Ground Electromagnetic Survey (GEM-2) technique to map the hydrocarbon contaminant dispersion in the subsurface at Barry Docks, Wales, UK

Rahman YACCUP[1] and Peter BRABHAM[2#]

(1) Researcher, Malaysian Nuclear Agency, Ministry of Science and Innovation
(rahman@nuclearmalaysia.gov.my)
(2) Senior Lecturer, School of Earth and Oceanic Sciences, Cardiff University
(Brabham@cardiff.ac.uk)

Abstract

The Geophex GEM-2 electromagnetic (EM) instrument provides a rapid multifrequency technique for shallow geophysical exploration. Survey applications include; ground contamination, hydrogeology, groundwater contamination mapping and archaeological investigations. This highly portable hand-held instrument, when linked with active GPS tracking provides typical 1.5 ground point spacing and allows a surveyor to collect around 20,000 data points per hour over five frequencies. GEM-2 uses an active EM signal to detect variations in subsurface conductivity. EM currents result in a secondary magnetic field that is measured together with the original transmitted signal, using a receiver coil on the EM instrument. The depth of ground penetration attained is dependent on a number of factors, and the most significant is the ground conductivity and the chosen EM wave frequencies. Typically five wave frequencies are used in the surveys; 825Hz, 7075Hz, 16075Hz, 31025Hz and 40075Hz. This paper presented the results from the investigation at Barry Docks site undergoing redevelopment from a 50 year old oil terminal into future residential use. Typically, polluting contaminants will increase the electrical conductivity of the ground materials and ground water. However measured ground conductivity values actually depend upon the types of hydrocarbon present. Some pure hydrocarbons are electrically resistive but their conductivity values may also increase through time due to biodegradation over many years. This research programme carries out detailed GEM-2 surveys in conjunction with chemical sampling to investigate this conductivity and ground chemistry relationship on the first layer of the GEM-2 data. The study shows that the high conductivity zones correspond to the location of the hydrocarbon storage tanks, although there is a tank response showing no such signal.

Keywords: Electrical Conductivity, Hydrocarbon contamination, GEM-2 System, Barry Docks

1.0 Introduction

Today, soil and groundwater contamination is increasingly recognised as being a serious environmental problem. This is due in the main to drastically increased use of hydrocarbon products and other metallic material in industrial activities, especially where the waste is not managed properly. UK residential areas also contribute a large amount of domestic waste which also greatly increases the number of sources of land and groundwater contamination. Hydrocarbons are usually introduced into the environment by uncontrolled discharges into drains, drainage system fractures, and accidental spills, leaking storage tanks, fractures in pipelines, sewers and purge chambers. This paper will discuss one of the contaminated sites at the Barry Dock which has the multiple sources of the contamination using the integrated geophysical and geochemical technique.

2.0 Research Objectives

Two main objectives in this research are:

a) To map the distribution of hydrocarbon distribution using geophysical technique
b) To define the qualitative relationship between the chemical distribution and the geophysical data

3.0 Site information

Barry Docks is located between Barry Island and the mainland (Barry Town) on the southern coast of Wales. The site was originally the tidal river estuary of the River Cadoxton flowing into the Bristol Channel. This site was developed in the late 1800s into a major docks complex. This site has a complex ground contamination issues related to the ground pollution arising from the historical dock activities, as a result of railways, landfill and numerous tank storage areas for hydrocarbons and other chemical products. It was also famous as a major coal exporting port at the end of the 19th century.

Generally, Barry Docks can be divided into four zones based upon the historical activities and land use which include: the South Quay, West Pond, Mole and the Tanks Farm between the dock and the West Pond as shown in Figure 1. This research study only concentrates on the West Pond and Tank Farm zones. Topographically, the site is generally almost flat with less than 10m in elevation Above Ordnance Datum (AoD)

Figure 1: The study area showing the zones

The rapid development of the Barry Docks was a result of the booming coal industry in Wales at the end of 19th century. The dock was built in 1884-1889 between Barry Island and Barry (mainland) by damming the River Cadoxton. A causeway was also built between Barry Town and the Island to provide a rail link and develop the island for tourism. The area between the dock and the causeway became a large pond known as West Pond. The West Pond was used as a landfill site in the mid 1950s by progressively dumping steelworks slag from progressively moving railway sidings.

In term of geological setting, Barry Island is famous for the exposed unconformity between horizontal Permo-Triassic beds and the dipping underlying Carboniferous formations. The Permo-Triassic deposits consist of the Penarth Group (PNG; grey to black mudstones with subordinate limestones and sandstones) (Figure 2). Superficial deposits of tidal flat deposits overly the bedrock in the study area especially along the former Cadoxton River.

4.0 Contamination issues on the site

The historical activities are a major concern to site re-development. This is why the geophysical investigation has been carried out at this site. This activity including the docks, oil storage tanks and a locomotive scrap yard, making the site potentially contaminated by hydrocarbons. In terms of expected geophysical results, the heavy metal will generate a lower resistivity and higher conductivity due to it being conductive. The hydrocarbons will generally give a high resistivity. However, after considering the biodegradation processes and the 60 year period of the hydrocarbons being dumped on the sit.e, the resistivity of contaminated zone may be lower.

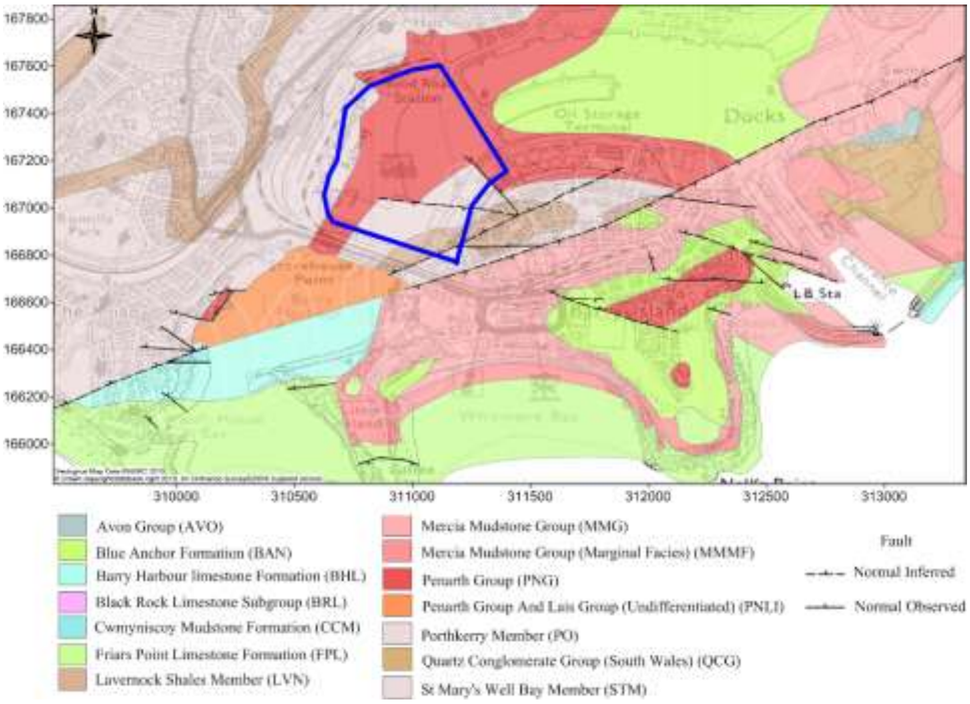

Figure 2: Geological map of the study area

5.0 Research Methodologies

The investigation of the ground pollutants at Barry Dock was concentrated at the tank farm and the West Pond area located at the western end of Dock No.1. Geophysical surveys (Ground Electromagnetic Survey GEM-2) had been carried out at the old tank farm area. At the time when the survey has been carried out, all tanks had been totally demolished. The water and soil samples were collected over the whole area at the tank farm and the West Pond site from the trial pits and the bore holes. Twenty nine boreholes and about a hundred trial pits data were included in the analysis (Figure 3 and Figure 4).

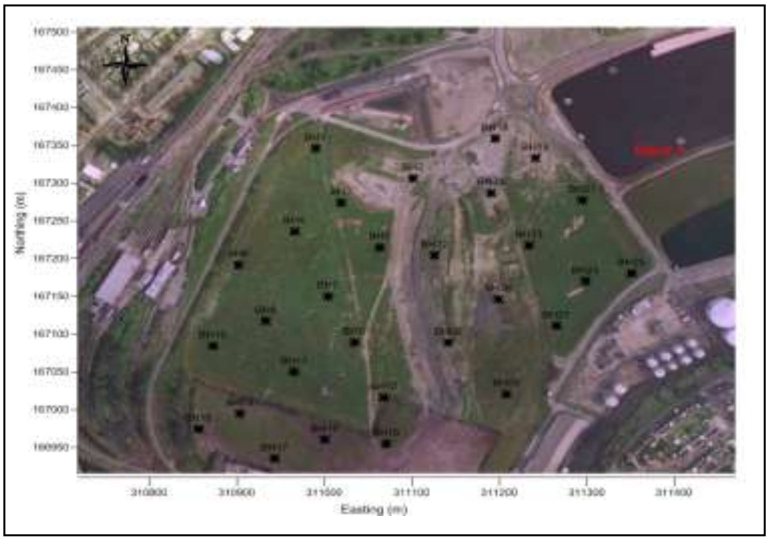

Figure 3: Showing the location of the boreholes where the groundwater has been collected for analysis (Barry Docks)

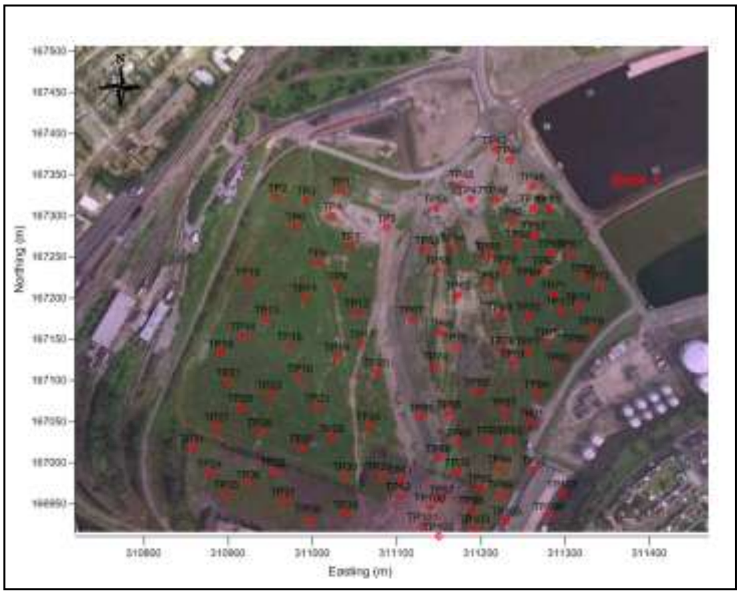

Figure 4: The location of the trial pits where the soil samples were collected

The GEM-2 is an active method that uses an electromagnetic (EM) signal to detect variations in subsurface electrical conductivity. These currents result in a secondary electromagnetic field that is measured together with the original transmitted signal, using a receiver coil on the EM instrument (Figure 5). The secondary field is then separated into two orthogonal components, the real and imaginary (quadrature) components, representing respectively the vector components of the field in-phase and 90 degrees out of phase with the primary. The quadrature component provides a measure of the apparent ground conductivity whilst the real (in-phase) component is responsive to buried metallic objects. Figure 6 shows the field setup for the GEM and GPS

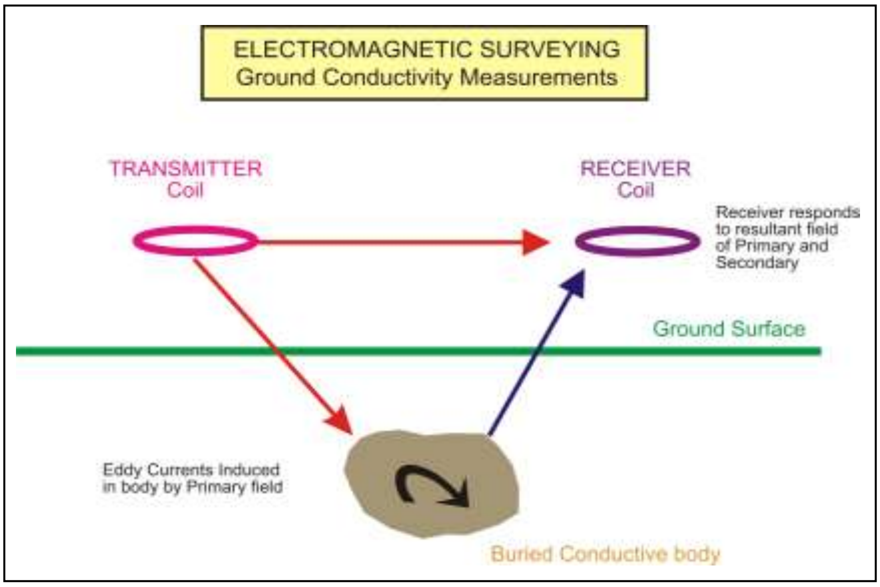

Figure 5: The schematic diagram showing the principle of the EM technique for site investigation

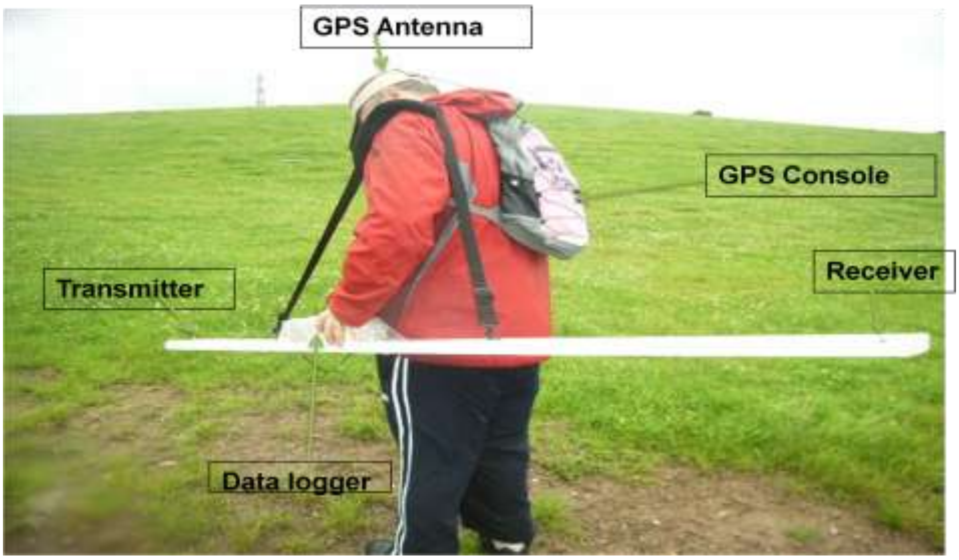

Figure 6: Showing the setup of GEM-2 and the GPS device

6.0 Results and Discussion

6.1 Geochemical results

Geochemical data has been plotted using Surfer 9 software to better define its distribution across the site. The soil analysis represents depths between 0m and 2m of Total Petroleum Hydrocarbons (TPHs) distribution throughout the study area. The distributions are compared to the electrical conductivity results at the similar area and closer depth. The TPHs content is calculated by adding all the aromatic and aliphatic hydrocarbons present in the soil samples which has a number of carbon compounds from 6 to 40 ($C_6 – C_{40}$).

The TPHs distributions are mostly located at the middle of the study area but little sign of it being present in the north. However, a high concentration of the TPHs ranges between 1000 to 3000ppm is recorded at the north at the farm tank zone (Figures 7). TPHs distribution patterns occur in such a way that can be described based on these factors:

a) The highest concentration of TPHs distribution at the middle of the study area can be explained due to fact that area was formerly railway tracks and sidings.

b) The low concentration of TPHs at the West Pond area is believed to be due to the ground works carried out in 1996 which skimmed the top soil and took it off site.

However, the presence of high concentrations of TPHs at the tank farm in the northern zone may be associated with the presence of the historical hydrocarbon storage tanks. But, why is it found there and not in the entire tank farm zone area? This question may be answered by taking into account the two factors below;

a) Demolition of the storage tank which only ended at the end of 2000 to early 2001. This means that the research is carried out 10 years after it was demolished. This period is considered short for contaminants to migrate to a more stable environment in the middle of the area. So, the TPHs have a tendency to remain in this area.

b) The second possibility is geared more to the occurrence of a leak or spills of TPHs in the area. It may occur in other areas, but more seriously there, so this will take a longer time to clean up by natural processes.

6.2 GEM-2 results

Using the Gem-2 instrument, a survey of five different depths of electrical conductivity layers has been obtained. The estimated depths of each layer are calculated using the 'Skin Depth Nomogram'. According to the Figure 8, the depth of penetration can be calculated by using the material conductivity and the frequencies of the electromagnetic wave used in survey. Geological information of the site shows that it was originally formed of tidal flat deposits, the expected marine clays probably have electrical conductivity the ranges between 1 - 1000 mS/m (10^{-3} – 1.0 S/m). But, for this study the electrical conductivity used to define survey depth was calculated by getting an average of the conductivities from the GEM-2 survey. Around 180,000 data points have been used for the calculation and the average value obtained is 0.8362 S/m. By using this value, the depths of the layer represented by the respective frequencies are shown in the Table 1.

The first layers calculated have a close depth values which as expected do not give significant different results on the material conductivity distribution in those layers (Figure 8). It is reported that during the site investigation, groundwater strikes were encountered in the made ground between approximately 3m bgl and 6m bgl (4m AoD and 1m AoD) and in alluvium typically between 10mbgl and 12 mbgl (-3m OD and -5m OD). Generally, when a GEM-2 survey is carried out, the groundwater level in the selected boreholes were between 3m bgl and 6m bgl. Due to this, the conductivity of the material in these layers is increasing slightly.

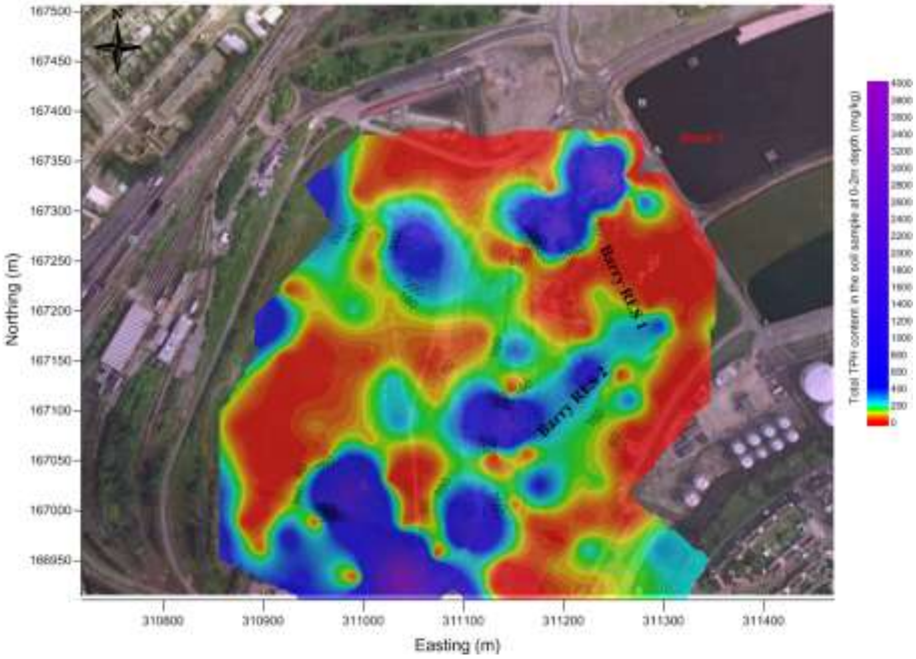

Figure 7: The HC distribution has a strong relationship with old railway tracks, sidings and the tank farm zone

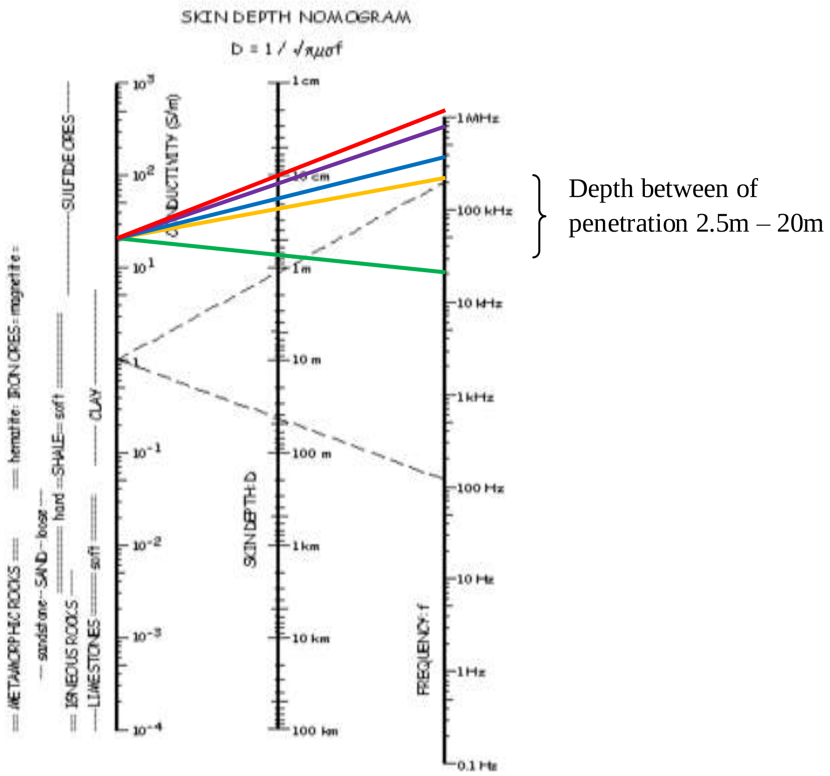

Figure 8: ‘Skin Depth Nomogram’ diagram is used to determine depth of layers

Table 1: The expected depth of the electromagnetic wave penetrated into the ground based on the electromagnetic frequency used.

EM Wave Frequency (Hz)	**Expected depth (m)**
40075	2.6
31025	3.2
16075	4.5
7075	6.0
875	19.0

The interaction between the conductivity of the material and the distribution TPHs is shown in Figure 9, where the value of the conductivity is chosen from the 2.6m depth. In this figure, two major observations can be made regarding the relationship of this picture.

a) The high conductivity zones are located at the base of the old tanks or adjacent to the tanks except for tank No. 3, which did not show any significantly high conductivity values. This meant the conductivity is likely to have a relation with any chemical content stored in the tank. Due to the reason that all the tanks are used to store hydrocarbon based products, the high values of the conductivity at the tank farm area is significant and most likely due to the presence of this material.

b) An interesting part is at the south where the TPHs give a response by showing higher concentration. This then also been observed as a higher conductivity zone by the GEM-2. Qualitatively, the higher conductivity occurred due to high concentration of the TPHs presence in this area. It also shows the high conductivity value observed at the tank No. 5, 6 and 7 where the TPHs are also found to be higher.

7.0 Conclusions

Generally, the Barry Dock research site is complex in terms of its geological setting, hydrogeological properties and complex industrial history due to variety of past activities on the site. The contamination on the site is complicated, with an integration of both heavy metals and hydrocarbons (only hydrocarbon is presented in this paper). The overall distribution pattern of HC is showing the high concentration dominantly in the southwest and in the middle of the study area. A high concentration of HC can also be found in the north where the historical storage tanks were once located.

In the tank farm zone, the HC distributions shows a good correlation with the GEM-2 results with high concentration zones (high electrical conductivity) are dominant in the south (railways and sidings area) and at tanks No 1, at tank numbers 5, 6 and 7 at the north. This is likely to have occurred because the storage tanks (tar and other petrochemical liquids) were probably leaking or had spills on the ground over the period of its operation

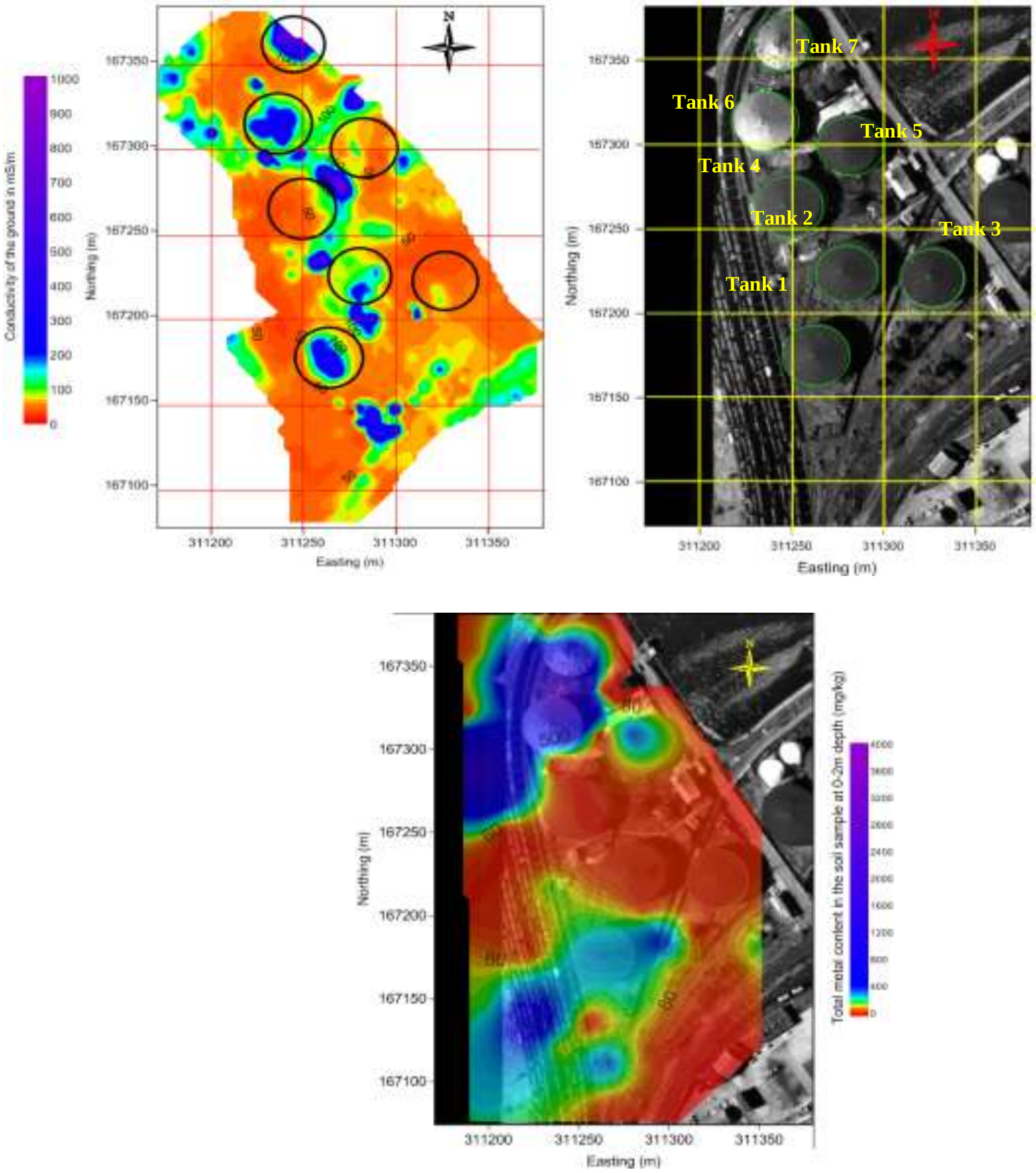

Figure 9: Showing interaction between the conductivity of the material and the TPHs distribution.

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