measure the potential difference (**Figure 3**).

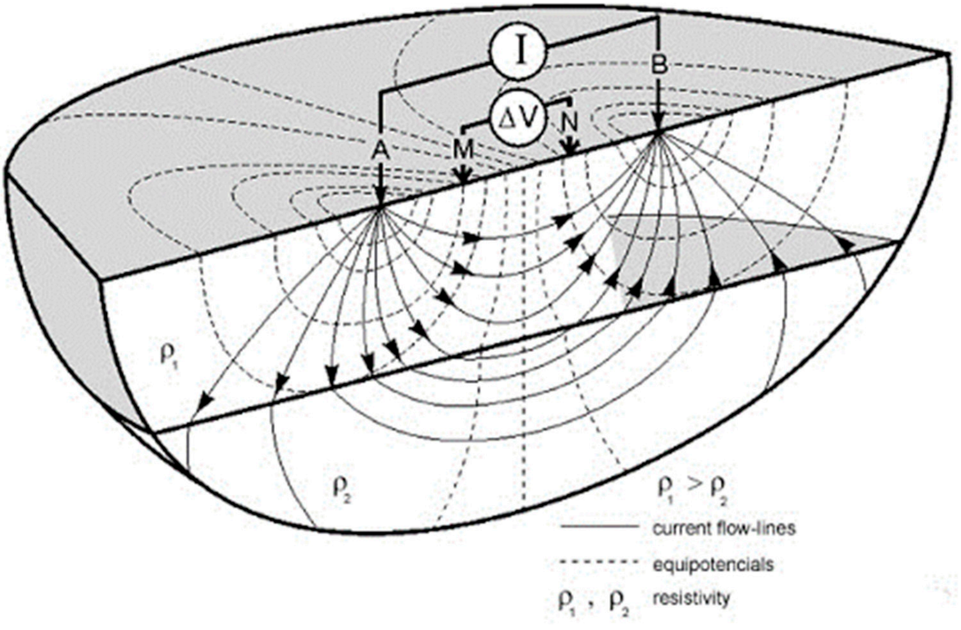


**Figure 3.** Single resistivity measurement. (Original figure provided by (Knödel et al., 2007).

The Ohmic resistance (R) of the ground is calculated using the formula:

$$R = \frac{V}{I} \tag{1}$$

where V is the potential difference, and I is the electrical current injected into the ground. By taking the position of the four electrodes into account, the electrical resistivity can be calculated using the formula:

$$\rho = R\frac{2\pi}{G} \tag{2}$$

where the geometric factor G can be calculated using the formula:

$$G = \frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN} \tag{3}$$

The electrical resistivity calculated from equation *(2)* corresponds the true electrical resistivity only in cases of a homogeneous and isotropic media. However, the earth is, in most cases, heterogeneous so the previous calculations do not generally yield the true electrical resistivity of the ground. The electrical resistivity calculated by the equation *(2)* represents a kind of weighted average, although this is not mathematically correct (Cook and Van Nostrand, 1954), of the resistivities of the different subsurface materials and is called the apparent resistivity.

*Induced Polarization*

The induced polarization method can be considered as an extension of the resistivity method, as a similar configuration as described in **Figure 3** is required. In addition to the measurement of the electrical resistivity another parameter called apparent chargeability is measured. This parameter describes the ability of the ground to store current in form of electrical energy during the injection of the current, acting very similarly to a capacitor.

In order to measure the energy stored, after each current injection (on time) there is an intermediate pause step where no current is injected (off time). During the off time instead of the voltage being zero, because no current is applied, the stored electrical energy is released and is recorded by the instrument as a gradual drop in the voltage before it drops down to zero (**Figure 4**).

The apparent chargeability as defined by Siegel (1959) is the ratio between the secondary voltage immediately after the current is turned off (Vs) and the primary voltage, while the current is on (Vm), as can be seen in **Figure 4**. In reality, the secondary voltage cannot be accurately measured because when the current turns off electromagnetic effects are produced. These electromagnetic effects can be several orders of magnitude higher than the secondary voltage, and this makes it very difficult to separate the two signals. For this reason, modern instruments record the chargeability by integrating over the voltage curve several milliseconds after the current is turned off (**Figure 4**[zoom] and equation (*4*)).

$$m = \frac{1}{V_m} \int_{t_1}^{t_2} V_s(t)\, dt = \frac{\sum_{i=1}^{n} (M_i T M_i)}{\sum_{i=1}^{n} T M_i} \tag{4}$$

Where V(t) is the function of voltage over time, $V_m$ is the voltage before the current cut off, $M_i$ is the integral chargeability and $T_i$ is the time window of the $i_{th}$ gate.

It is obvious that the chargeability is a dimensionless parameter which cannot be larger than 1 because the secondary voltage will always be lower than the primary. It is possible to encounter negative apparent chargeability values that can be explained in view of negative sensitivity areas (Dahlin and Loke, 2015). This means that the apparent chargeability can range from -1 to 1 V/V or -1000 to 1000 mV/V. The latter form (mV/V) is more commonly used.

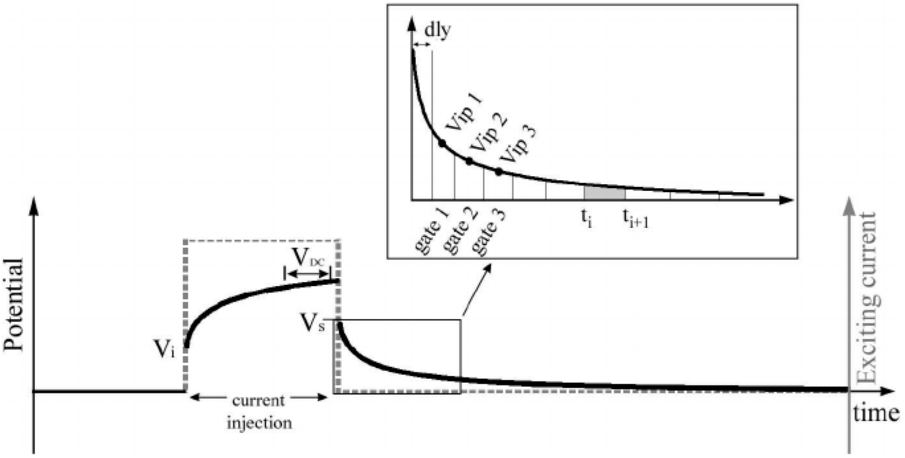


**Figure 4.** Chargeability as defined by Siegel (main plot) and as measured by modern instruments (small plot).(Gazoty et al., 2012)

Unfortunately, the necessity to measure the chargeability during the “off time”, as it is described previously, can significantly increase the acquisition time. Recent advances in the IP method suggest to measure the IP during the “on time” (Olsson et al., 2015) which dramatically reduces the acquisition time. Furthermore, modern instruments can record the full waveform of the injected current and the recorded signal and advanced signal processing algorithms can be utilized to process the recorded data more accurately (Olsson et al., 2016).

### *Electrical Resistivity Tomography*

The principles described in the previous sections, describes a single measurement, using four (4) electrodes or a quadrupole, which gives very limited information about the subsurface due to the presence of heterogeneities. For that reason, in a DCIP survey we perform hundreds of single measurements using several combinations of electrodes that are preplaced and connected to the instrument. The instrument performs a series of single measurement with 4 electrodes, based on a given predefined sequence, until all the desired 4-electrode combinations are measured. This type of survey is often called Electrical Resistivity Tomography (ERT) and can be further explained in **Figure 5**. The total number of possible combinations could be thousands, however several specific configurations, called electrode arrays, are more frequently used.

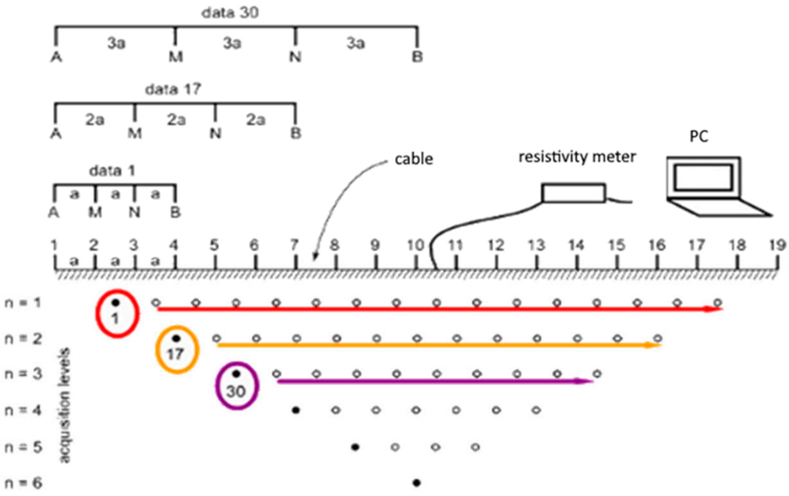


**Figure 5.** DCIP field survey (Loke and Barker, 1996).

As discussed previously, during a DCIP survey current is injected into the ground and the potential difference is recorded between several receiver pairs. For the 2D case, several arrays offer advantages and within this thesis work the multiple-gradient array (Dahlin and Zhou, 2006) was used. The multiple-gradient array has high signal to noise (S/N) ratio making it particularly suitable for IP measurements. The observations (apparent resistivities) can be plotted in a pseudo-section and illustrate a distorted representation of the distribution (**Figure 6**) of the electrical properties in the ground.

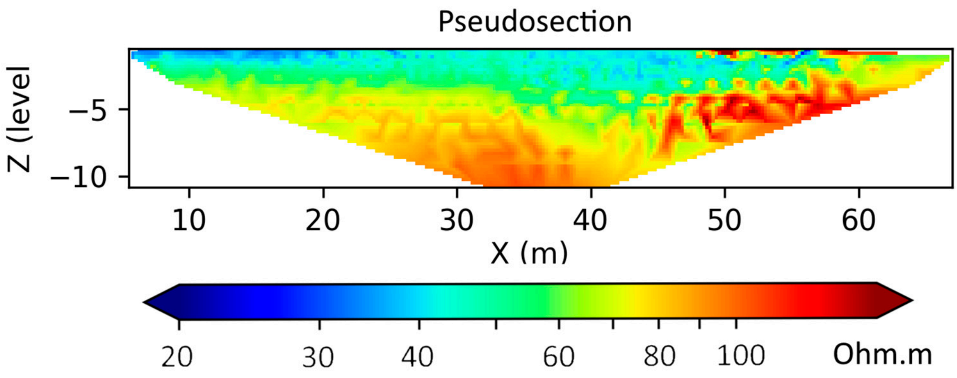


**Figure 6.** Pseudosection that represents the distribution of apparent resistivities in the ground (observations).

### *Forward Modelling*

The forward modelling involves the calculation of the response of a model representing the earth's structure for which the electrical resistivity distribution is known. To solve this problem, for given source locations the current flow inside the model needs to be simulated. The equation that governs the current flow in the ground is the Poisson equation:

$$\nabla\,(-\sigma\nabla V) = \nabla J \tag{5}$$

Where V is the potential, σ represents the subsurface conductivity and J describes the current sources.

Although analytical solutions do exist for simple geometries (Cook and Van Nostrand, 1954) for more complex geometries they do not exist. For complex geometries, the eq. 5 is solved using a numerical approach such as the finite element method (FEM) which is used in this work (Loke et al., 2014). In FEM the earth is divided into a finite number of smaller homogeneous and isotropic cells, called elements. Each element is assigned a value of the electrical properties, as described extensively in (Tsourlos and Ogilvy, 1999) and the solution to eq.(5) is approximated.

### *Inversion*

As previously described, it is rather straight forward to calculate the response of an array given a known distribution of the electrical properties. However, the distribution of the electrical properties is usually unknown and needs to be determined. That can be achieved through an iterative process called inversion, which tries to find the distribution of parameters that gives theoretical measurements that best fit the real data. The smoothness constrained inversion (Tsourlos and Ogilvy, 1999) is the algorithm that is used in this work to solve the inverse problem and is briefly described in **Figure 7**.

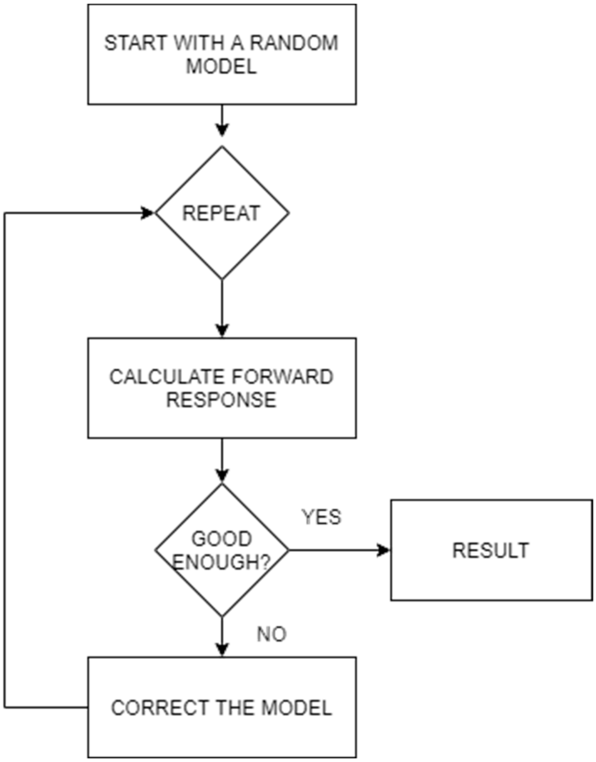


**Figure 7.** Simplified diagram that describes the general inversion algorithm.

To begin with, a homogeneous earth is most commonly used for the initial model. The model response is calculated (forward solution) then the model is compared with the observed measurements and the misfit is computed. If one of the stopping criteria is met the process terminates, otherwise the model is updated, and the process is repeated. The criteria for terminating the process that are commonly used include a maximum number of iterations, no further improvements in the solution or a solution with an acceptable misfit.

The observations are used by the inversion algorithm to find the distribution of parameters (resistivities) that will generate synthetic measurements (forward response) that are as close as possible.

The distribution of the electrical properties (inverted profile, **Figure 8**) can be associated with the lithology and with the presence of water or contaminants. The connection however is not trivial and a priori information about the area of investigation is required to interpret the results. Last, it is important to mention that the distribution of the electrical properties can vary through time because of seasonal variations, such as temperature changes and rainfall events, changes in groundwater level and geochemistry. The last is of great importance in this thesis work, because during the in-situ bioremediation the properties of the subsurface are changing, therefore one inverted profile captures a single time-step of the overall changes.

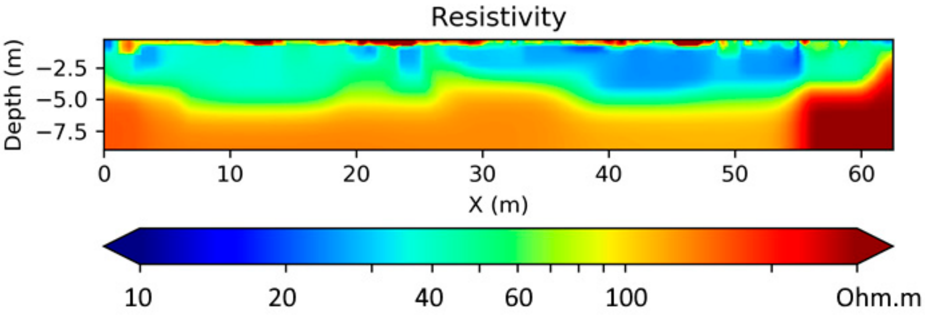


**Figure 8.** Calculated distribution of resistivities (properties) in the subsurface.

## 3.2 Complementary methods

### 3.2.1 Seismic refraction tomography

The seismic refraction method estimates the velocity at which elastic waves propagate into the subsurface. A source such as a hammer, explosion or an accelerated weight drop is used to generate, in this case, compressional waves (P-waves), although shear waves (S-waves) could be used as well. The generated waves contain information about the media that they are propagated through and are recorded at several receivers, the geophones, placed at different distances from the source. The experiment is repeated by moving the source to other positions, thus generating more waves, to obtain further information about the elastic properties of the subsurface (P wave velocity) that can be used to describe lithology.

In the traditional seismic refraction method, the first arrivals are used to estimate the depth to the refractors, interfaces where the elastic properties (P-wave velocity) increase. The groundwater table (Fernández-Baniela et al., 2021) or the transition from one lithological unit to another (Jusoh et al., 2010) are examples of refractors that can be identified by the seismic refraction method.

Seismic Refraction Tomography introduces a more advanced approach where instead of identifying refractors (surfaces) a model of the elastic properties of the subsurface (P-wave velocity) is estimated. That is achieved by an inversion approach, similar to the one described for the DCIP, where a system of non-linear equations are solved to generate a model of the P-wave velocities for the subsurface (White, 1989).

### 3.2.2 Membrane interface probe

The Membrane Interface Probe (MIP) is a logging method where a probe, equipped with sensors, is directly pushed into the ground in a way similar to a cone penetration test (CPT). First and foremost, the probe is equipped with a detector that can measure the volatile hydrocarbon and solvent contamination at different depths. Moreover, other sensors attached to the probe can estimate the electrical conductivity and hydraulic permeability of the geological units at different depths.

The method is efficient for mapping the contaminants in-situ in the subsurface (Mousavi et al., 2020; Wu et al., 2022), while at the same time information that can be used to describe the lithology can be provided. However, the MIP method only provides time specific single point information about the subsurface and additional methods are needed to achieve more continuous spatial coverage.

### 3.2.3 Temperature profiling

The monitoring of the soil temperature is essential when deploying geoelectrical monitoring systems because the electrical properties are directly affected by the temperature. Even though the electrical properties are affected by temperature, it is not possible to delineate the temperature of the subsurface from the DCIP data, making it paramount to use external probes for that purpose.

The variations of the temperature can be used to understand the changes that take place in the subsurface and understand how the geoelectrical signal can potentially be affected. The effects of seasonal variations can be observed by monitoring the temperature of the soil at different depth intervals. Furthermore, rainfall events can also affect the temperature of the soil, apart from changing the water saturation, and therefore may be identified from the soil temperature data.

### 3.2.4 Hydrochemical sampling

Groundwater was collected in three annual campaigns, in October of 2017 2018 and 2019 (Åkesson, 2022). Furthermore, a monitoring program was performed by the Geological Survey of Sweden (SGU) adding an extra dataset approximately every third month per year (Åkesson, 2022). **Figure 9** shows the equipment that was used to collect water samples. The samples were collected by using an Eijkelkamp peristaltic pump and all monitoring wells were pre- purged before sampling started. During the pre-purging process field parameters (i.e., water temperature, oxidation-reduction potential [ORP], pH) were monitored and the purging carried out until stable reads were obtained. Samples from the annual campaigns were analysed by SYNLAB AB (Malmö, Sweden) and the samples from the monitoring program by ALS AB (Sweden), both authorized for the analysis. To compare the two laboratories, duplicates were taken in September 2018 and showed acceptable differences between the results, as they were smaller than the reported errors, except for the samples from the Source zone. For more detailed information about the groundwater chemistry collection see Åkesson et al. 2022. The data of September 2018 included here are analysed by SYNLAB.

**Figure 9.** Equipment used for hydrochemical sampling (Photo by Sofia Åkesson).

## 3.3 Area of Investigation

In Alingsås (South Central Sweden, see **Figure 10**), an industrial-scale dry-cleaning facility (Alingsåstvätteriet) started operating in 1963, supplying cleaning services for the military. Sometime during the 1960s or 1970s, a single spill of approximately 200 L of PCE leaked into the ground, resulting in the formation of a DNAPL source zone beneath the building with a plume extending out under the parking lot. That is the only documented spill; however, other instances of undocumented spills could have occurred in the past. Today, the use of PCE has ceased, and the facility is operating under the Administrative Region Västra Götaland as a laundry and textile cleaning (water only) unit, taking care of approximately 40 tons of textiles per day for the regional hospitals. Responsibility for the remediation is shared between the Swedish Government, through the Swedish Geological Survey (SGU) and the current owners (Region Västra Götaland). Due to ongoing operations in the building, in-situ remediation is the favoured approach for treatment of the contaminated mass.

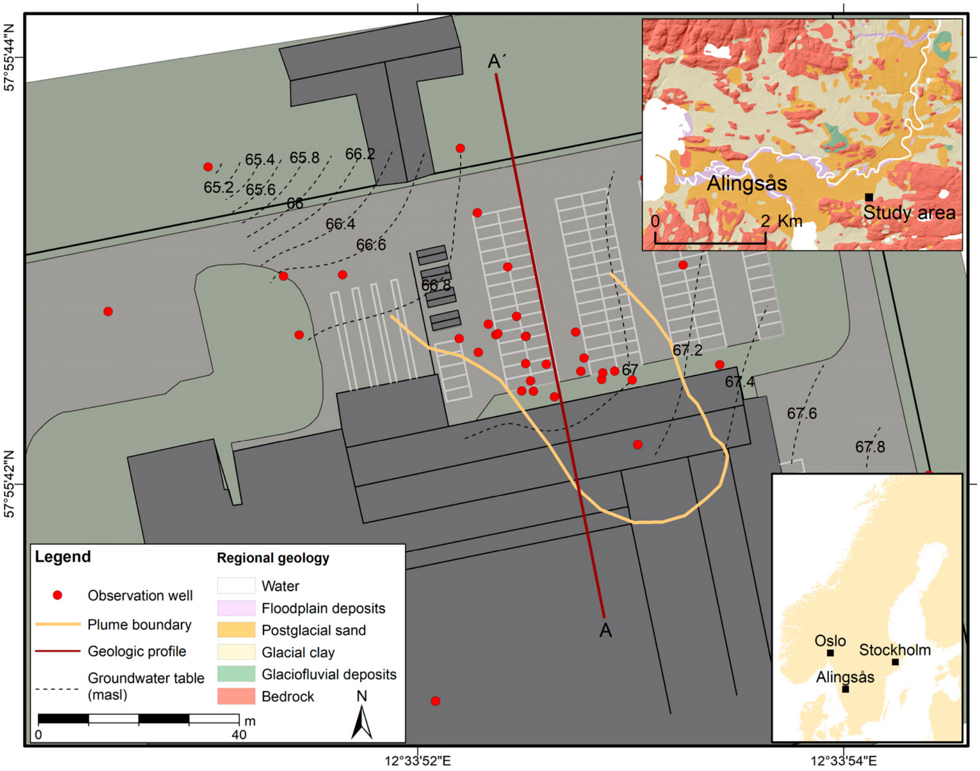


**Figure 10.** Overview of the Alingsås site where the observation wells (red circles), the groundwater level (black dashed lines), the plume boundaries (orange line) and the regional surface geology (top right, created with data from SGU Jordarter, 1:25,000–1:100,00

In the area of investigation, the depth to the crystalline bedrock varies between 2 to 12 m. The sediment overlying the bedrock is deposited in a fining upwards sequence. It consists of a unit of sand with lenses of silt and clay, followed by a layer of clay and on top of the sediment, about 1 m of fill material is present. The geological conceptual model, modified from Branzen (2013), is presented in **Figure 11**. The sedimentary units show a varying inner heterogeneity with lenses of both finer and coarser material occurring. The bedrock topography slopes gently towards N. The depth to the water table varies between 1.5 to 2 m below the ground surface and the groundwater flows from SE towards NW as can be seen in **Figure 10** (black dashed lines).

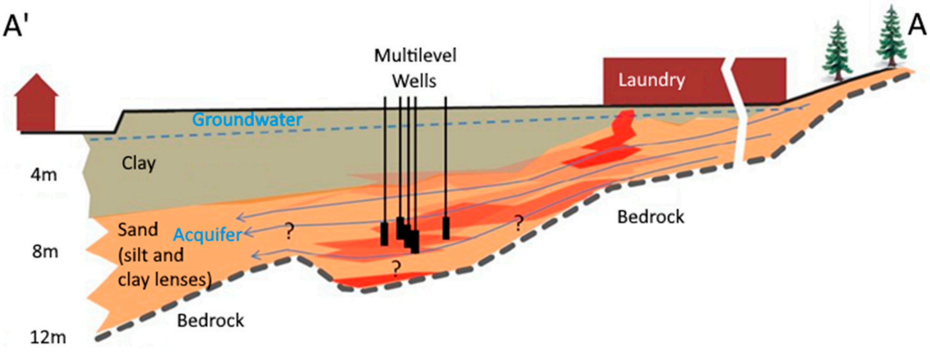


**Figure 11.** Geological conceptual model (S-N). (Modified from Branzen, 2013).

In order to determine the best approach for treatment of the contamination and to stop further spreading, a pilot in-situ remediation program was launched in November 2017, using a direct push injection method on the north side of the laundry building (Figure 3). In order to evaluate the best approach for a future full-scale remediation scenario, two different remediating agents were injected into the plume at different locations, for comparison. In injection area A (west side, see **Figure 12**) Provectus ERD-CH4™ substrate containing a carbon source (electron donor) in the form of vegetable oils together with acids and a bacterial consortium (Dehalococcoides mccartyi, Desulfovibrio, Desulfitobacterium and methanogenic archaea bacteria) was injected in two phases between the 7th and the 17th of November 2017, at a total of 32 points. In injection area B (east side, see **Figure 12**) CAT100™ substrate containing granular activated carbon, zero-valent iron and Trap & Treat® bacteria concentrate were injected, together with a methane inhibitor, between the 28th and the 30th of November 2017, at a total of 37 points. In both cases, the products were injected from a depth of 3 m and downward until reaching the top of the bedrock.

**Figure 12.** Alingsås field site. DCIP monitoring lines (solid blue) with the arrow that indicates the direction of local coordinates, interpreted DNAPL plume boundaries (pink dashed line), the observation wells used to collect the water samples (black asterisk) and the injection points of CAT100 (orange) and Provect CH4 (purple). The dashed black lines indicate the groundwater level measured in September 2017.

# 4 Geoelectrical monitoring

To monitor dynamic processes in the ground a geoelectrical measurement sequence can be repeated several times on the same electrode spread (Dimech et al., 2022). Geoelectrical monitoring describes the continuous or periodic measurement of geoelectrical properties of the subsurface over time (Chambers et al., 2009; Caterina et al., 2017; Fernandez et al., 2019; Sjödahl et al., 2008; Johansson and Dahlin, 1996). The frequency of the measurements depends on the speed of the dynamic process that is of interest. This technique can be used to track changes in subsurface properties that may be related to natural or human-induced processes.

In the context of monitoring bioremediation treatments, the complex conductivity was used to monitor the injection of ZVI (Flores Orozco et al., 2015). Furthermore, cross-borehole DCIP monitoring was used to better understand the flow path of remediation agents (Lévy et al., 2021) and monitoring the spreading of remediation agents (Lévy et al., 2022). Recent field-scale numerical study suggests that DCIP monitoring can be used to monitor the DNAPL mass reduction close to the source zone (Almpanis et al., 2021). However, the study does not consider the effects that the remediation agents, which are often used in bioremediation treatments, have on the DCIP measurements. It is therefore challenging to delineate information regarding the spreading of the remediation agents and the mass reduction of the DNAPL from DCIP measurements (Sanuade et al., 2022).

## 4.1 Following the changes in the subsurface

The DCIP monitoring is carried out by repeating the geophysical survey consecutive times and often requires several data acquisition campaigns in the area of investigation. The frequency that each individual measurement is recorded, and the timespan of the monitoring survey depends on the overall scope. Frequent measurements are needed to capture and understand the more rapid changes, for example due to rainfall events, and longer survey experiments are required to make it possible to identify changes that are usually slower, such as remediation experiments. Furthermore, the seasonal variations (yearly) due to temperature are usually dominant in the shallow layers, introducing the challenge of identifying changes that relate to environmental (gas migration, leachates, contaminations etc.) or engineering geology (quality control of soil stabilization, internal erosion in dams) problems.

Geoelectrical monitoring can be performed in different ways, with different levels of ambition:

i. Manual installation of electrodes, electrode cables, instrument, etc., and management of the measuring process at each time of measurement (Leroux and Dahlin, 2006; Ulusoy et al., 2015).

ii. Permanently installed electrodes, but manual connection of electrode cables and instrument followed by manual management of the measuring process at each time of measurement (Dahlin et al., 2014; Johansson and Dahlin, 1996)

iii. Permanently installed electrodes, electrode cables and instrument with fully automated data acquisition and transfer (Chambers et al., 2009; Nivorlis et al., 2019; Sjödahl et al., 2008).

The first approach requires high precision in the positioning of the electrodes to avoid geometrical noise due to inconsistent electrode locations, and even so differences in the exact location and depth of insertion of the electrodes add uncertainties. For practical and economic reasons, the first as well as the second approach will not provide sufficient temporal resolution for applications with rapid changes, e.g., following rainfall events or the like, and there is always a large risk for inconsistencies due to human error. The last approach, on the other hand can provide data with high temporal resolution and consistency provided that the data acquisition system including software and setup is designed in an adequate way.

Furthermore, it is important to have a system that can acquire frequent data for long periods which would require the DCIP equipment (cables, electrodes and instrumentation) to be deployed in the field introducing several risks (damage to the equipment, public safety and theft). This can be solved by deploying a permanent installation, where the cables and the sensors are buried under the ground and the instrument is stored safely in a nearby building (if possible) or a locked container.

To achieve frequent measurements, for example daily, robust routines for data collection need to be developed to make it possible to automatically collect DCIP without the need of an on-site team. In addition, schemes for managing the collected data should be present, so that data are safely archived and backed up after the collection. Lastly, tools for quality control of the entire procedure are important to be in-place and produce warnings in case of failure.

The work presented in this paper focuses on fully automated DCIP tomography. **Figure 13** (bottom) shows a picture from the field campaign for the permanent monitoring installations and **Figure 13** (top) shows the respective hardware. Geoelectrical monitoring is a valuable tool for understanding the subsurface and tracking changes over time. It can provide critical information for managing natural resources, protecting the environment, and ensuring the safety and stability of civil engineering projects.

**Figure 13.** Permanent monitoring system installed in Alingsås. Hardware (top) and geophysical installations (bottom).

## 4.2 Monitoring systems and applications

When it comes to geoelectrical monitoring, there are a number of instrument options. The LGM 4-point light 10W is a low-power resistivity meter, which together with accessories is suitable for long-term, unattended monitoring of subsurface electrical properties (Grinat et al., 2010; Ronczka et al., 2020). The PRIME (Passive-Resistive Imaging of the Earth) system is a geoelectrical monitoring system developed by the British Geological Survey (BGS) for imaging the shallow subsurface using electrical resistivity measurements (Chambers et al., 2022). The system is designed to provide high-resolution mapping of the near-surface geology for geological, environmental, and engineering applications. GeoMon 4D is a geoscientific monitoring system developed by the Geological Survey of Austria (GBA) for the continuous monitoring of geological and environmental processes (Amabile et al., 2017). The system integrates a range of geophysical and hydrochemical monitoring techniques, including geoelectrical monitoring, to provide a comprehensive understanding of subsurface processes over time. Also, the LSI G.Re.T.A. (GeoRestivimeter for Time lapse Analysis) for permanent geoelectrical monitoring is an Italian geo-resistivimeter made by LSI Lastem with the help of scientists from Politecnico di Milano. It has been used for real-time monitoring of irrigation dams and canals (Arosio et al., 2017; Tresoldi et al., 2020, 2019). Lastly, OhmPi (Clement et al., 2020) is a newly developed open hardware resistivity instrument, suitable for lab measurements and small scale field projects which offers a relatively cheaper alternative but requires assembly of the electronics components.

Some commercial companies offer resistivity monitoring solutions with inhouse instrument and software solutions, for example Subsurface Insights (Versteeg and Johnson, 2013) and HGI (Rucker et al., 2014) in the USA.

Commercially available instruments that are designed for regular ERT/DCIP surveying can be used for monitoring as well, but do not provide a monitoring solution out of the box. They may therefore require additional equipment and in some cases an external computer for flexible configuration. As the encapsulation and interface of these instruments are made for rough field conditions rather than monitoring the cost and complexity of the systems can get high.

The Iris Syscal Pro can be paired with the Syscal Monitoring Unit and the Comsys Pro Software, to enable autonomous acquisition however i) additional hardware and software must be purchased. ii) the number of scientific articles using the instrument is very limited iii) There are no established processing routines for the incoming data. The instrument was used for monitoring of dissolved CO2 in a shallow aquifer (Auken et al., 2014) but there was a need for custom made addons.

MPT-DAS-1 is an autonomous system for measuring resistivity and IP, in both time-domain and frequency domain (although the frequency domain measurements are done using a square wave). The system offers a so-called data stream mode which allows users to store incoming data streams of up to 128 points which is not suitable for larger monitoring experiments.

The AGI SuperSting™ Monitoring System is an add-on module that can be used with the AGI SuperSting™ Wi-Fi, which is an electrical resistivity and IP imaging system used in geophysical surveys. The monitoring system gives the SuperSting™ Wi-Fi an extra layer of functionality by making it possible to keep an eye on how well the system is working while data is being collected, with data visualization tools and functionality for problem identification.

Another common instrument for geoelectrical measurements is the ABEM Terrameter LS2. The instrument offers several key features which enable the acquisition of high-quality resistivity and IP data such as i) constant current transmission ii) recording of full waveform data iii) no digital filters in the hardware. Even though, there is an internal Linux computer, which enables an advanced user to control the instrument via another computer, there are no solutions available that can automate the data collection. The instrument has been used for automated measurements via custom made scripts (Doetsch et al., 2015) but the code is not publicly available and therefore cannot be used by the scientific community.

Moreso, solutions that can control the flow of data and process them as they come are not available for most instruments that were described previously. In most geoelectrical monitoring applications, even when a continuous measurement collection is established, several time-steps of data are collected and are processed in a so-called batch mode. There is a need for open access tools that enable efficient geoelectrical monitoring for a broad spectrum of applications utilizing modern hardware (Versteeg and Johnson, 2013).

## 4.3 Towards real-time monitoring

The complexity and volume of geophysical monitoring data demand the development of effective data processing and management systems. As the amount of data gathered from numerous sources continues to increase, manual handling and processing become increasingly time-consuming and prone to error. Using automated data pipelines can expedite data analysis, enhance data quality, and eventually improve the precision and consistency of geophysical monitoring interpretation and reporting. In geophysical monitoring, where fast processing and interpretation of data are critical for making informed environmental and resource management choices, data pipelines are particularly useful.

Data pipelines enable academics and geophysicists to pre-process, clean, and analyse geophysical monitoring data in a standardized and methodical manner. By automating the data processing workflow, data pipelines decrease human error and ensure that all incoming data undergo the same processing stages. This consistency is essential for preserving the integrity of the monitoring results and for facilitating comparisons between datasets or across time. In addition, data pipelines can be built to contain quality control measures and error handling procedures, ensuring that possible errors are discovered and resolved early on in the analysis process.

In addition, data pipelines can be connected with event-driven systems, such as Python's watchdog package, which monitors incoming files and automatically triggers the data pipeline when new data arrives. This feature ensures that the most recent data is processed and analysed without delay, boosting the monitoring process's efficiency and shortening the time between data collection and actionable insights.

Lastly, long-term monitoring surveys employing geoelectrical techniques, i.e., ERT and DCIP tomography, are powerful for identifying and tracking subsurface changes over time. Yet, it can be difficult to analyse and visualize geoelectrical data, particularly for large datasets. Developing a user-friendly and interactive dashboard might therefore aid academics and geophysicists in quickly analysing and visualizing geoelectrical monitoring data. The application enables users to examine raw, filtered, and inverted data and includes interactive capabilities, such as panning and zooming, to investigate geoelectrical data in greater depth. To process and visualize the geoelectrical data, we utilized Python tools such as NumPy, SciPy, and Plotly. The app provides an interactive way to visualize the geoelectrical monitoring resistivity and chargeability data over time, which is essential for interpreting subsurface changes, identifying potential hazards in long-term monitoring surveys, and providing a higher level of control for automated systems in general.

# 5 Results

## 5.1 Paper I

Paper I adopts a multimethod approach for site characterization by using the MIP, SRT and DCIP method.

First, the MIP soundings were used to create the geological profiles (**Figure 14**) and describe the geology in the study area. The concentrations of the contaminants measured by the MIP soundings, show that the highest concentrations of contaminants are found in the clay layer. Also, the presence of a thin sandy layer above the bedrock acts as a porous media that flushes the contaminant downstream.

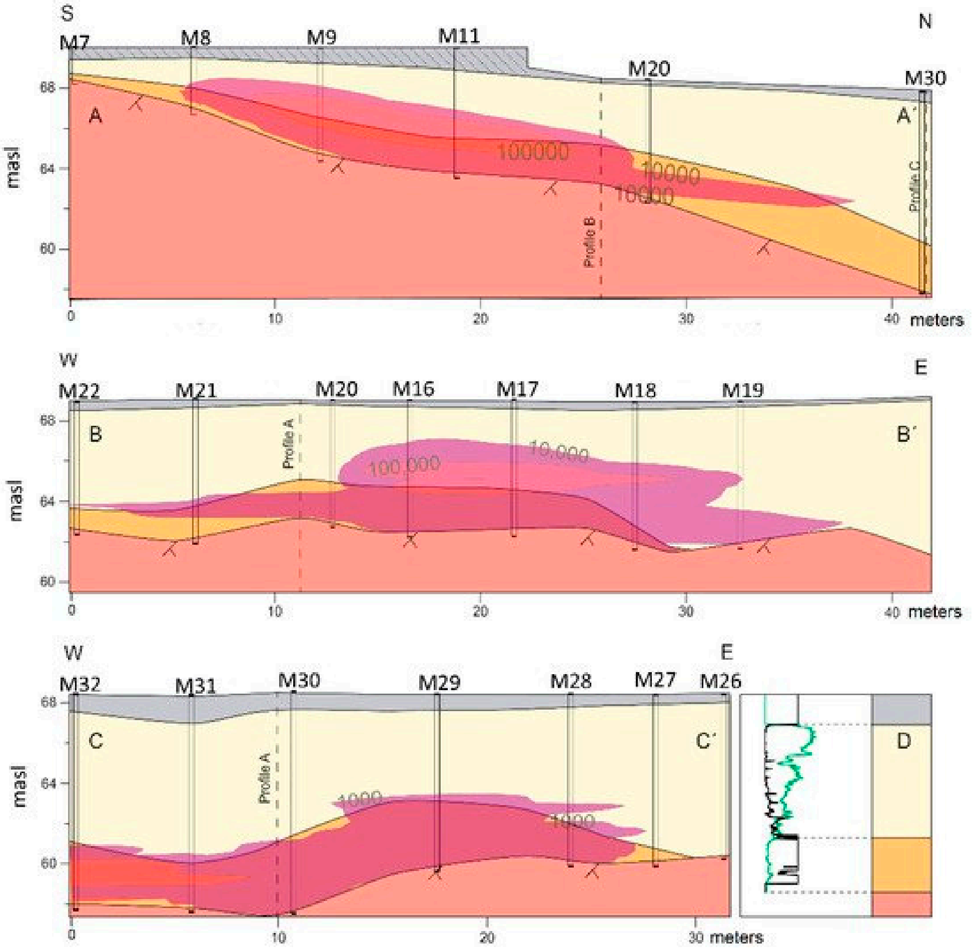


**Figure 14.** Geological profiles created from MIP data. Filling material (grey), fine material (yellow), coarse material (orange) and bedrock (red). The contamination is indicated by the purple contour map.

The contaminants sink into the sediments, since they are heavier than water, until they reach an impermeable layer, and then they can continue to migrate along its slope. In Alingsås, the crystalline bedrock is expected to act as an impermeable layer, although there are no drillings to verify that the contaminants haven't spread in there. For that reason, the SRT was used to estimate the bedrock topography for a larger area covering the parking lot. The bedrock topography from the SRT was used together with the MIP to create the final map. The results (**Figure 15**) show that the bedrock slopes downwards towards NNW, and this, together with the NW groundwater flow, can explain the extension of the plume.

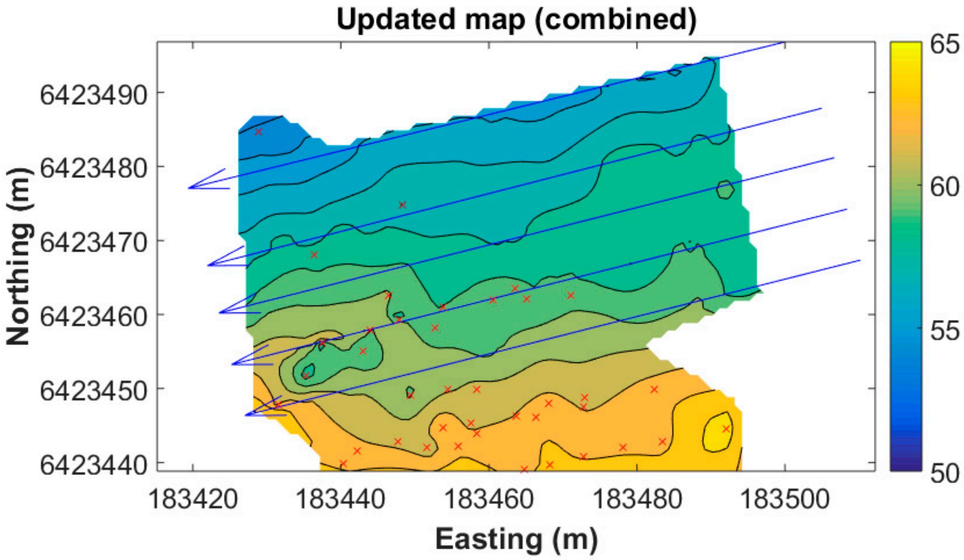


**Figure 15.** Final bedrock topography estimated by combining the results from the MIP and SRT methods.

Last, the DCIP monitoring system data collected before the bioremediation was initiated, has been used to map the geology in the area. The results are in good correlation with the geological profiles (**Figure 14**), although the lithology seems more heterogeneous than was previously thought. Furthermore, there is a strong temporal increase in the electrical resistivity observed in Line 3 and Line 4 that can be correlated with high concentrations of contaminants in those areas (**Figure 16**). The correlation between the geoelectrical measurements and the contaminants, as well as the heterogeneity of the soil, is evident in the inverted result of the cross-hole tomography (**Figure 17**).

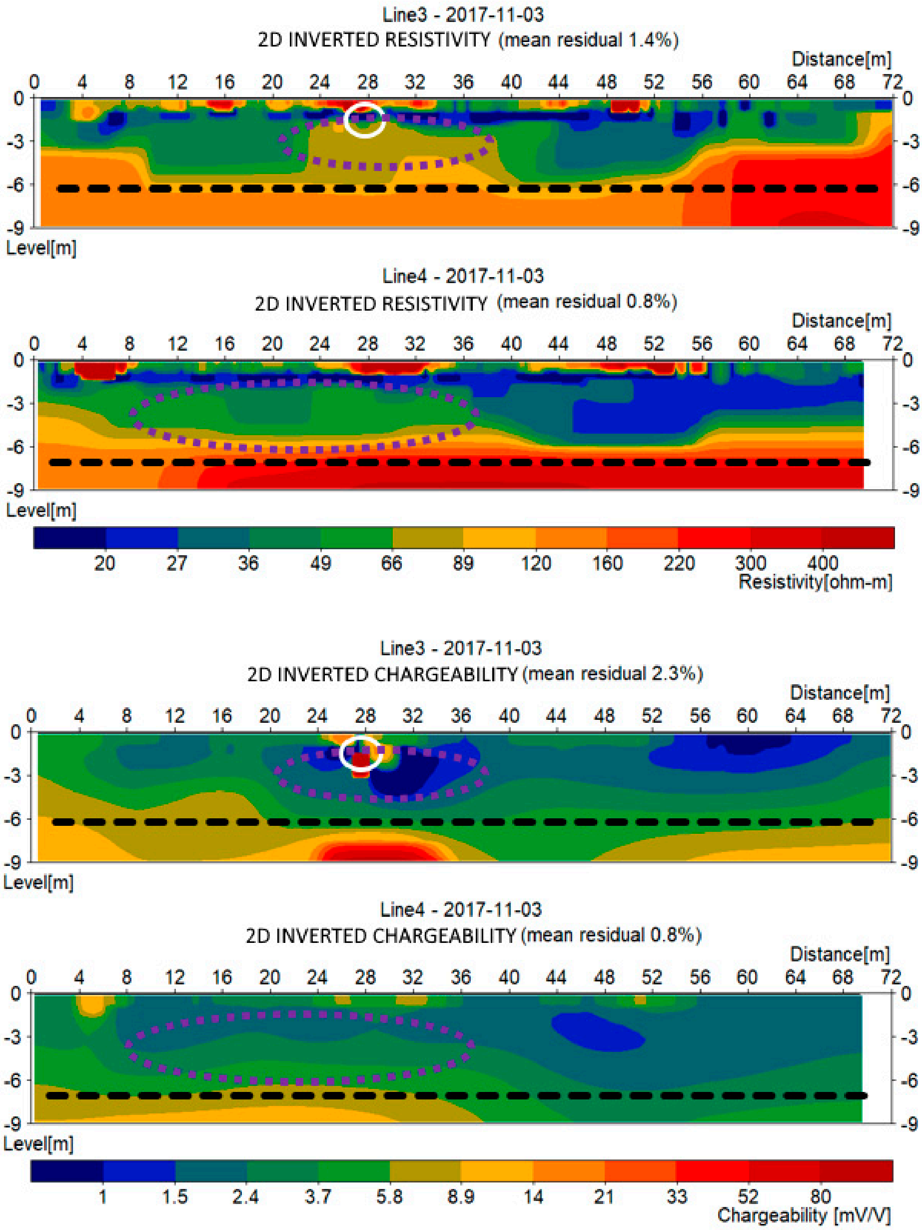


**Figure 16.** DCIP results from the baseline survey, November 2017 showing the interpreted bedrock (black dashed line), the interpreted contamination (purple dashed circle) and the location of buried metal infrastructure (white circle).

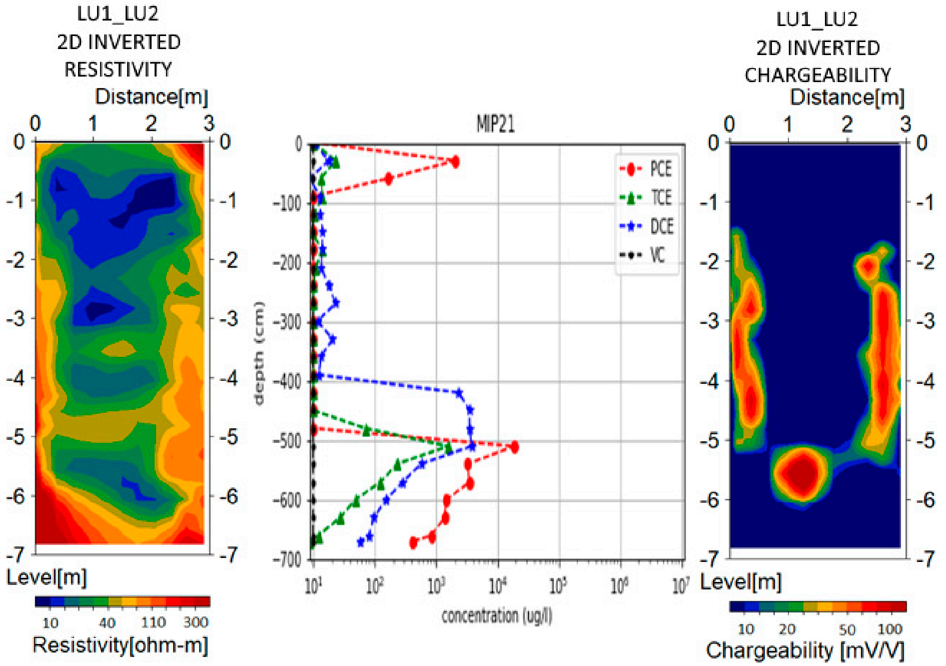


**Figure 17.** Inverted cross-hole tomography results for LU1-LU2. Resistivity (left), chargeability (right) and concentration from MIP sounding (middle).

## 5.2 Paper II

A robust scheme for pre-processing, inversion and visualization of monitoring data is presented. 20-months of daily data were used in this work.

First, the time-series data from individual quadrupoles were filtered using first a median filter and then a low pass Butterworth filter to remove outliers. The proposed approach is very fast and can be used to effectively remove outliers from the data before the inversion.

The proposed workflow for efficient processing and inversion of time-lapse datasets was first tested against a synthetic geoelectrical dataset that simulates a yearly time-lapse experiment. For this purpose, a baseline geoelectrical model was constructed (**Figure 18**, top) and the geoelectrical properties of each unit were altered (**Figure 18**, bottom) to generate 365 forward models where each model represents every single day of the experiment. The simulated models were generated using pyBERT, which is based on the open source software pyGIMLi (Rücker et al., 2017).

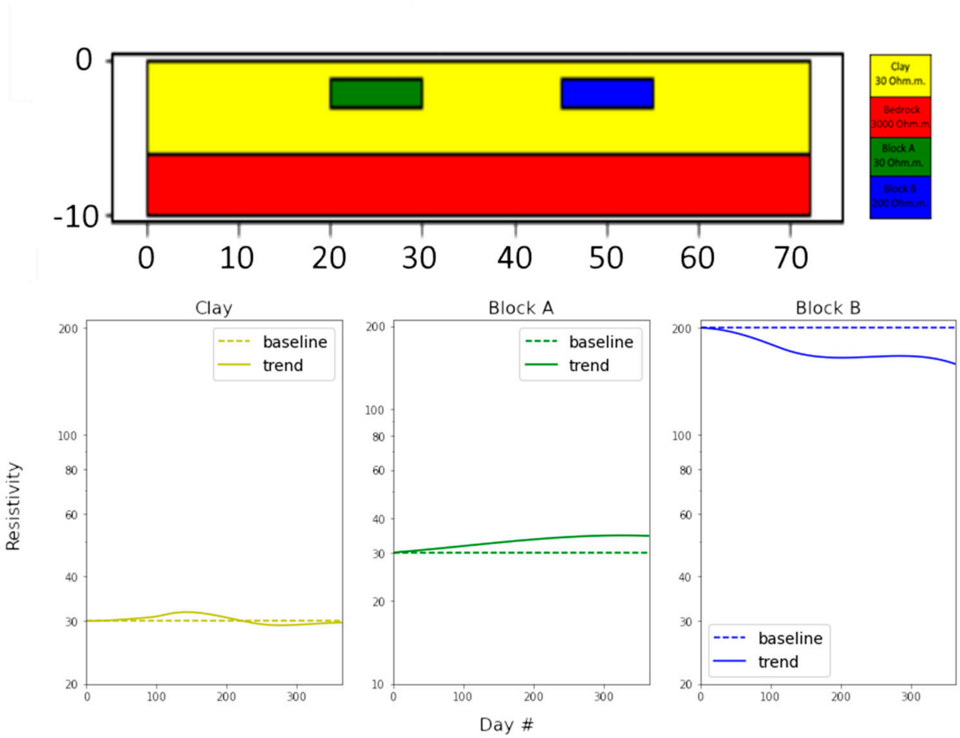


**Figure 18.** Geoelectrical units of the baseline model (top) consisting of clay (yellow), crystalline bedrock (red), block A (green) and block B (blue). The introduced resistivity variation is presented for the clay (bottom left), block A (bottom center) and and block B (bottom right).

**Figure 19** illustrates the inverted baseline model (top) and the results of the time-lapse inversion for the entire experiment. The resistivity of block A (**Figure 19**; bottom left, green line) is resolved accurately with a small deviation from the starting model. Furthermore, the resistivity changes compared to the baseline (**Figure 19**; bottom right, green line) show that the general trend is resolved relatively well, especially for the first 6 months. The resistivity value for block B (**Figure 19**; bottom left, blue line) is not resolved as well as for block A, which can be attributed to an inherent issue of the inversion as it is generally smoothing the results. However, even in this extreme case it is possible to follow the general trend relatively well (**Figure 19**; bottom right, blue line). The result is promising as in time-lapse experiments it is mainly the variation of the electrical properties during time that is used in the interpretations. If the actual values are of interest, then an inversion scheme with sharp boundaries and the use of a-priori information (Fortier et al., 2008) needs to be used instead, however this is beyond the scope of the work presented in this paper.

The suggested methodology can be efficient to handle noisy data that can potentially contain also missing values, without excluding entire quadrupoles from the final dataset. The analysis of the synthetic experiment shows that the suggested methodology appears to be applicable to large monitoring datasets. However, as it was discussed previously, in cases where the seasonal variations are dominant, or changes of lower amplitudes are to be investigated a more detailed analysis should be used. Even so, the proposed methodology can be used to highlight periods of interest in a large dataset, e.g., few years of high frequency monitoring, which otherwise would have been extremely time-consuming to investigate.

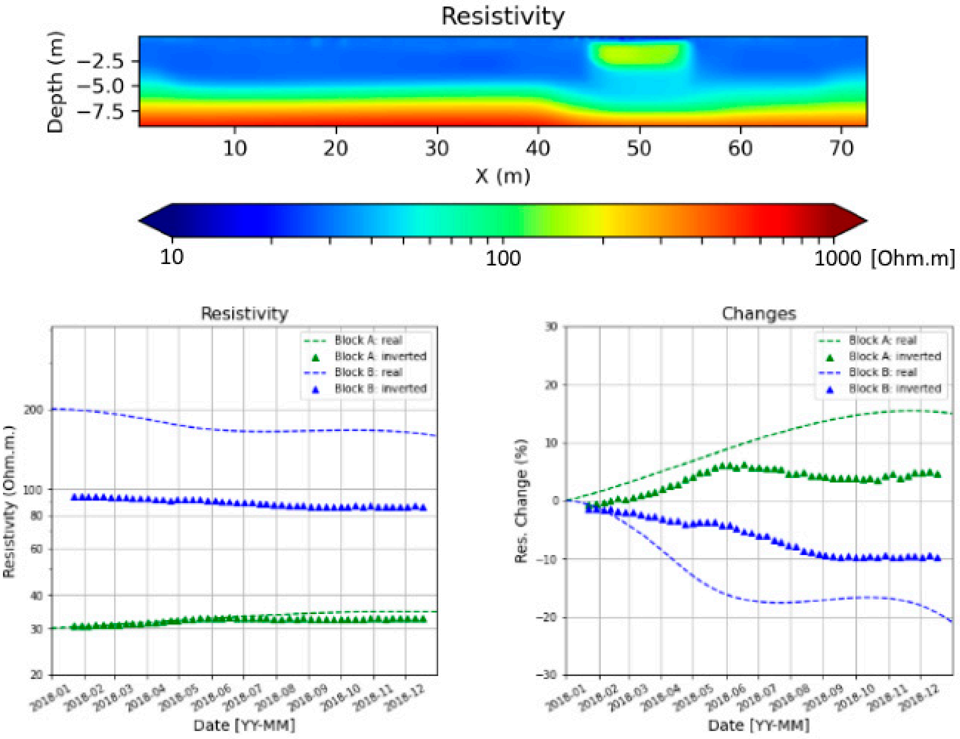


**Figure 19.** The inverted result of the baseline model is presented on the top figure. The time-lapse inversion results are presented on the bottom figure with green for block A and with blue for block B. The left figure shows the average resistivity and the right figure shows the average resistivity change.

The data were inverted using the time-lapse algorithm. First, using the data from the baseline a reference profile was calculated and then weekly (median) profiles were computed for the entire dataset (20 months). The weekly profiles were finally inverted against the reference baseline profile.

The inverted results (**Figure 20**) show that the two treated areas behave differently during the 20-month period after the remediation program was launched. The area treated with the iron particles (Line 3) shows a general decrease in the electrical resistivity that dominates the entire time period. On the other hand, the area treated with the mixture of bacteria (Line 3) appears more resistive as the time progress.

**Figure 21** illustrate the change in resistivity and chargeability for three areas of interest, the two treated areas and a reference area that no treatment took place. A block of 10x2 meter was selected for each area and the average value for the % change in resistivity and the change in chargeability is presented. It is evident that the resistivity values in the area where they injected the iron particles (**Figure 12**, east area) are reduced significantly when compared with the baseline. On the other hand, the area where they injected the bacteria (**Figure 12**, west area) and the untreated area (**Figure 12**, end of Line 3) appear to change in a very similar way. That could mean that either the method fails to identify changes due to the effects of remediation or the experiment was unsuccessful.

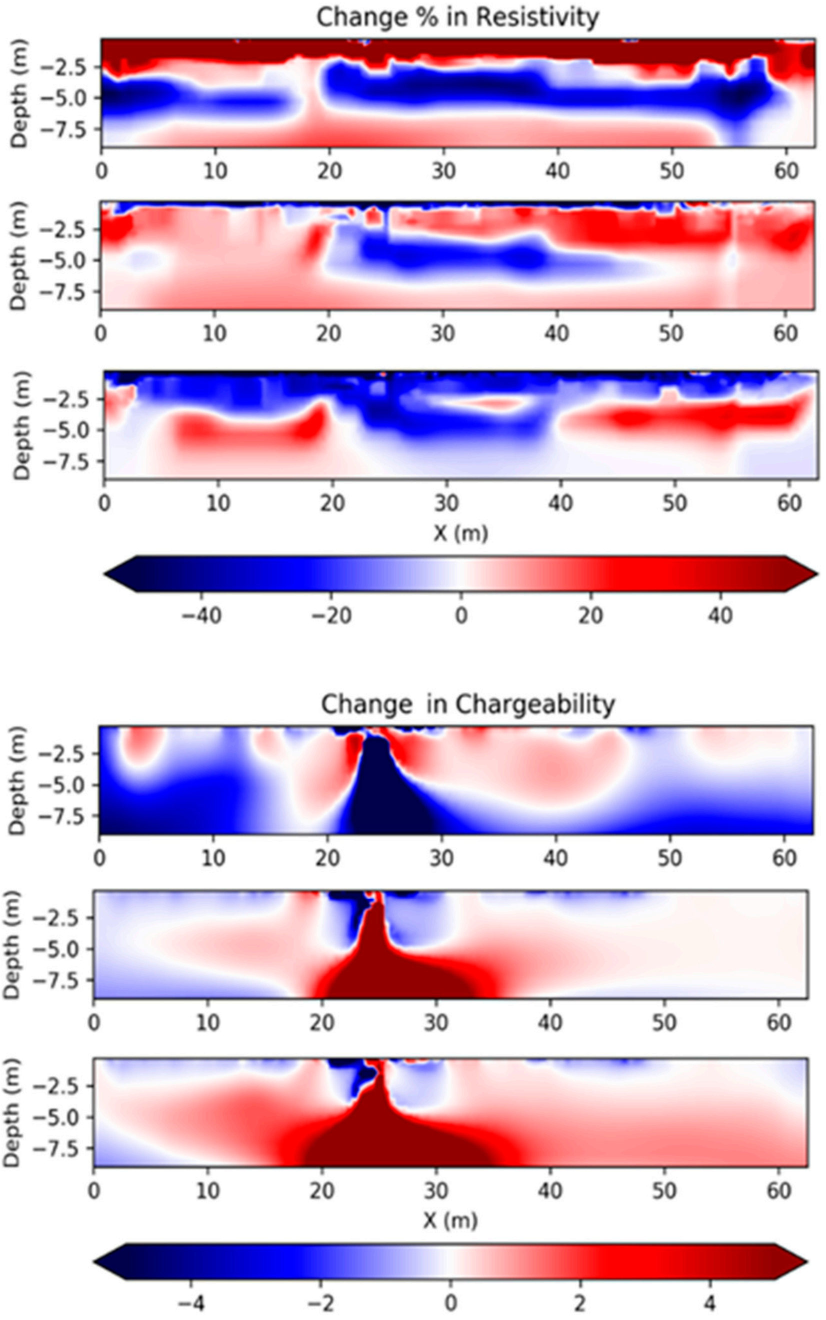


**Figure 20.** Examples of time-lapse inversions of Line3: from dates 2018-03-08 (top row), 2018-10-21 (middle row) and 2019-02-27 (bottom row). Percentage change in resistivity (top three) and absolut change in chargeability (bottom three) compared to baseline dataset.

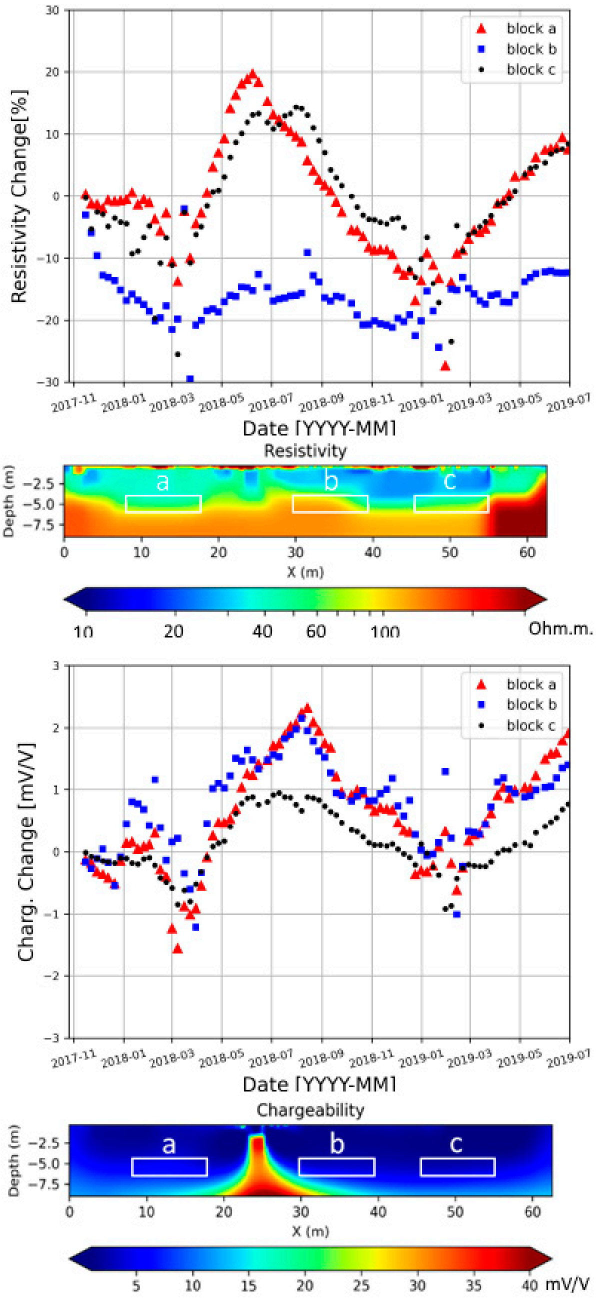


**Figure 21.** Analysis of the time dependent variations of resistivity (top) and chargeability (bottom) for Line 3. Resistivity is represented as percentage changes of inverted data respect to background, while chargeability is the absolute variation of inverted integral chargeability respect to background values. The values of the plots are calculated averaging inside the three areas (a, b, c) highlighted in the inverted results from the baseline below the respective time dependent variations.

Figure 22 shows part of the results from an extensive hydrochemical survey that was performed to monitor and validate the in-situ pilot bioremediation (Åkesson et al., 2021). The analyses were performed on water samples collected from wells with filters in the sand media, which are located between the crystalline bedrock and the clay layer. The data are sampled in boreholes that are closely located to Line 3 and 4 Figure 12. The concentration of PCE is dramatically decreased after the bioremediation was initiated and the concentration of the degradation products, specifically cis-DCE, is increased, for both area a (corresponding to samples in LU4) and area b (corresponding to samples in LU6). Based on the hydrochemical data, it seems that degradation is occurring in both area a and area b, hence the difference in the geophysical response is mainly due to the bioremediation agents.

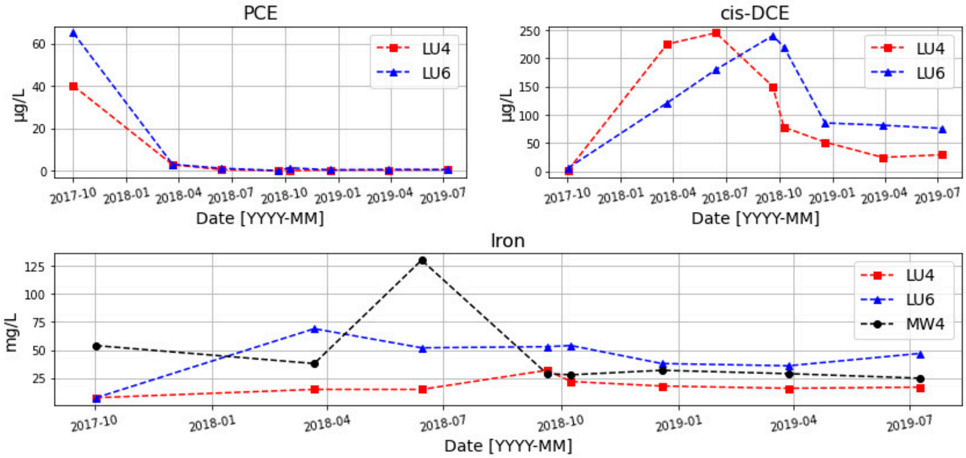


**Figure 22.** Hydrochemical results that show the PCE (top left), cis-DCE (top right) and iron (bottom) concentrations in the water samples (see Figure 8 for boreholes location). Water samples were collected by Sofia Åkesson and the WSP on behalf for the Swedish Geological Survey.

## 5.3 Paper III

The resistivity and induced polarization (DCIP) imaging highlights several changes that can be challenging to interpret. The results show a significant seasonal variation, which shall be considered in the interpretations and can be potentially missed if not sufficiently frequent data are taken. For the same reason, it is important to collect water samples during the same period (i.e., each October), if it is not possible to acquire them more frequently. In addition, the geophysical imaging provides insights about the spreading of the injected fluids, which is critical for the overall evaluation of the experiment (**Figure 23** and **Figure 24**). However, it is not possible to quantify the effects of the remediation using the geophysical imaging alone. On the other hand, the groundwater chemistry data (**Figure 25**) are critical for a qualitative analysis of the contaminants in the water but are limited to the accessibility of collected water samples, both in terms of frequency and spatial coverage. The results from this work illustrate how the two methodologies complement each other to increase the overall understanding of the changes that are expected to follow an in-situ remediation experiment.

The groundwater chemistry data can provide quantitative results about the concentration of the contaminants in the ground in the coarse-grained sand layer but not in the fine-grained clay layer where it is challenging to collect water samples. Geophysical imaging can potentially be used to provide qualitative answers for that. That was achieved by correlating the geophysical imaging with the groundwater chemistry results for the coarse-grained sand layer, where both are available, and then use the information to describe changes in the fine-grained clay layer (**Figure 26**). Overall, the results indicate that the remediation is ongoing and successfully reducing the concentration of the contaminants in the ground.

The correlation between the geophysical imaging and the groundwater chemistry shows that chloride ions and iron ions are the main chemicals that can be correlated with resistivity (**Figure 25**). That is to be expected, since iron is introduced into the system through the injection of the remediation fluids and chloride is released during each degradation step. That shows that the geophysical monitoring can provide good insights when it comes to the spreading of the remediation fluids. On the other hand, the direct correlation between the resistivity and the contaminants (PCE, TCE and *cis*-DCE) is weak and it could be challenging to delineate information regarding the concentration of contaminants without the use of groundwater sampling (**Figure 23**). The Induced Polarization also shows a significant increase which can be correlated to the spreading of the remediation fluids and possibly the treatment downstream at Area X where there are significantly higher concentrations of contaminants in the water (**Figure 24**).

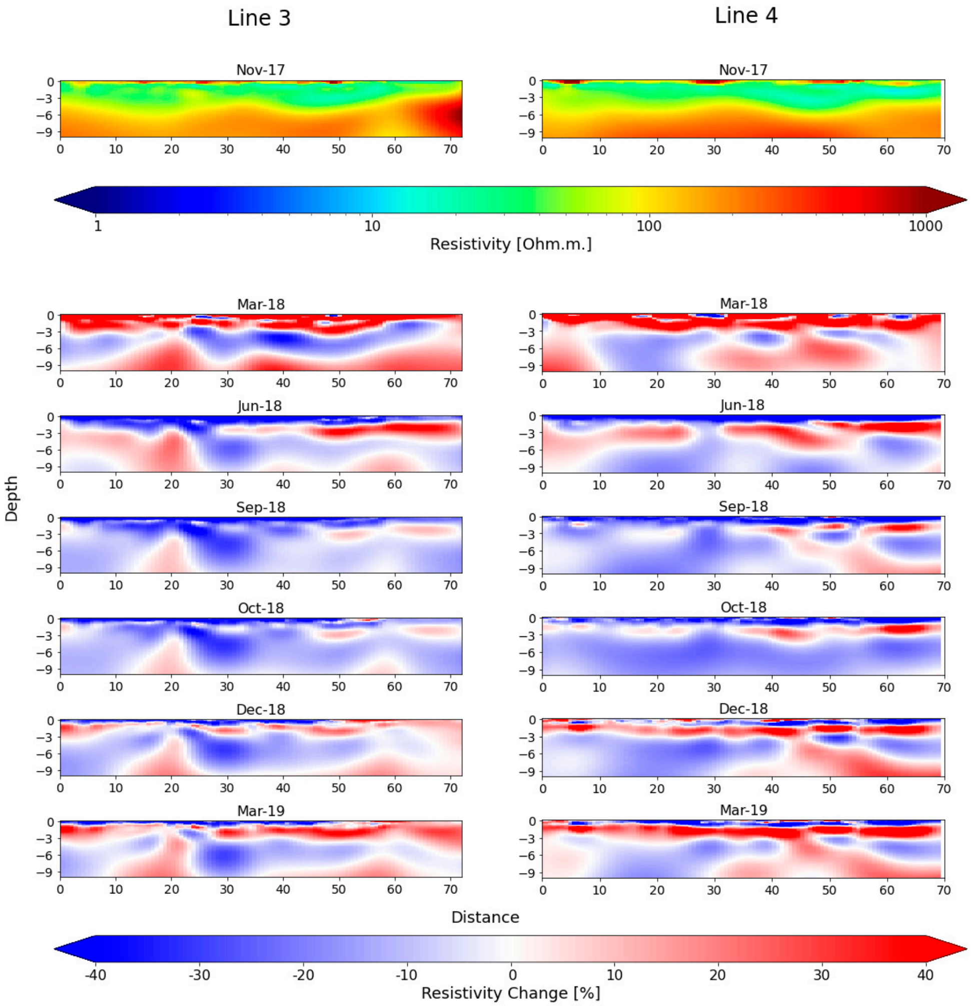


**Figure 23.** Geophysical results for Line 3 (left) and Line 4 (right). The baseline resistivity profiles are presented on top and the resistivity changes (as percentage respect to the baseline) for each sampling day are presented below.

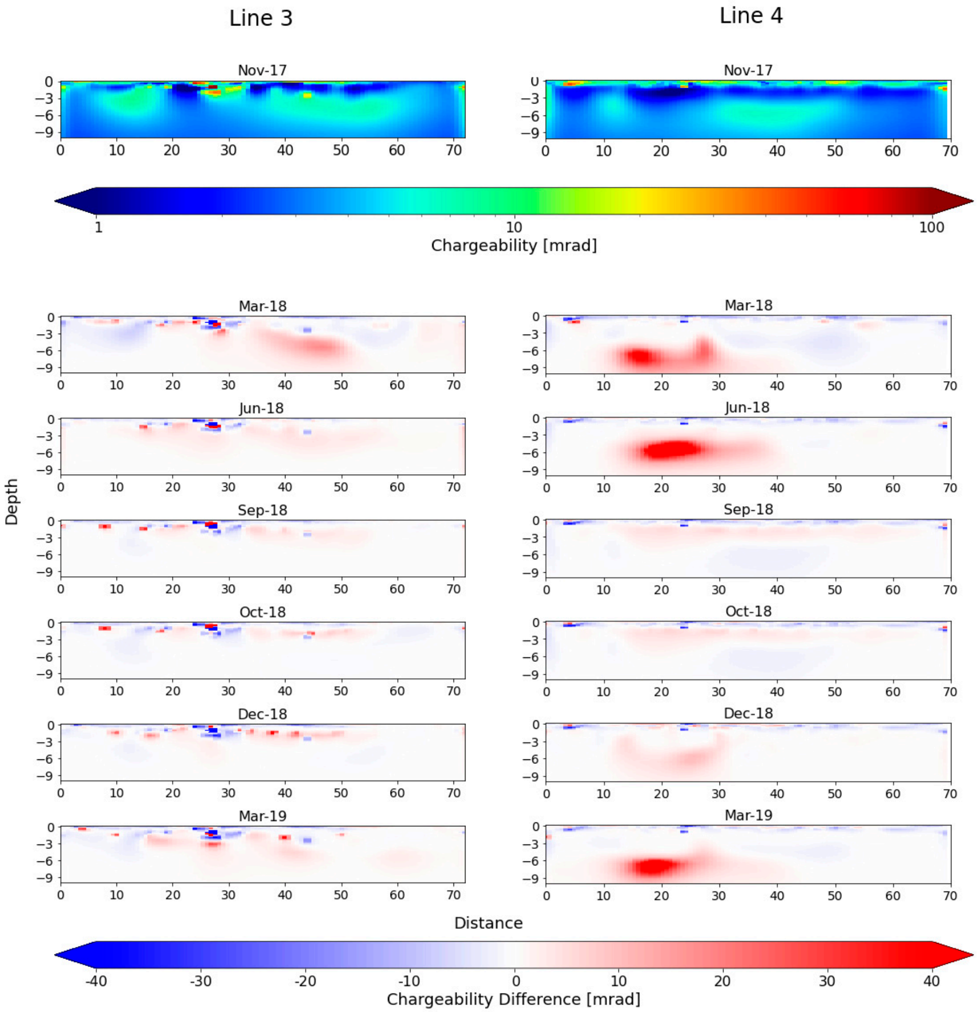


**Figure 24.** Geophysical results for Line 3 (left) and Line 4 (right). The baseline IP profiles are presented on top and the phase changes (as mrad difference respect to the baseline) for each sampling day are presented below.

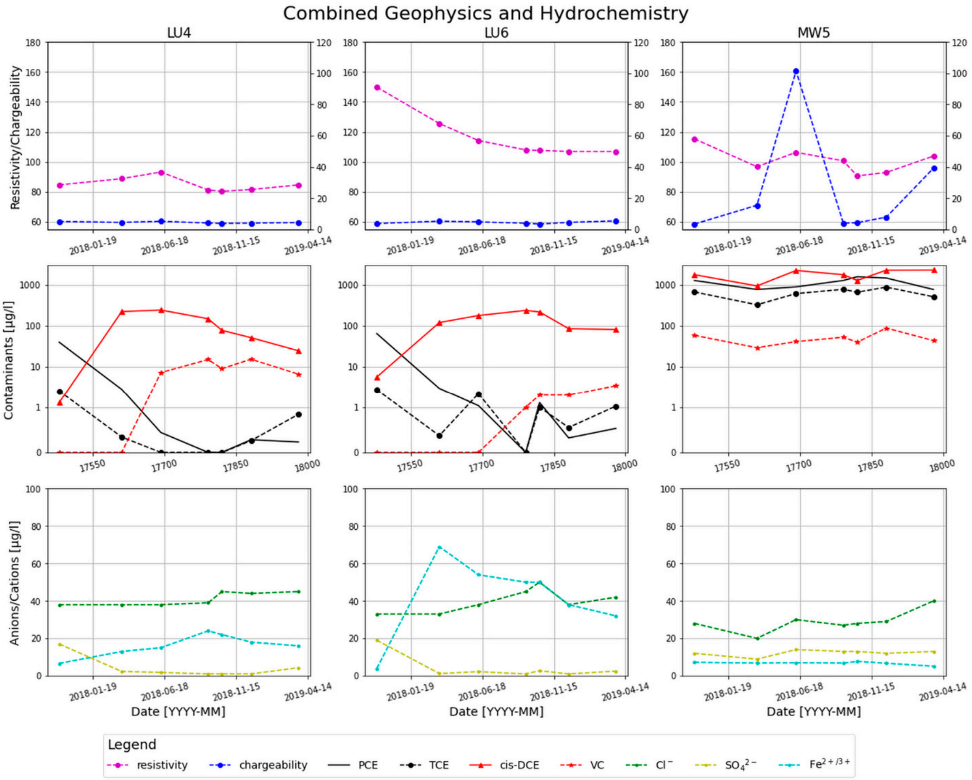


**Figure 25.** Geophysical results combined with groundwater chemistry data from the monitoring wells LU4 (representing Area A), LU6 (representing Area B), and MW5 (representing Area X, down gradient). The figures show 1st row: the average resistivity (purple); 2nd row: PCE (black), TCE (black with dots), cis-DCE (red solid), VC (red dashed), and 3rd row: chloride ion (green), sulphate ion (yellow) and iron ion (blue). The contaminants (2nd row) are plooted using a “SymLog” scale; logarithmic for values greater than 1 and linear for values less than 1.

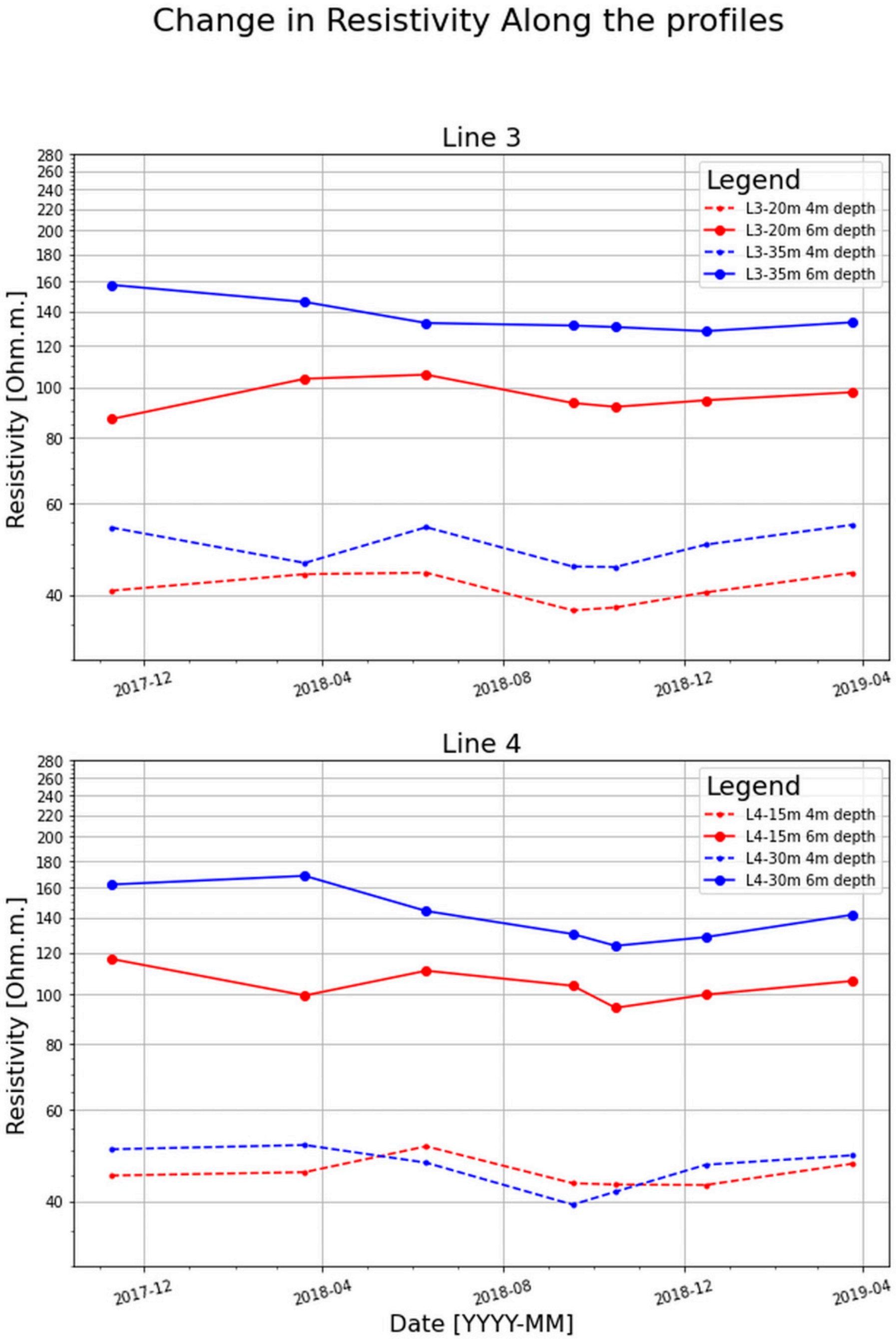


**Figure 26.** Resistivity changes in the soil along Line 3 (top) and Line 4 (bottom) for the low hydraulic permeability layer (dashed line) and the high hydraulic permeability layer (continuous line). The west and east part of the profile are represented by the red and the blue colour respectively.

## 5.4 Paper IV

In this paper, a comprehensive methodology for collecting, processing, and displaying geoelectrical monitoring data is presented. The suggested methodology consists of three major components:

i) monitoring software that is responsible for data collection (**Figure 27**)
ii) processing routines that can handle the data as soon as they are acquired (**Figure 28**)
iii) an interactive dashboard to view the data (**Figure 29**)

The proposed methodology has been evaluated in multiple scenarios and successfully implemented at four test sites. It is robust and may be implemented without substantial programming expertise. The interactive dashboard enables geophysicists and stakeholders to exchange data with minimal effort. Furthermore, the routines are adaptable and can be utilized with various datasets. Advanced use the software as the foundation of the monitoring workflow and introduce specific filtering functions that can be applied based on the monitoring project's requirements.

The final version of the GeMeasPy (data collection) software has been fully developed, tested, and validated. It has been integrated into the system or platform of interest, and its performance has been assessed in depth. The software is now deployable and commercially viable. The GeMonPy (data processing) program has been tested and deployed effectively in an operational setting. This verifies the software's ability to work as planned in real-world conditions. We evaluate the technology readiness level (TRL) for the data gathering and processing software to be eight and seven, respectively. The geoelectrical dashboard is evaluated in a realistic setting that closely mimics its intended operating context. This illustrates the performance of the software and identifies any required modifications. Hence, we consider the TRL to be five.

The proposed methodology has been automated and may generate data for geoelectrical monitoring applications as close to real-time as possible. In a few seconds, our Python code can process and show incoming data, and the delays are caused by third-party inversion tools.

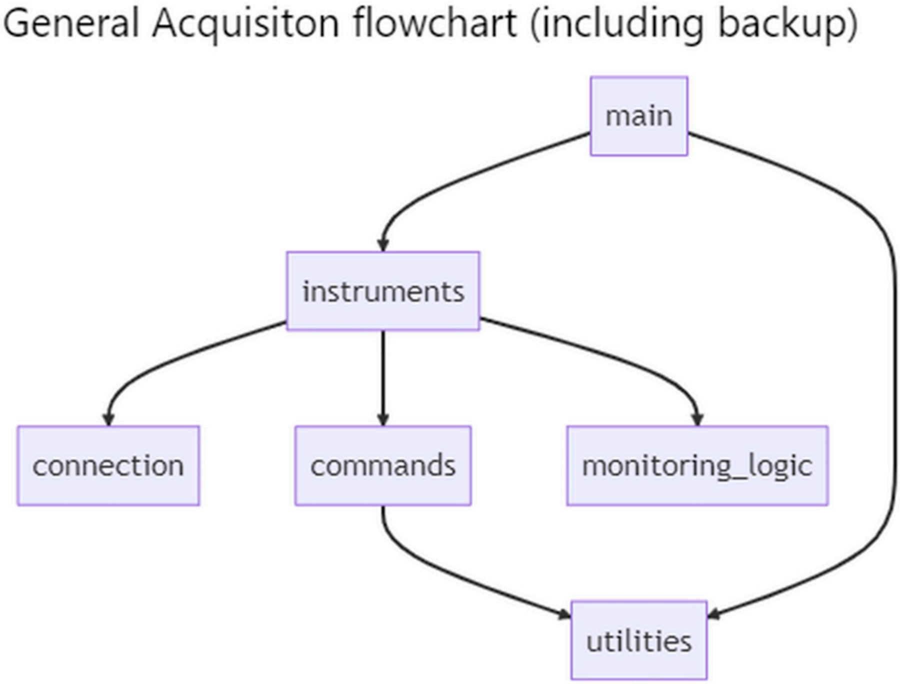


**Figure 27.** Diagram describing the schema of the automated monitoring system, based on the Terrameter LS2.

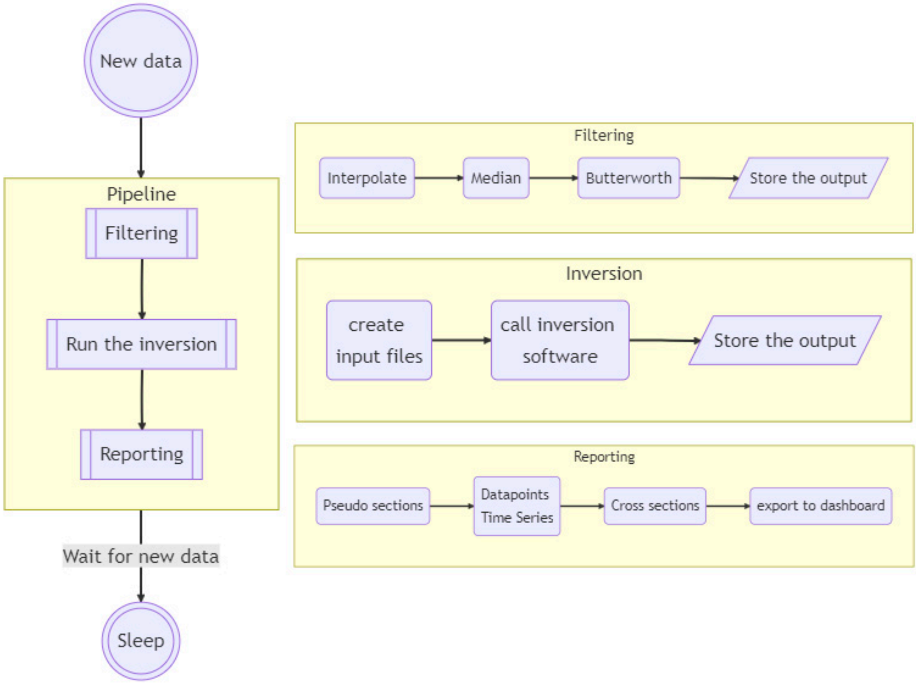
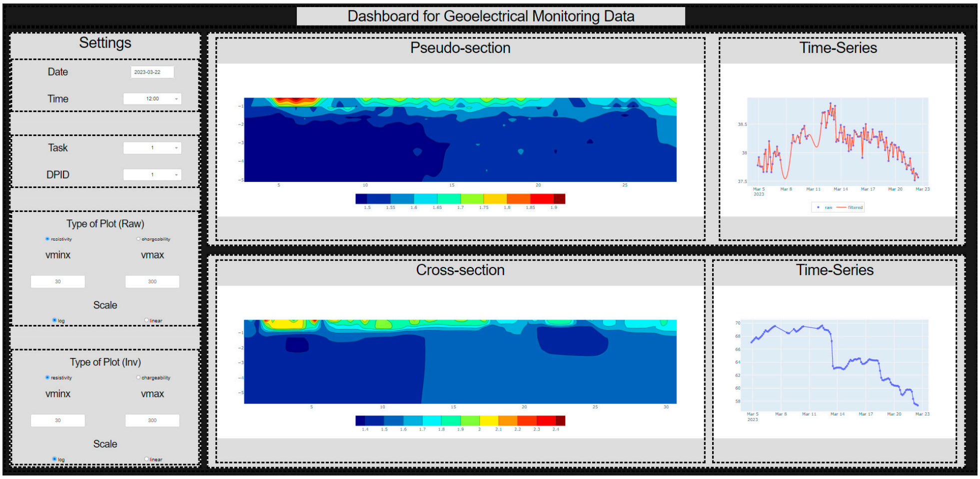


**Figure 28.** Complete dataflow proposed that is aimed for close to real-time monitoring results.



Date 2023-03-22

Time 12:00

Task 1

DPID 1

Type of Plot (Raw)

● resistivity ○ chargeability

vminx 30

vmax 300

Scale

● log ○ linear

Type of Plot (Inv)

● resistivity ○ chargeability

vminx 30

vmax 300

Scale

● log ○ linear

**Figure 29.** Interactive geoelectrical dashboard. The dashboard runs on a webserver and users can log-in using their credentials. It is possible to visualize the data by selecting date, time, task and measurement id. Further visualization options will require the source code to be modified.

# 6 Conclusions and future research

The work presented in this thesis demonstrates the use of the DCIP method for investigating a site contaminated with chlorinated solvents. Furthermore, DCIP monitoring is used to follow an initiated in-situ remediation treatment in a site in Sweden. In addition to the geoelectrical data complementary methods were used, including surface refraction tomography (SRT), geotechnical drilling, membrane interface probe (MIP) and water sampling for hydrochemical analyses. The data from each method were analysed individually but were evaluated together, in different steps of the work, to acquire a gradually more detailed model of the changes in the subsurface. The application of the suggested methodology shows promising results for following the changes caused by the remediation treatments.

For the successful application of the DCIP monitoring method, an autonomous monitoring system (based on a commercially available geoelectrical instrument) was developed. The system enables the robust and frequent acquisition of high quality geoelectrical data. Also, routines for automating the necessary processing steps, to deliver the geophysical end-product (i.e., the inverted cross-section) daily, were developed.

The work adds a specific but significant contribution to the advancement and application of geoelectrical monitoring. This information can hopefully lead to the application of cost-effective remediation treatments in contaminated sites. The open-source tools that were developed can significantly lower the required expertise to deploy and maintain geoelectrical monitoring systems. As such, this research can hopefully enable a wider use of geoelectrical monitoring systems for environmental, engineering and other applications, leading to more efficient resource use and reduced risks.

## 6.1 Main scientific contributions

A main scientific contribution from this work is the development of an autonomous DCIP monitoring system that can be used for continuous monitoring of the subsurface processes. The system was used to deliver daily geophysical data that were used for the baseline investigation (Paper I) and the analysis of the effects of the remediation (Paper II + Paper III). The data collection element of the system has been tested and successfully applied in other DCIP monitoring experiments, which are not presented as part of this work. Routines for handling the data, to enable automated processing of the incoming data flow, were developed and tested against synthetic data (Paper II). The results from the synthetic experiment show that the proposed schema is sufficient to describe the changes due to the remediation treatment and were used to analyse the geoelectrical data on a weekly basis (Paper II). The proposed schema was then integrated to form a software that can fully automate the flow of geoelectrical data, from data collection to visualisation, which is made available to the research community as an open-source tool (Paper IV).

A multimethod approach was used to update the existing geological conceptual model about the area and provide a better understanding of the subsurface conditions. The existing geological conceptual model was based on the results of the MIP soundings, which is a direct push method. The main downside of direct push methods is the limited coverage that they offer. For the purpose of investigating the depth to bedrock, which is critical on how the contaminants migrate in the area of investigation, the SRT method was used. The information from the direct push method was used to calibrate the SRT data, where the two methods overlap, and then the data were analysed together to create a map describing the bedrock topography covering a much larger area than previously (Paper I). The results from the baseline DCIP investigation were also evaluated together with the MIP soundings, that provide information regarding the contaminants concentration. The results are promising in identifying contaminated soil, providing that a good geological conceptual model exists (Paper I).

There are seasonal changes present in the data, due to changes in the temperature or ground conditions, therefore, as this study suggests it is important to have frequent measurements (i.e., daily) to successfully capture, understand and exclude such effects from the interpretation. Especially in Alingsås (and other areas with similar climate) the frozen ground that could be present during the winter will have a strong effect on the quality and the results of the DCIP monitoring (Paper II). The analysis of the temperature profile shows that the temperature effects could have a significant impact on the data for up to 3 metres below the surface, but they are mild for larger depths (Paper III). The exact numbers will be different for other climates or site conditions and could also differ from year to year therefore it is important to install sensors to measure a vertical temperature profile (Paper III). Overall, the temperature effects become extremely important for shallow investigations, as the temperature effects are much more severe (Paper II + Paper III).

The daily DCIP monitoring data were used to evaluate the effects of the in-situ bioremediation experiments. The results from the analysis show that it is possible to follow the injected remediation agents, especially in cases where they have a strong geoelectrical response. For that reason, it is possible to follow the spreading of one remediation agent that was used in the area (CAT100™) but not the other (Provectus ERD-CH4™). That can be explained due to the high iron concentration

(ZVI) which is present in the CAT100™ that gives a strong geophysical response (Paper II + Paper III).

The analysis of the groundwater samples can provide useful insights about the hydrochemistry conditions and how they change over time, following an initiated bioremediation treatment. Unfortunately, they can only provide limited information, both spatially but also temporally. Therefore, the combined use of a DCIP monitoring system and hydrochemical analysis can increase the overall understanding of the changes that are expected to follow an initiated bioremediation treatment (Paper III). The DCIP data are sensitive to bulk changes and are therefore better suited to understand the spreading of the remediation agents (Paper II + Paper III). The DCIP results could possibly provide insights about the changes due to the degradation of the contaminants, but further research is needed to establish a clearer link between the contaminants and DCIP results (Paper III).

## 6.2 Suggestions for future work

There are still challenges to be addressed and issues to be resolved for making DCIP an industry standard for monitoring applications. Below a summary of the main issues is presented.

### 6.2.1 Joint inversion of geophysical data

The multimethod approach that was used in this work was sufficient to understand the underlying bedrock topography. The bedrock topography model that was generated by the combined analysis of the geophysical (SRT) and the geotechnical (MIP) data used to support the interpretation of the DCIP data. Future research could focus on further improving the geoelectrical result by combining overlapping data from different methods. For example, that could be done by introducing structural constrains during the geoelectrical inversion (structural constrain inversion) or by inverting the data from two (or more methods) simultaneously (joint inversion). The coupled or jointed inversion should produce more realistic representations of the subsurface that could support better interpretations.

### 6.2.2 Geoelectrical analysis of the remediation fluids

The exact chemical composition of the remediation fluids is often not fully disclosed as companies try to avoid sharing proprietary recipes. Therefore, it would be valuable to perform lab measurements as an add-on to the existing field technology, specifically to investigate the remediation fluids and their geoelectrical signature. Furthermore, the spreading of the remediation agents in different porous media, and specifically how that affects the DCIP measurements, should be investigated further in controlled lab experiments. Lastly, different injection strategies should be investigated to ensure proper delivery of the remediation agents within the treatment zone.

### 6.2.3 Coupled hydrochemical and geoelectrical modelling

The hydrochemical and geophysical data used in this work were analysed separately and the results from the analysis were used to make a joint interpretation. The hydrochemical data can provide quantitative information about the dissolved contaminants in the water, which can be used to produce contaminant transport models. Future research should focus on using the results from such models to constrain the geophysical inversion and produce more realistic models. Also, coupling contaminant transport models and geophysics is an ambitious but much needed step.

### 6.2.4 User-friendly and scalable monitoring system

The deployment of DCIP monitoring systems should be simplified by making the tools user-friendly and scalable. The specific goal was partly addressed in this thesis, with the automation of the data collection and analysis of the geophysical data. Also, the development of the dashboard makes it possible for non-experts to visualise the DCIP monitoring results. However, there is a need for further development of open-source tools, that should be well documented and maintained to promote transparency. Tools that can be used for data-driven filtering of the geophysical data, based on recent AI developments such as Convolutional Neural Networks (CNNs), can provide more reliable routines to exclude possible outliers from the collected datasets. This is necessary step for the industry to adapt the methodology for environmental and engineering applications.

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Printed by Media-Tryck, Lund 2023 NORDIC SWAN ECOLABEL 3041 0903

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Division of Engineering Geology
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ISBN 978-91-8039-723-0
ISRN LUTVDG/(TVTG-1045)/(1-182)/(2023)

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