TRIP A2: ELECTRICAL GEOPHYSICAL METHODS FOR ENVIRONMENTAL APPLICATIONS

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ABSTRACT

Accurate and high resolution characterization and monitoring of the contaminant domain is needed to efficiently address environmental problems in the subsurface. Limited, or no direct access to the area of interest complicates characterization and remediation efforts. Advanced geophysical methods can be used to characterize the subsurface.

Electrical resistivity imaging (ERI), a widely used and well established geophysical method, is increasingly used in environmental investigations, especially for hydrocarbon plume characterization, and monitoring of degradation processes. The induced polarization (IP) method, an extension to common resistivity imaging, can provide additional insight in subsurface characterization utilizing the same network of electrodes and typically the same instrumentation. ERI and IP can offer a lot of advantages in environmental applications such as inexpensive data with high temporal and spatial resolution. Such data can be used quantitatively if constrained by a small number of direct (e.g. geochemical) data.

Implementation of ERI and IP is straightforward, requiring a network of electrodes on the ground surface or in boreholes. Advances in instrumentation allow for the efficient acquisition of large data-sets that can produce 2D and 3D images of the subsurface. Caution should be taken for correct data collection and processing to avoid erroneous interpretation of electrical geophysical data-sets.

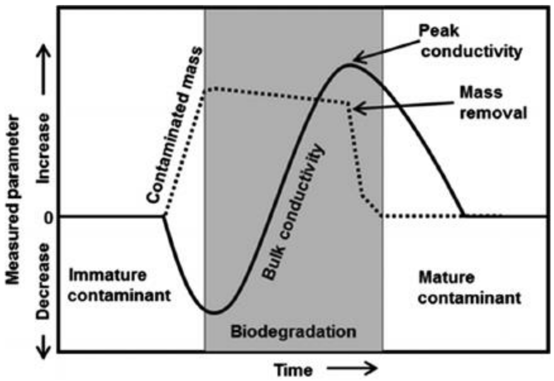
INTRODUCTION

Environmental contamination is a worldwide problem directly affecting humans (e.g. health, property values) and ecosystems. Contamination can also impact valuable and often limited resources (e.g. groundwater, surface water, soils). The problem is exacerbated by the vast differences in impacted sites from a leaking underground storage tank to mega sites that stretch across several industrial facilities. Although contamination is primarily the result of anthropogenic activities such as manufacturing, mining and improper waste disposal, some natural processes can also contribute to environmental degradation. This can result in a wide variety of contaminants, across a range of concentrations and different media. Subsurface characterization for environmental purposes can be challenging since it can occur across a variety of depths, often with no surface footprint. To efficiently address environmental problems in the subsurface, accurate and high resolution characterization and monitoring of the contaminant domain is needed.

Subsurface characterization for environmental applications is an inherently difficult task due to:

- very large number of contaminants at varying concentrations,
- variety of host media,
- different depths and extend of impacted media.

Continuous advances in characterization methods and protocols, changes in regulatory standards, and the update of existing and development of new remediation systems further complicate this task. In



1: Figure 1: Conceptual model of the hydrocarbon electrical conductivity properties change with time. The electrical conductivity of the subsurface is dropping as a result of the contaminant release; when degradation processes become significant the conductivity starts to increase, until the contaminant mass has been largerly removed / re-mediated and the system returns to the original condition (adapted from [Heenan et al., 2015]).

recent years, novel applications of near surface geophysical methods has shown the potential that exists for enhancing subsurface characterization. Advances in technology and improved understanding of geophysical signals have allowed for geophysical methods, such as electrical resistivity, to be used for environmental applications such as hydrocarbon mapping and delineation [Atekwana and Atekwana, 2009; Flores Orozco et al., 2012], mapping and characterization of buried waste and engineered structures (e.g. landfill boundaries) [Soupios et al., 2007; Tsourlos et al., 2014], geological characterization [Robinson et al., 2015], contaminant leak detection and monitoring [Johnson and Wellman, 2015], monitoring enhanced remediation[Williams et al., 2009a; Flores Orozco et al., 2011] and monitoring natural attenuation [Heenan et al., 2015].

Electrical resistivity imaging (ERI), a widely used and well established geophysical method, has been successfully used to characterize hydrocarbon plumes, and in some instances to monitor degradation processes [Atekwana and Atekwana, 2009; Atekwana and Slater, 2009; Heenan et al., 2015]. Hydrocarbon contamination and related processes (e.g. degradation) appear to significantly alter the subsurface electrical properties due to the production of electrically conductive degradation end products such as organic acids, increased dissolved ion concentrations resulting from mineral weathering, hydrocarbon emulsification and solid phase precipitates [Atekwana and Slater, 2009]. In recent decades, the conductive layer model has been develop to describe the links between hydrocarbon contamination in the subsurface and ERI signals. This new conceptual model extends the traditional model that requires the hydrocarbon plumes to act strictly as insulators. It suggests that the conductivity of the contaminated area will increase as the plume ages, resulting in higher condutivities relative to the bulk formation [Sauck, 2000, p.200; Atekwana et al., 2004; Atekwana and Atekwana, 2009; Heenan et al., 2015] (Figure 1). The suggested change of electrical conductivity is visually described in Figure 1; the initial hydrocarbon contamination causes an increase in organic contaminated mass and a corresponding decrease in conductivity. As biodegradation intensifies, contaminant mass decreases resulting in increasing biodegradation byproducts (i.e. increased ionic concentration), that lead to the observed decrease of bulk conductivity. Upon completion of the degradation processes, the system is expected to return to the original state (as far as electrical properties is considered).

The induced polarization (IP) method is a natural extension of the resistivity method where not only the resistive, but also the capacitive properties of the earth are measured [Rubin and Hubbard, 2005; Reynolds, 2011]. Although the IP is a well-established geophysical method, especially in the mineral exploration field, it has seen limited use for environmental applications until very recently mainly due to instrumental and computational limitations [Kemna et al., 2012]. In certain cases, IP surveys can offer additional information about the subsurface conditions. For example, IP has been repeatedly shown to provide diagnostic information on organic contamination, including (bio)degradation processes [Atekwana and Slater, 2009; Schmutz et al., 2010; 2012; Revil et al., 2012; Heenan et al., 2013]. The majority of this work though is based on laboratory experiments under controlled conditions, allowing for the links between geophysical signals and biogeochemical processes to be assessed [Schmutz et al., 2010; 2012; Heenan et al., 2013; Personna et al., 2013]. Conceivably, IP measurements may offer more information on hydrocarbon plumes, and associated bio-geochemical processes during environmental characterization and monitoring. However, broad use of the method in environmental applications has been hindered due to issues with acquisition of IP data such as data quality, processing, survey time requirements, and data interpretation. Recent field applications have highlighted the benefits of the IP method vs ERI and/or conventional monitoring but also emphasized the need for high quality data acquisition and processing [Williams et al., 2009b; Flores Orozco et al., 2011; 2012; 2015; Ntarlagiannis et al., 2015]. It should be highlighted that during IP surveys ERI data are inherently collected.

The need for more sustainable remediation methods [U.S. Sustainable Remediation Forum, 2009] highlight the need for robust tools suitable for efficient long term monitoring. Geophysical methods offer the monitoring capabilities including cost efficiency, spatial and temporal resolution required for long term monitoring, but lacked the technological background (e.g. communication, power needs) for long term autonomous operation. Technology advances in the recent years effectively overcame such problems rendering ERI and IP methods prime candidates for long term monitoring operations. Heenan et al. [2015] for example, used an ERI system to monitor the evolution of the British Petroleum (BP) Macondo well oil spill on Louisiana beaches for a period of ~ 18 months. The system was operated remotely with periodic visits (every few months) for preventive maintenance (Figure 2).

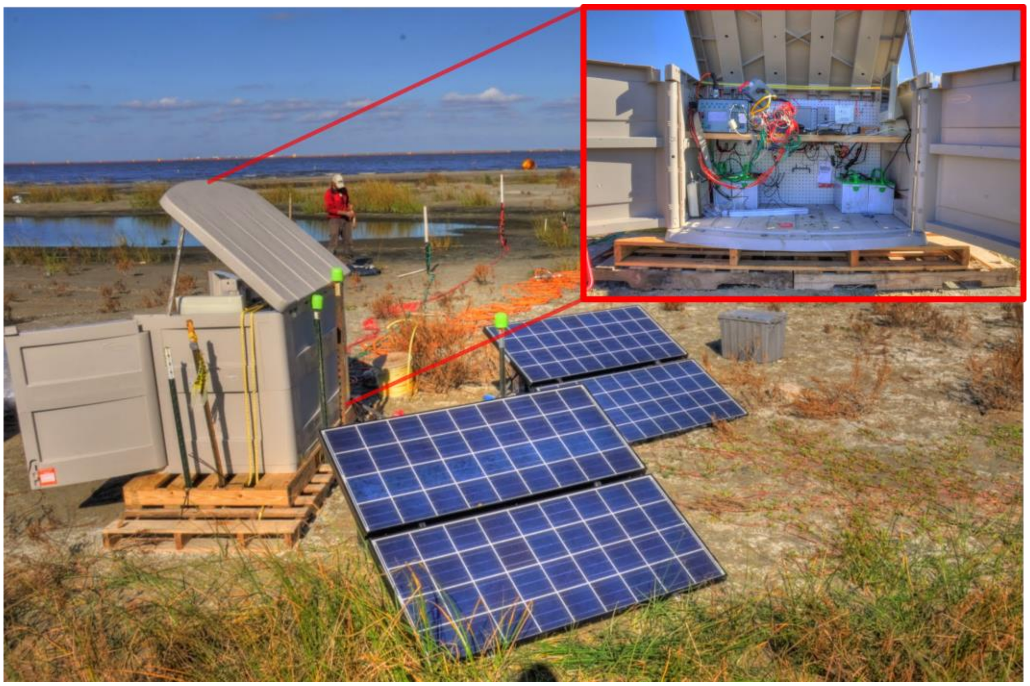


Figure 2: Long term ERI monitoring system built around standard off the shelf ERI instrumentation (Syscal Pro - Iris Instruments [IrisInstruments, 2016]). The system was anchored, secured in a weatherproof housing, powered by sun and remotely accessible through cellular connection. Modified from Heenan et al. [2015]

METHODS

Electrical properties of the subsurface

In the absence of metallic minerals, electrical current travels in the subsurface via electrolytic (σ_{ele}) and surface conduction (σ_{surf}). Both pathways involve ionic charge transport with σ_{ele} considering the fluids in the interconnected pore space, and σ_{surf} the electrical double layer at the mineral grain – fluid interface. Electrolytic conduction is directly related to fluid properties, ionic concentration, saturation and porosity [Binley and Kemna, 2005]. Surface conduction is a complex electrical property controlled by the surface area of the material, and the pore size or grain size distribution [Lesmes and Frye, 2001; Weller et al., 2010; 2013]. Surface conduction depends on fluid properties and mineralogy to a lesser degree [Lesmes and Frye, 2001; Weller et al., 2010]. Electrolytic and surface conduction pathways are commonly modeled to add in parallel [Waxman and Smits, 1968]

In terms of measurements, the real (σ') component of the measured complex conductivity (σ^*) represents electro-migration and the imaginary (σ'') parts represents charge polarization. These are related to the measured conductivity magnitude ($|\sigma|$) and phase (φ):

$$\sigma^* = |\sigma|e^{i\varphi} = \sigma' + i\sigma'', \qquad (1)$$

$$\sigma' = |\sigma|cos\varphi, \qquad (2)$$

$$\sigma'' = |\sigma|sin\varphi, \qquad (3)$$

where i = $\sqrt{-1}$. Based on the model of parallel conduction paths for electrolytic and surface conduction,

$\sigma' = \sigma'_{ele} + \sigma'_{surf}$, (4)

$\sigma'' = \sigma''_{surf}$ (5)

ERI is a widely used geophysical method that aims to model the subsurface conductivity ($|\sigma|$) structure of the area under investigation. ERI uses a network of electrodes to inject current *(I)* into the ground via two transmitting electrodes, and then measures the resulting potential drop *(ΔV)* among one, or more, pairs of receiving electrodes [Binley and Kemna, 2005]. The true subsurface conductivity distribution is estimated via inverse methods from a large number of measured transfer resistance (R) values,

$$R = \frac{\Delta V_p}{I} \quad (6)$$

where ΔV_p is the measured voltage, and *I* is the injected current.

The IP method measures the complex electrical properties (i.e. electromigration and polarization mechanisms) of the area under investigation [Binley and Kemna, 2005; Kemna et al., 2012; Revil et al., 2012]. Many modern instruments offer the option to acquire IP measurements in addition to ERI surveys, utilizing the same network of electrodes. Time domain IP measurements record the resistance magnitude (R) and an apparent chargeability m_a (mV/V),

$$m_a = \frac{V_s}{V_p}, \quad (7)$$

where V_p is the primary voltage, and V_s is the secondary voltage immediately after current shut off. The secondary voltage only exists when polarization mechanisms are significant. Since V_s is small relative to V_p and thus difficult to measure, an integral measure of m_a over a decay curve measured over a period of time (t) following current shut off is used:

$$m_a = \frac{1}{(t_2 - t_1)} \frac{1}{V_p} \int_{t_1}^{t_2} V\,(t)dt \quad (8)$$

The field IP parameters chargeability (m_a) and phase (φ) shift are both measures of the polarization strength relative to the electromigration strength (e.g. Slater and Lesmes, 2002). Consequently,

$m_a = -k\,\varphi$, (9)

where the constant of proportionality *k* can be experimentally derived in the laboratory (Mwakanyamale et al. 2012).

Field surveys

Electrical resistivity imaging (ERI) aims at determining the spatial distribution of resistivity ρ in the subsurface, typically with the use of four electrode measurements [Rubin and Hubbard, 2005]. ERI surveys utilize electrodes on the surface of the earth, in boreholes or a combination of the two. Surface surveys are typically categorized as either 'profiling' or 'sounding'. Profiling describes ERI surveys aiming at lateral variability (at a constant depth) while sounding (vertical electrical sounding – VES) is used to determine the change of electrical properties with depth at a single location. The development of modern multichannel ERI systems that are capable for simultaneous measurement of multiple pairs of electrodes and for the automated acquisition of a large number of measurements allows for efficient acquisition of large datasets. This effectively led to the wide adoption of imaging approaches where both VES and profiling are combined to produce 2D, and even 3D, images of the subsurface apparent resistivity [Rubin and Hubbard, 2005; Slater et al., 2010; Johnson et al., 2012; Heenan et al., 2015; Robinson et al., 2015; Ntarlagiannis et al., 2016].

Surface electrical surveys can be extended by placing electrodes in a single, or multiple, boreholes [Rubin and Hubbard, 2005]. The electrodes can either be placed permanently, or downloaded for each use, in uncased boreholes, or in PVC lined boreholes with sufficient slotted/open intervals; in some cases electrodes can be permanently placed (wrapped) on the outside of pvc boreholes. When two or more boreholes are used for resistivity surveys, the suggested term is electrical resistivity tomography (ERT).

ERT offers certain advantages over ERI such as high resolution with depth, and does not require surface access (e.g. below buildings). The disadvantages are that boreholes are needed, survey area is constrained by the boreholes, and data acquisition and processing might be more complicated and challenging. Very often surface electrodes are combined with borehole electrodes to provide more accurate image of the subsurface.

Field application of the IP method is similar to the ERI method, where four electrodes are used (two for current injection, and two for potential/chargeability measurement). Additional care should be taken to utilize electrode configurations that provide high S/N ratio, and maintain good contact with the ground (e.g. [Mwakanyamale et al., 2012]). In addition to the voltage difference measured during ERI surveys, in an IP survey the voltage decay with time, after current injection has stopped, is measured. The recorded gradual voltage decrease is a complex function of charge polarization at the interfaces (e.g. fluid-grain) and charge conduction within the fluid and the along the grain [Binley and Kemna, 2005]. The IP method has its origins ore prospecting, specifically for disseminated metallic minerals [Telford et al., 1990; Kemna et al., 2012]. Advances in instrumentation, along with better understanding of the underlying processes, led to the resurrection of the IP method in recent decades. IP is now more routinely used in environmental, and other, near surface geophysical applications, due to the unique sensitivity in interfacial processes [Rubin and Hubbard, 2005; Kemna et al., 2012; Revil et al., 2012; Ntarlagiannis et al., 2016].

DATA ACQUISITION AND INTERPRETATION

A variety of standard electrode configurations have been developed over the years that offer different survey characteristics and can be suited for different applications (Figure 3). In addition, custom made sequences can be utilized that address the specific objectives of each project [Rubin and Hubbard, 2005; Reynolds, 2011; Tsourlos et al., 2014]. In a typical survey, multiple measurements are acquired along one transect (2D) or multiple transects (3D). Measurements are acquired using a variety of electrode combinations and electrode separations (Figure 4) to create the so called pseudo-section. For the pseudo-section, a lateral and vertical position of the measured point is assigned for each data acquisition (Figure 4). The lateral position of the measurement is usually the midpoint of the 4 electrodes and the vertical depends on electrode separation; the depth increases as the electrode separation increases. Using all the measurements, the pseudo-section can be created, which shows the subsurface resistivity – termed apparent resistivity (ρ_a)- distribution assuming homogenous half-space. The true resistivity is then calculated using inverse methods. Figure 4 also highlights some of the limitations of such surveys showing areas with limited numbers of measurements (towards the ends).

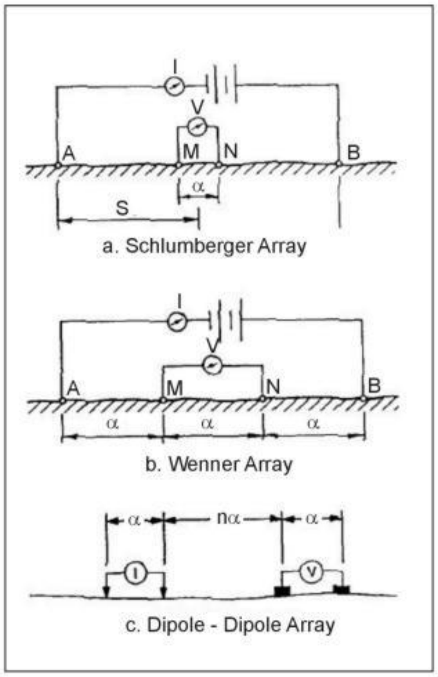


Figure 3: Common electrode configuration used for ERI/IP surveys. 'α' is the electrode (dipole) separation distance, and 'n' is the dipole separation factor (image from https://archive.epa.gov).

The apparent resistivity (ρ_a) is calculated from the measured resistance (equation 6) using the geometric factor *k* according to the following equation:

$$\rho = k * R \qquad (10)$$

The geometric factor depends on the electrode position and can be estimated using the general equation:

$$k = \frac{1}{AM} - \frac{1}{BM} + \frac{1}{BN} - \frac{1}{AN} \qquad (11)$$

where A is the location of electrode used currrent injection, B for current return, M is the electrode for the potential measurement and N is the potential measurement return (Figures 3, 4). For the most common surveys *k* is known (table 1).

Table 1: Geometric factor for common arrays. 'α' is the electrode separation distance, and 'n' is the dipole separation factor.

Array type	Geometric factor (*k*)
Wenner	$2\pi a$
Schlumberger	$\pi(n(n+a))/a$ $\pi(n^2/a)$, if $a \ll n$
Dipole – dipole	$\pi an(n+1)(n+2)$
Pole-pole	$2\pi a$

The true distribution of subsurface resistivity, and chargeability, can be estimated using inverse methods. Since this is a non unique problem, the solution is typically the result of a regularized optimization problem involving the minimization of an objective function comprising both data misfit (measured vs. modeled) and a correction term accounting for deviations from the desired model attributes [Binley and Kemna, 2005].

An important, but often overlooked, parameter for accurate electrical data processing is the reliable quantification of measurement errors; the inversion then needs to be weighted by a model reflecting the measurement error. A common method for error

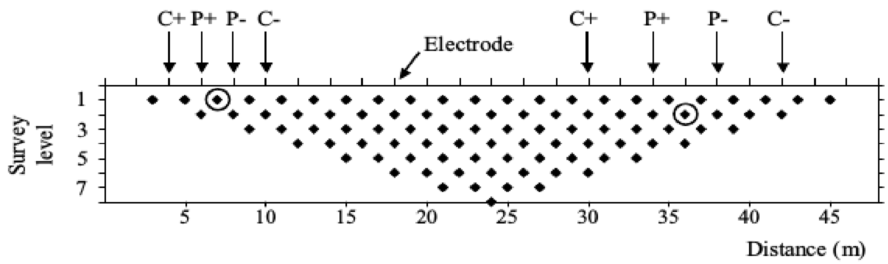


Figure 4: Typical ERI field survey. Circles identify the location assignment for the two measurement configurations shown. Each survey level corresponds to a different electrode spacing. (from [Binley and Kemna, 2005])

quantification is use of reciprocal measurements, whereby the potential and current electrodes are switched. As per the principle of reciprocity, differences between normal and reciprocal errors can be used to quantify the error in a measurement [Koestel et al., 2008].

An example of data acquisition, the resulting pseudo-section, and the inverted image can be seen in Figure 5. In this simulation exercise, we can see the true subsurface model (Figure 5a), and the resulting pseudo-section using the Wenner configuration (Figure 5b). Using inverse methods, an image of the subsurface resistivity can be reconstructed (Figure 5c). The inverted image appears to be closer to the real subsurface model, than then pseudo-section. The Wenner configuratin has poor lateral resolution, and is reflected in the inverted image (Figure 5c). A combination of multiple configurations could

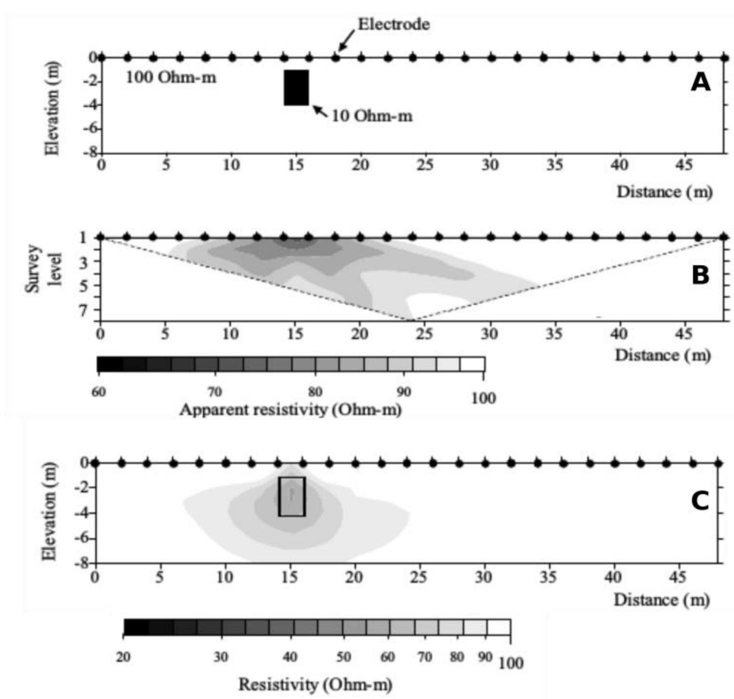


Figure 5: Example of electrical data acquisition and processing. A) the true model of subsurface, B) the pseudo-section of the acquired data, and C) the inverted image of 'real' resistivity distribution. (adapted from [Binley and Kemna, 2005])

provide a more accurate representation of the subsurface. Details and further information on data processing and inversion can be found in many textbooks [Telford et al., 1990; Rubin and Hubbard, 2005; Reynolds, 2011].

CASE STUDIES

Characterization of an organic contaminant plume.

The successful use of electrical methods for environmental applications has been demonstrated in many field projects. Ntarlagiannis et al. [2016] used ERI and IP to characterize, and monitor, the contaminant plume associated with an olive oil mill waste (OOMW) deposition pond (Figure 6). Data processing and inversion of the field ERI dataset revealed that the organic plume is characterized as a region of high electrical conductivity consistent with the conceptual model for the electrical structure of a biodegraded LNAPL contaminant plume. Furthermore, inverting of the IP dataset, they showed that the plume is also

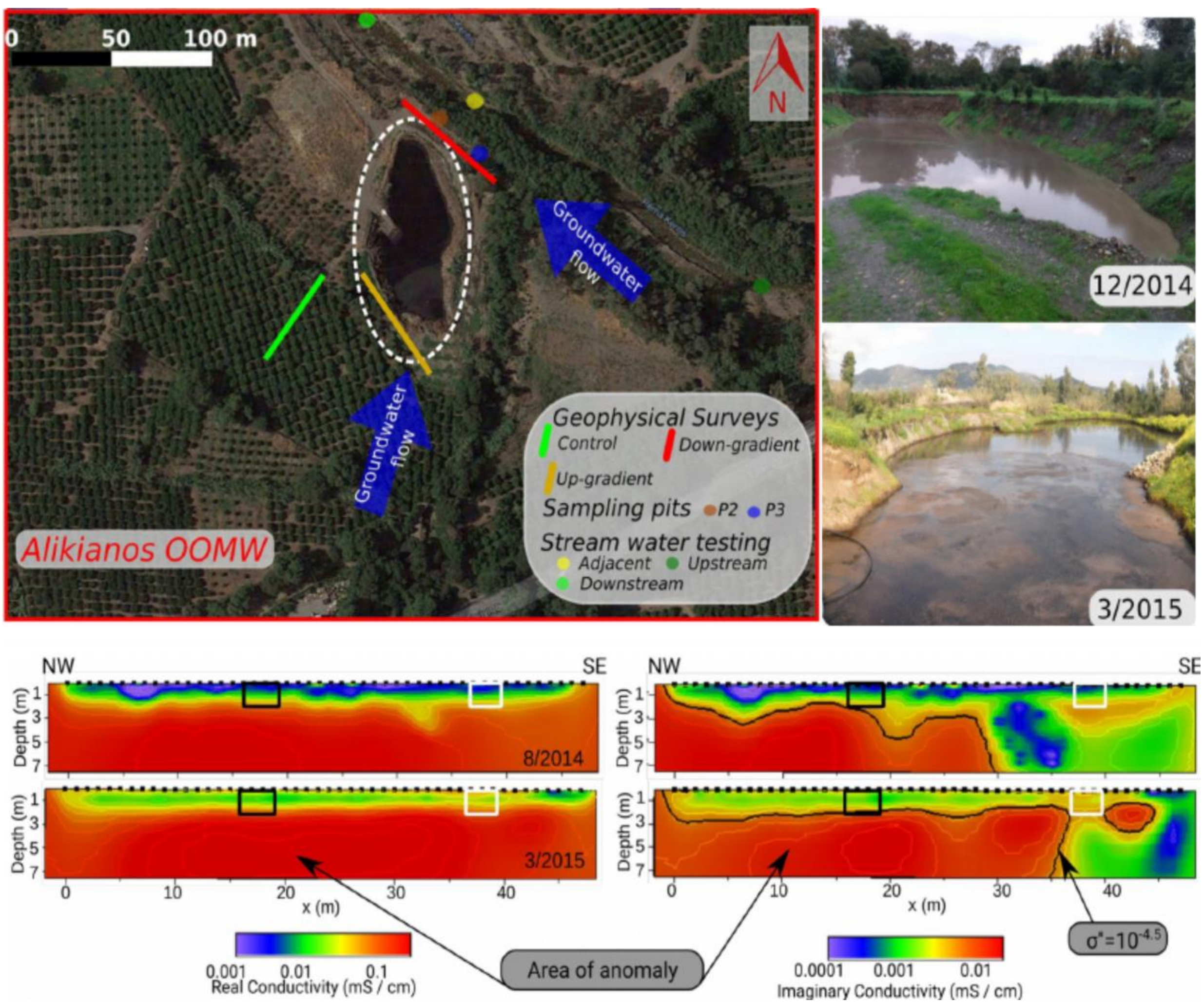


Figure 6: Map view of the Alikianos OOMW showing the areas where geophysical surveys have been performed, the geochemical sampling locations, and groundwater flow. On the upper right corner two images of the pond filled with increasing volume of organic waste. Characteristic imaging results from the down-gradient geophysical survey line are shown (bottom). ERI images (left) show the elevated conductivities as the result of organic contamination. IP (right) images delineate the plume more accurately, and are more sensitive to temporal changes. Adapted from [Ntarlagiannis et al. 2016].

characterized by a region of high polarizability that is more localized to the known plume location (based on conventional monitoring) relative to the high conductivity region in the electrical conductivity image. This observation is attributed to the fact that electrical conductivity is more strongly controlled by hydrogeological and geological characteristics of the site that mask the response from the biodegraded plume. This result encourages the use of field IP to improve the spatial delineation of organic contamination in the subsurface. However, more laborious field procedures are required to acquire reliable field IP data and the inversion of field IP data remains more challenging than resistivity data alone.

Long term monitoring of a young hydrocarbon plume in saline environment.

Geophysical methods are increasingly being used for detection/monitoring of microbial processes within earth media [Atekwana and Slater, 2009]. Although most of the previous work is on freshwater systems (mainly groundwater), the Deepwater Horizon (DH) oil spill into the Gulf of Mexico in 2010 allowed researchers to study an oil spill from it's early stages in a variety of brackish to saline environments. Heenan et al. [2015] deployed and autonomous resistivity monitoring system on Grand Terre, Louisiana, in an effort to monitor natural degradation processes in hydrocarbon-impacted beach sediments as a result of the DH accident (Figure 7). A 48-electrode surface array with a 0.5-m spacing was installed and was programmed to obtain twice-daily images of the resistivity structure of the shallow subsurface impacted by oil (Figure 2). Over the course of approximately 18 months, they observed a progressive decrease in the resistivity of the DH spill-impacted region, consistent with previous observations in fresh water environments (Figure 8). The observed change in conductivity is in agreement with the

Figure 7: The location of the autonomous ERI monitoring system on Grand Terre barrier island, LA. Oil observations from the BP response team are also shown. From [Heenan et al., 2015]

hydrocarbon conductive model, suggesting increase of conductivity as a hydrocarbon plume ages [Atekwana and Atekwana, 2009].

Detailed analysis of pixel/point resistivity variation within the imaged area showed that long-term

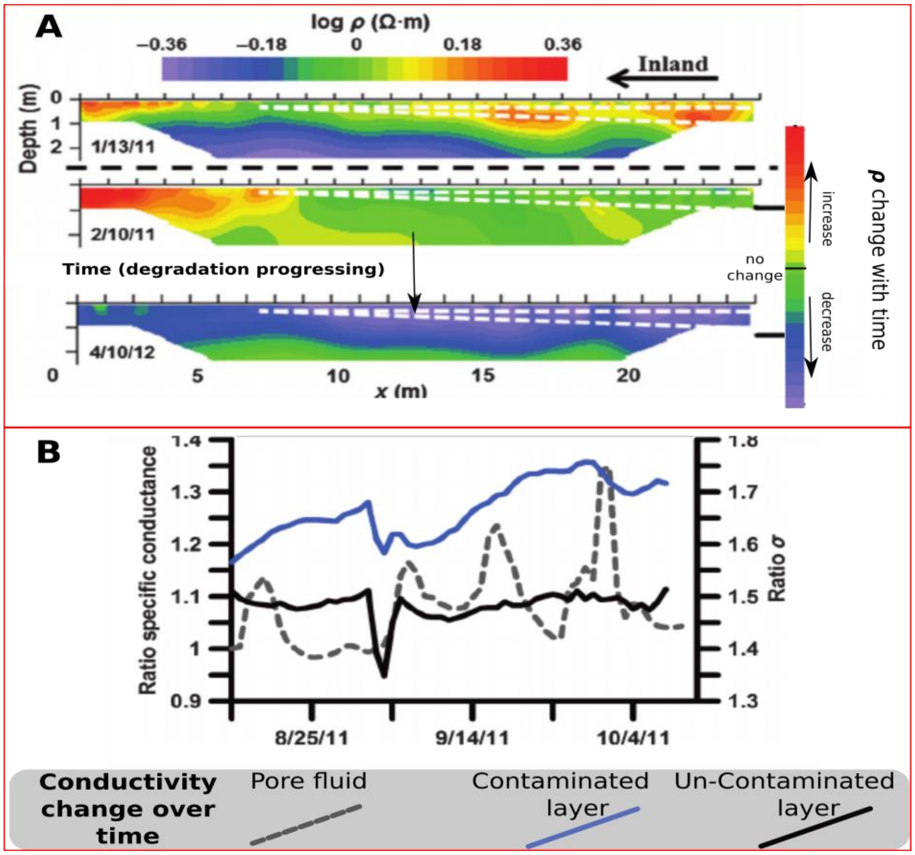


Figure 8: [A] Background resistivity (top) and ratio resistivity changes (bottom) from the ERI monitoring system. Overtime changes show resistivity decrease over time. The primary change is associated with the inferred location of the DH impacted oil layer. [B] Single pixel ratio conductivities change provide further evidence on the resistivity decrease of the DH oil impacted layer vs. the non impacted one. Modified from [Heenan et al., 2015]

decreases in resistivity were largely associated with the DH-impacted sediments (Figure 8). A microbial diversity survey revealed the presence of hydrocarbon-degrading organisms throughout the test site. This is consistent with the history of the site experiencing continuous hydrocarbon impacts (due to seeps and/or accidental spills). However, hydrocarbon degradation activity was much higher in the DH-impacted locations compared to non-impacted locations, suggesting the presence of active hydrocarbon degraders, supporting biodegradation processes. The results of this long-term monitoring experiment suggested that resistivity might be used to non-invasively monitor the long-term degradation of crude oil spills.

Electrical geophysical characterization for waterborne applications.

Electrical geophysical imaging can be used in waterborne configurations. Slater et al. [2010] used continuous waterborne electrical imaging (CWEI) to study hyporheic exchange at the Columbia River, at Hanford, WA. For over 40 years, starting in 1943, fluids containing radioisotopes and metals, generated during reactor fuel fabrication and chemical separation processes, were discharged to the shallow subsurface of the U.S. Department of Energy (DOE) Hanford 300 Area. Although studies in the 1990's predicted the decline of U in the groundwater, the concentrations remained largely unchanged. It was imperative to better understand and characterize U discharge, from the plume to the Columbia River. To achieve this goal, it was necessary to capture the spatial distribution of the primary lithologic units along the river corridor as well as spatio-temporal complexity in surface water–groundwater exchange driven by variations in stage levels on the Columbia River [Slater et al., 2010].

The research involved a novel implementation of CWEI to accurately resolve lithologic variability along a major river corridor by determining the spatial variation in the electrochemical polarizability, a property closely related to lithology, in addition to the electrical resistivity as routinely captured in CWEI studies.

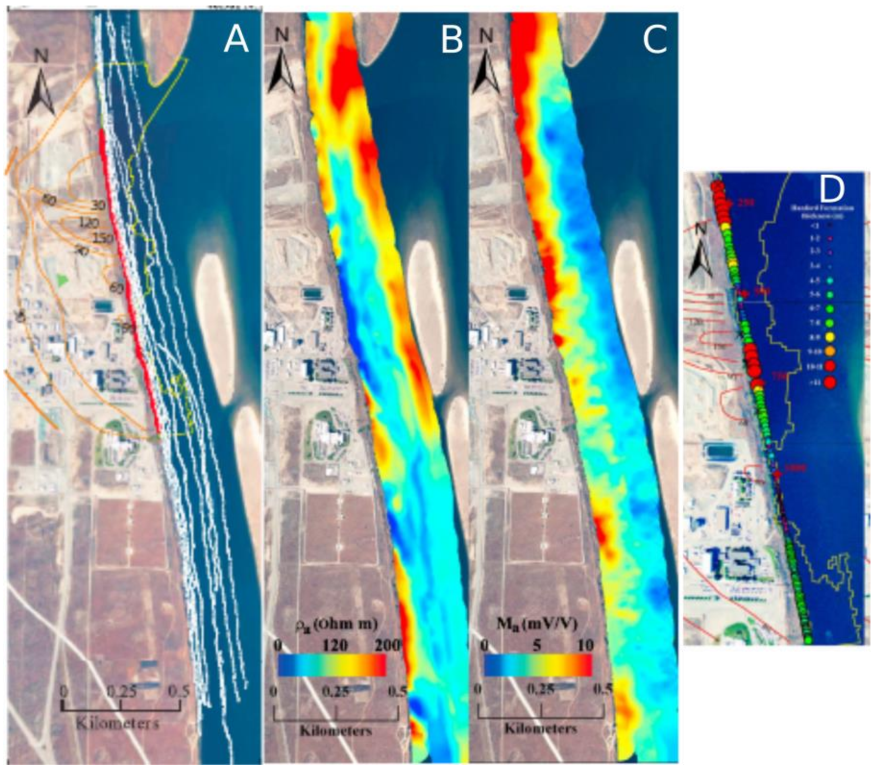


Figure 9: A) map of the CWEI tracks in the Columbia river. B) apparent resistivity and C) chargeability at the pseudodepth of 8.5m. D) Deteailed lithologic characterization of the surface / groundwater interface as estimated by the electrical data. Adapted from [Slater et al., 2010].

The raw CWEI data were processed and inverted to produce subsurface image of resistivity and changeability (measure of polarization) (Figure 9). The electrical data were used to estimate measures of lithologic variability with the use of established petrophysical relationships. Finally, the lithologic variation appeared to be the controling factor on hyporheic processes and U discharge in the river (Figure 9).

In another waterborne ERI implementation, Mansoor and Slater [2007] were successfully able to identify and characterize landfill contamination leaks into a wetland system. They were able to use conventional ERI survey in the brackish Kearny Freshwater Marsh, NJ by developing and utilizing a custom survey configuration. The custom non-conventional electrode configuration ensured high S/N and good quality data collection even in the highly conductive brackish marsh. This research showed that ERI can be used to spatially and temporally monitor pore-fluid conductivity changes in a shallow-water wetland when constrained by common field data (e.g. surface water conductivity, depth T profiles). The study conclusively showed that water from marginal landfills will enter wetland soils as a result of intense rainfalls.

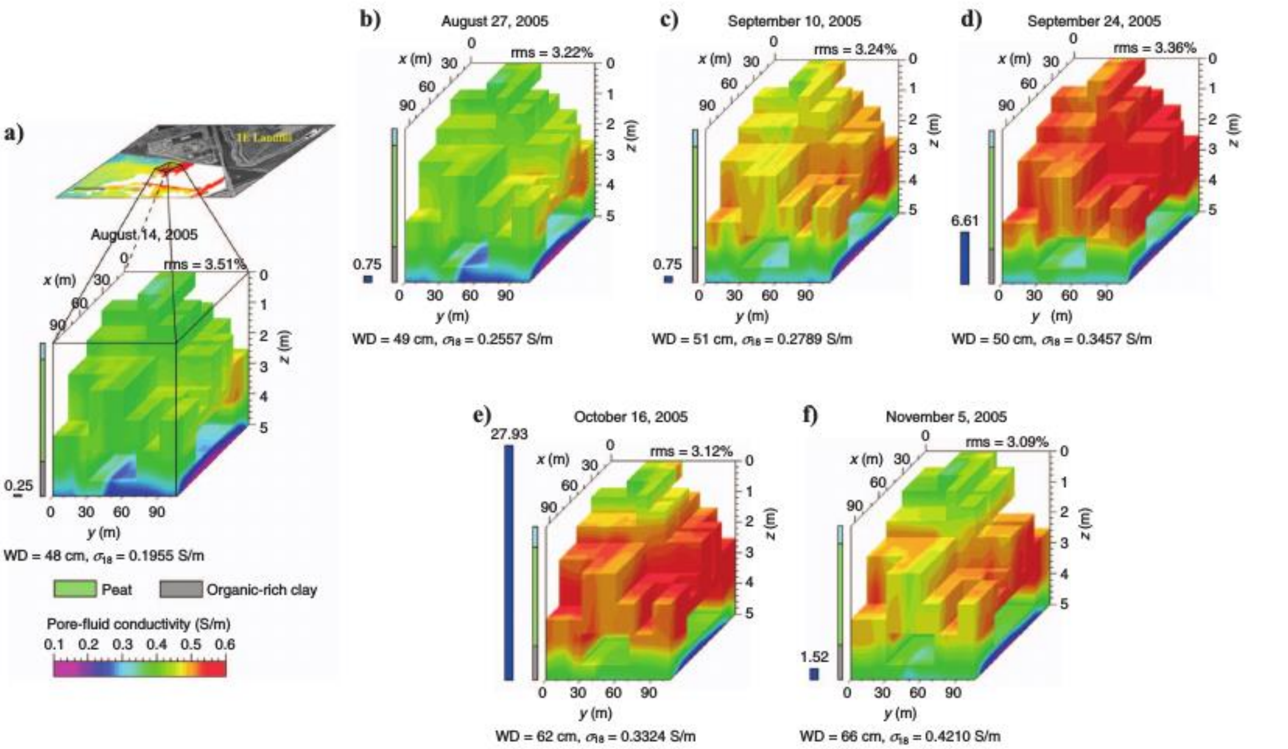


Figure 10: Subsurface pore-fluid conductivity models calculated from 3D inverted apparent resistivity data. Rainfall events are also shown to highlight the correlation between the event and marsh pore fluid conductivity changes. From [Mansoor and Slater, 2007]

CONCLUSIONS

Electrical geophysical methods such as ERI and IP offer unique advantages for subsurface characterization and monitoring related to environmental investigations. The current state of the art allows for efficient data acquisition and robust long term monitoring using ERI/IP. Geophysical methods can be used to delineate and monitor contaminant plumes. Additionally, ERI/IP are very well suited for monitoring long term remediation projects; the recent development of robust instruments with minimal power needs, and remote control capabilities, allow the autonomous operation in remote and sensitive environmetns. Better understanding of the signal source processes along with advances in processing and interpretation, could potentially allow the quantitative use of such tools. Implementation is not limited on land applications, with waterborne surveys becoming more common.

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