Time Lapse Electrical Resistivity Tomography (TL-ERT) as a Monitoring Tool of the Pollution in Areas of Olive Oil Mills' Wastes (OOMW)

Introduction and Problem Statement

The Mediterranean region accounts for no less than 97% of the world's olive oil production due to the favourable climatic conditions. Especially, Greece holds the third place worldwide in olive oil production and the island of Crete contributes approximately 5% to the total world olive oil production. The production procedure of olive oil generates large volumes of Olive Oil Mill Wastes (OOMW) with high organic load and rich in-inorganic constituents which lead to pollution of soil and water resources and therefore environmental degradation

The OOMW are usually disposed in evaporation ponds which are rarely of proper size and wastewaters often overflow affecting neighbouring systems (soil, surface and groundwater) and other professional activities of the residents (agriculture, livestock farming). The base of the ponds is permeable and thus, the probability for groundwater and deep soil contamination is high.

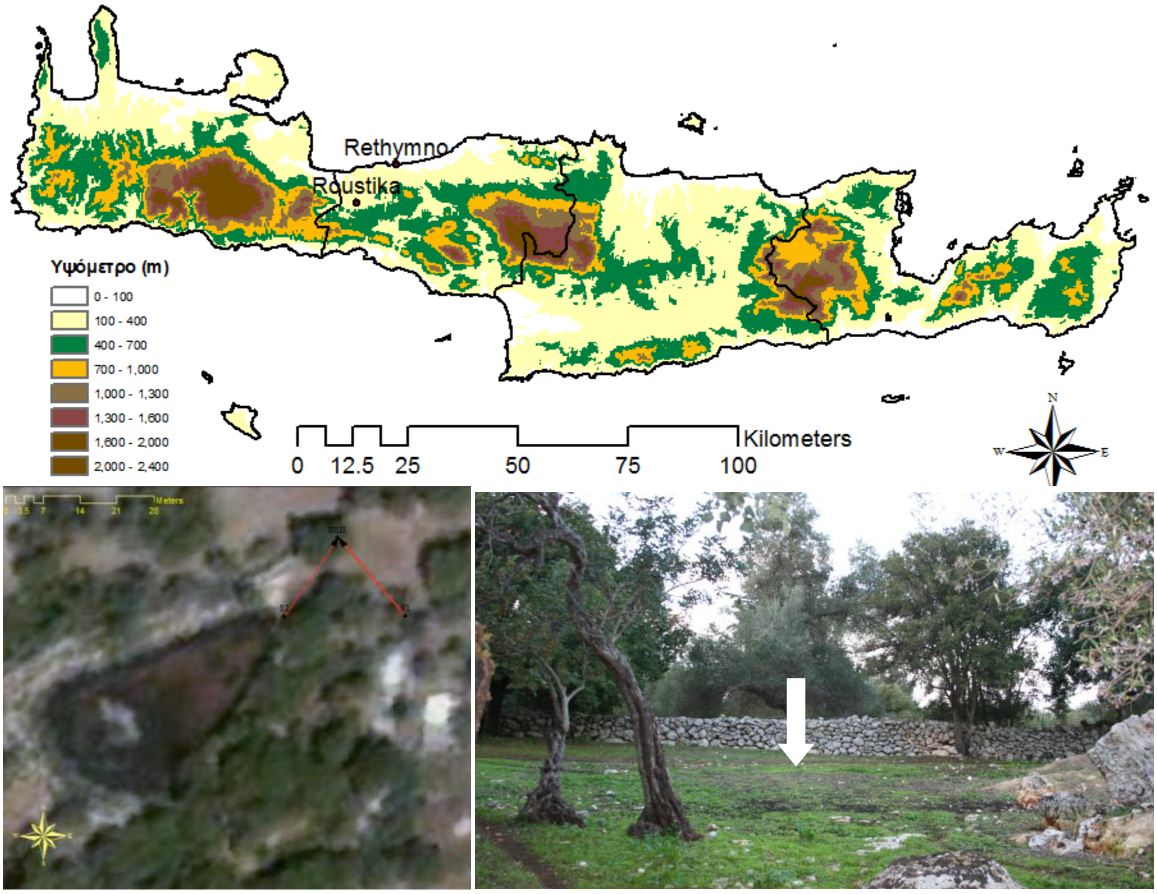

Figure 1: (up) The island of Crete (southern Greece) where the monitoring experiment was conducted. (down) Satellite image of the larger evaporation pond of the OOMW site where the geophysical ERT monitoring measurements were conducted. The white arrow in the left picure indicates the place where the borehole was drilled.

Consequently long-term disposal of waste, without necessary monitoring and protective measures, may cause changes in the physico-chemical parameters of the surrounding ecosystems, with the risk of future non-tissue degradation of the environment. Moreover, older waste sites often lack reliable geological or artificial barriers and depositional information, to minimize the possibilities of further environmental damages. The problem of environmental degradation and waste management are of major concern of earth scientists and the local authorities.

Geophysical methodologies in terms of Electrical Resistivity Tomography (ERT) can be used for monitoring the changes of the physical characteristics of the subsoil over time and identify the diffusion of the contaminants. An ERT monitoring experiment was conducted for the first time in an OOMW disposal site located in a test site in Crete. The purpose was to validate the resolvable capabilities of the method in capturing the spatial-temporal pollution caused by the low conductivity material of phenolic compounds.

Test Site, Crete (Greece)

Crete is the largest island of Greece and is situated at the south of the country. The test site where the ERT measurements were conducted is located in the countryside of the island and specifically in the village of Roustika, 21 Km south-west of the city of Rethymno. The ERT monitoring experiment focused on a private property at the west of road connecting Rethymno and Roustika. Within the property there two evaporation ponds, a larger one at the west and a smaller at the east, where the OOMW are stored. The property has also some scattered oil trees and is used as hosting place of sheep and goats (Fig. 1).

The Google Earth satellite image corresponding to the area of interest was extracted and rectified to the Greek Geodetic Reference System based on widely distributed ground control points, taken with a GPS with accuracy less than 1m. The ERT field data were gathered from flat area of almost 70 square meters at the east of the larger tank. The arrow indicates the location where the borehole was drilled (Fig. 1).

Field Strategy & Methodology

A drill hole was opened close to the larger evaporation pond and a plastic piezometer was installed inside the borehole that reached the depth of 16 meters from the ground surface. A custom made muti-clone cable was manufactured which could drive simultaneously up to 48 outputs (Fig. 2 middle). The cable was attached on the outer surface of the plastic piezometer gradually during its installation in the borehole (Fig 2 left). The cable outputs were placed on the plastic tube every 0.4m, the lead leaf covered each outputs by surrounding the tube. Each lead leaf (Fig. 2 right) was tightly fixed with plastic clamp ensuring the maximum connection between the cable output and the lead leaf. Totally 36 electrodes were placed inside the borehole starting from the depth of 2m and the reaching the bottom of the borehole (Fig 2).

Figure 2: (left) Installation of the multi-node cable on the outer surface of the plastic piezometer that was placed inside the borehole. Custom made multi-node cable with 48 electrode outputs (middle) and lead leaves that were used as borehole electrodes (right).

The ERT monitoring measurements were made in terms of surface-to-borehole mode. Stainless steel electrodes were used for the surface measurements and the length of the surface branch of the survey was 18.8 meters. The surface electrodes were placed along the vertical lines S1-BR and S2-BR in equal spaces every 0.4 meters. A dipole-dipole and gradient array configurations were employed to capture the surface, borehole and surface-to-borehole apparent

Time	Phase	Line	Array
28/1/2011	**T1**	S1BR	GRAD (forward & reverse) DD
Rainy weather Full tank with wastes Overflow of wastes a week ago		S2BR	GRAD (forward & reverse) DD
11/2/2011	**T2**	S1BR	GRAD (forward & reverse) DD
sunny weather Full tank with wastes Overflow of wastes a week ago		S2BR	GRAD (forward & reverse) DD
25/2/2011	**T3**	S1BR	GRAD (forward & reverse) DD
sunny weather Full tank with wastes Continuous overflow of wastes of the tank		S2BR	GRAD (forward & reverse) DD
18/3/2011 cloudy weather Full tank with wastes	**T4**	S1BR	GRAD (forward & reverse) DD **Optimized array with Jac method**
		S2BR	GRAD (forward & reverse) DD
15/4/2011	**T5**	S1BR	GRAD (forward & reverse) DD
sunny weather Full tank with wastes No overflow		S2BR	GRAD (forward & reverse) DD

resistivity measurements (Fig. 3). The gradient data were measured in a forward and reverse mode to evaluate and assess the noise level of the measurements. The time lapse resistivity data from totally 5 monitoring phases were collected from January 2011 until April of the same year.

Table 1: Monitoring phases of the ERT measurements

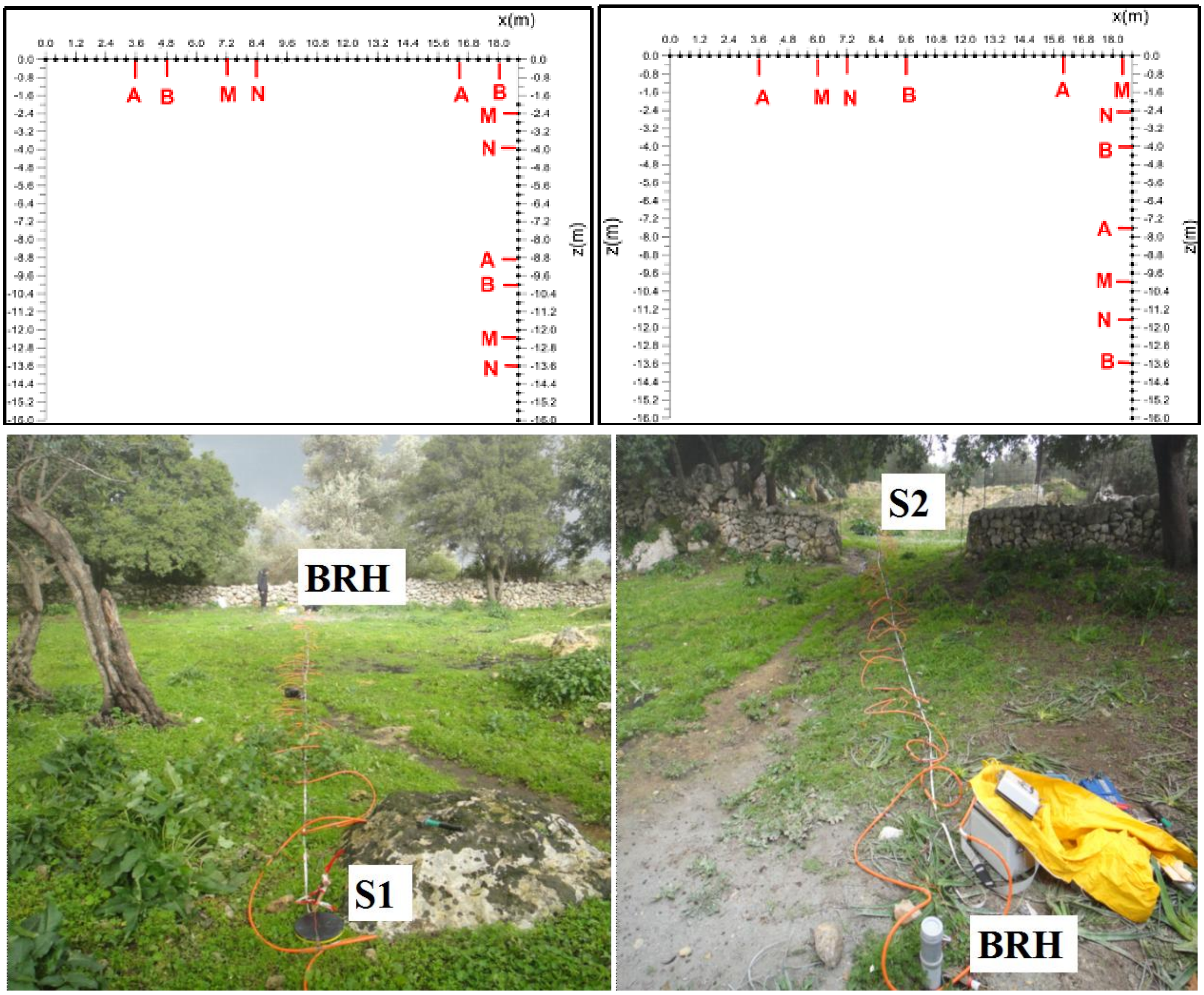

Figure 3: (up) Dipole-Dipole (left) and gradient (right) electrode configurations for the surface, borehole and surface-to borehole measurements. (down) Arrangement of the surface electrodes along the lines S1-BRH and S2-BRH, where BRH shows the location of the borehole.

Time Lapse ERT Results

The relative error between the forward and reverse potential readings measured with the gradient array of each of the monitoring phases was plotted against the corresponding forward potential measurements in logarithmic plot. These plots gave a clearer indication regarding the level of noise that contaminates the resistivity measurements which has an average level of almost 2%. Furthermore these plots were used in the pre-processing stage by removing totally less than 6% of the monitoring data that exhibited unrealistic high or low resistivity values.

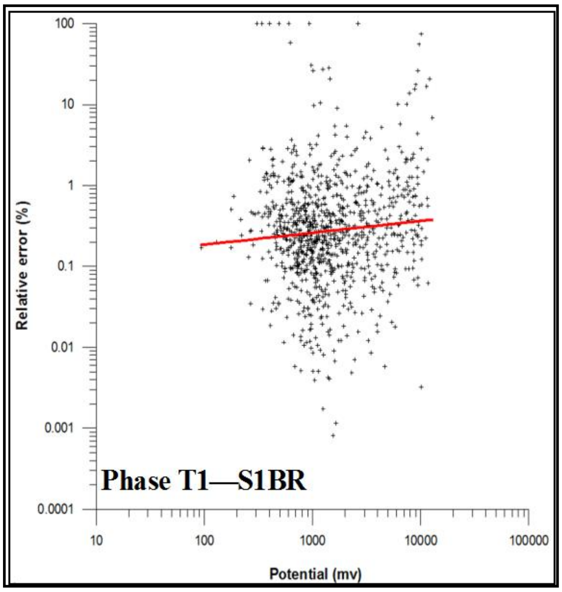

Figure 4: Logarithmic plots of potential error from normal and reverse Gradient measurements for phase T1 and the S1-BR measurements.

Each phase of the ERT monitoring data were processed individually with a standard inversion algorithm that could account for the surface-to-borehole field measuring mode (Loke and Barker 1996). Similar parameters were used in the inversion of the data where the program converged to a resistivity model after 5-7 iterations and RMS less than 4%. In general, the reconstructed models of all the phases and the two vertical directions showed comparable results. A thin surface high resistivity layer (~20cm/backfill material) is overlain a more conductive layer (clay and marl) and a deeper resistance layer (clay with sand). The image inside the borehole shows generally a conductive material.

In order to have a better insight regarding the time-lapse variation of the subsurface resistivity, difference images were extracted between the first phase (reference phase) and the remaining ones based on the simple formula $\frac{T_x - T_1}{T_1}$, where T1 is the resistivity inverted model of the first phase and Tx the inversion models for phases 2, 3, 4 and 5.

A unified color scale was used to represent the time-lapse resistivity variations for all the tomograms. A decrease in the bulk subsurface resistivity is expected in the ERT models due to the flow and the physical properties of OOMW. In general the ERT inversion models along S1 to BRH and S2 to BRH indicate a resistivity variation of +/-30% through the different monitoring phases. The decrease in resistivity values could be attributed to the movement of the conductive OOMW pollutants though the sandy marl of the area

The most promising area that could be attributed to the movement of OOMW is registered as a significant decrease (~30%) in resistivity values in the second and third phase. This can be seen as a circular area which is is extended along the horizontal distance of 14-14.8 m and 14.8-15.6m in tomograms S1-BR and S2-BR respectively. This area seems to move downwards within the fourth and fifth phase mainly in the S1-BR resistivity tomogram

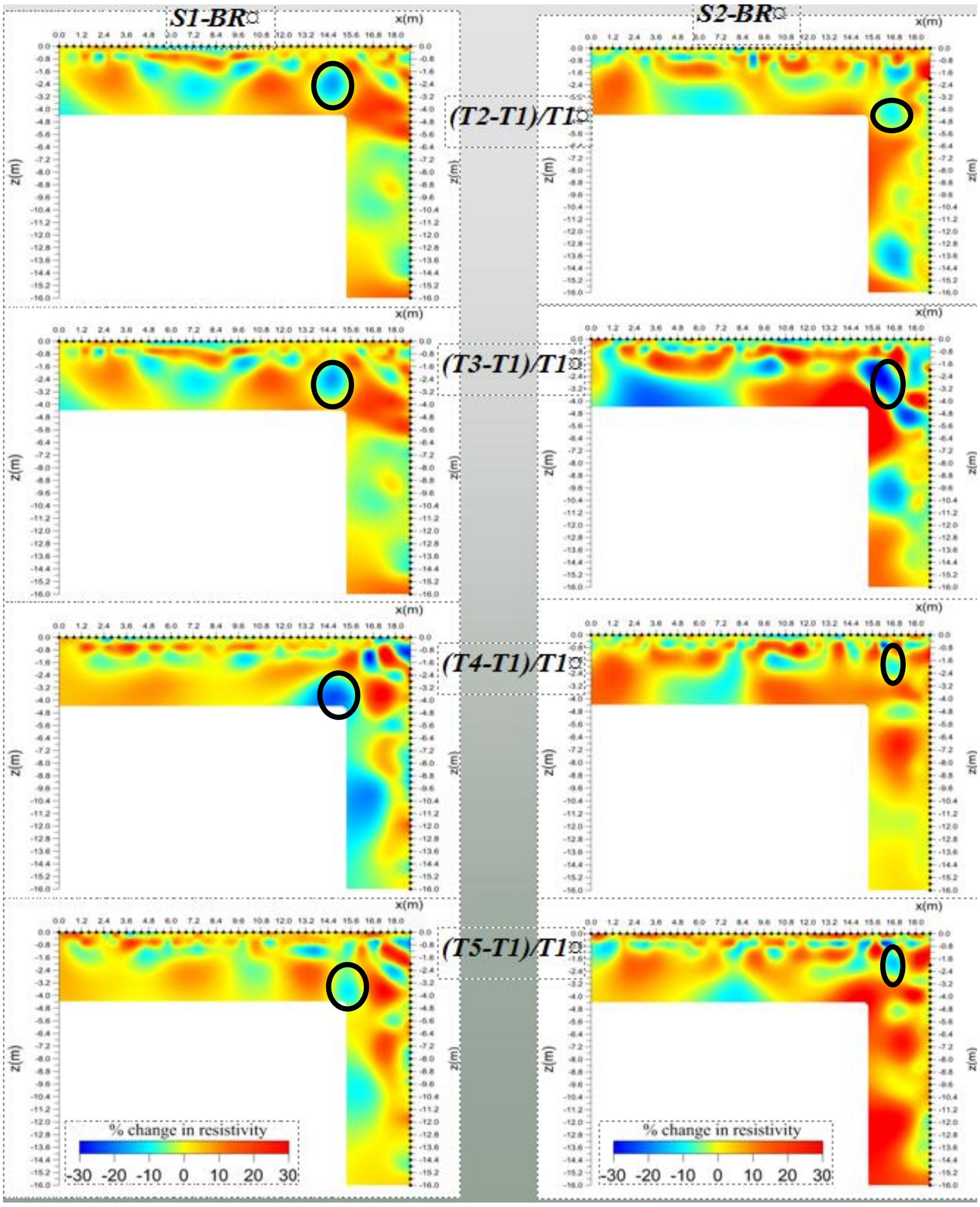

Figure 5: Results of the difference inversion of the ERT data collected along lines S1-BRH and S2-BRH for the five time phases. The results are plotted in terms of percentage relative change of the model resistivity of each phase with respect to the reference phase. The black circles indicate an area of reduced resistivity that could be attributed to the downwards movement of the OOMW.

Correlation between Geophysical and Geochemical Parameters

In order to proceed with the quantification of the ERT results, the research work went a step forward. The aim was to find correlation functions between the resistivity values extracted by the ERT monitoring and the geochemical elements measured through field sampling and subsequent laboratory measurements. A rectangular area was defined by the horizontal and vertical limits of X = 17.8-18.6m and Z = 0.6-4.2m respectively. The mean resistivity values of the values included within the above rectangular area was calculated assuming the different ERT inversion models corresponding to the phases T4, T5 and T6 of the S1-BR and S2-BR lines. This rectangular ERT area was chosen to account for the point information of chemical elements retrieved by the analysis of water samples from the depth of 1m depth inside the borehole. Furthermore the specific ERT phases were chosen since the electrical data were collected in similar dates with the water sampling. The synchronization of the ERT monitoring experiments with the water filed samples would enhance the validity of the extracted correlation functions.

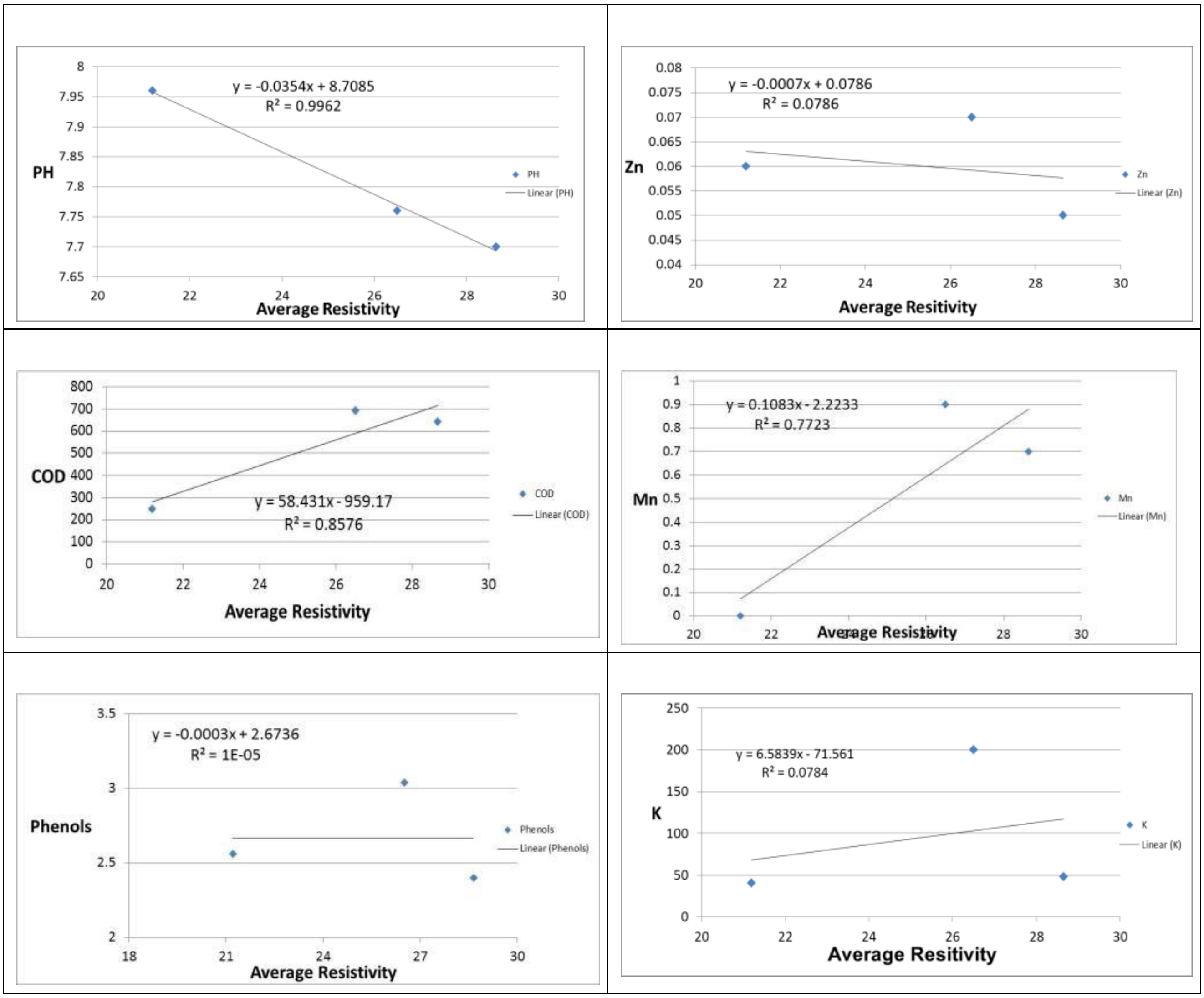

Figure 6: Correlation function between the inverted bulk resistivity (from ERT measurements) and measurements of various chemical elements.

The average resistivity extracted by the ERT sections was plotted against the measurements of the chemical analyses regarding PH, Zn, COD, Mn, Phenols and K (Fig. 6). A linear trend line was adjusted in each graph correlating in this way the resistivity with the variation of the different chemical elements. It can be seen that the resistivity exhibits positive linear correlation with COD and Mn, while PH and Zn are inversely proportional to resistivity. On the contrary phenols and K do not show any significant correlation with the resistivity (Fig. 6).

General Conclusions

Geophysical methods in terms of Electrical Resistivity Tomography can be applied in OOMW sites to survey larger areas with respect to the point information retrieved by soil/water sampling and subsequent chemical analyses. These preliminary results signify that the bulk resistivity reconstructed by ERT monitoring experiments show a correlation with specific chemical elements like Mn and COD. In this sense ERT could be used as a modern alternative in the original stage of monitoring and mapping the environmental pollution in OOMW areas providing solutions to address such environmental problems, by projecting the variation of specific chemical elements through the measurement of subsurface resistivity.

References

M. H. Loke, and R. D. Barker, Rapid least-squares inversion of apparent resistivity pseudo-sections using quasi-Newton method: Geophysical Prospecting, 48, 181-152, 1996.