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ASSESSMENT OF HYDROCARBON CONTAMINATION USING GEOPHYSICAL METHODS AND ITS IMPACT ON SOIL QUALITY IN AGRICULTURAL CONTEXT

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Abstract

This paper presents an integrated investigation of hydrocarbon-contaminated soils near the Petromidia refinery using advanced geophysical and hydrogeological methods, with implications for soil sciences in agriculture. The main goal was to identify and monitor contamination to assess its impact on soil quality and support sustainable land management strategies. Methods included electrical resistivity measurements (Vertical Electrical Soundings - VES), ground-penetrating radar (GPR) with 100 and 500 MHz antennas, and hydrogeological drilling for soil and groundwater sampling. Geophysical data were integrated with hydrogeological results to develop a hydrogeophysical model. The study revealed contaminants as thin hydrocarbon films within sandy layers and localized accumulations along NW-SE fault zones. Contamination is influenced by active infiltration, precipitation, and continuous pollutant influx. The resulting hydrogeophysical model accurately mapped the spatial distribution and migration pathways of pollutants, emphasizing soil vulnerability in the area. These findings are critical for assessing impacts on soil fertility and the agricultural potential of adjacent lands. This integrated approach provides a solid basis for remediation strategies and sustainable soil resource management.

Key words: *hydrocarbon contamination, geophysical methods, VES, GPR, hydrogeophysical model, soil quality.*

INTRODUCTION

Soil and groundwater contamination with hydrocarbons is a major environmental issue, significantly impacting agricultural land quality and water resources. This paper analyzes the extent and characteristics of hydrocarbon pollution in the petroleum discharge area of Vadu commune, Constanța County, where two pits measuring 50 × 100 m have been used for petroleum waste disposal. Over time, these deposits have led to extensive soil and groundwater contamination, reducing land fertility, excluding it from agricultural use, and posing risks to local ecosystems and human health.

Given the petroleum pollutant leaks into the subsurface and considering that once formed, the pollution plume moves randomly at a depth between 1 and 2 meters, it is necessary to use electromagnetic investigation methods, specifically the vertical electrical sounding (VES) method with a Schlumberger array, in parallel with ground-penetrating radar (GPR) investigations using single-frequency antennas (100 MHz; 500 MHz). The two methods validate each other, ultimately resulting in a more accurate stratigraphic succession and an exact determination of the water table level. These methods enabled the identification of hydrocarbon accumulation zones and the analysis of their interaction with the local geological structure, fault systems, and groundwater flow.

In addition to geophysical investigations, photogrammetry was used to develop a digital terrain model (DTM), providing a detailed representation of microrelief variations and potential pollution-induced alterations. Soil and groundwater samples were collected and analyzed for total petroleum hydrocarbons (TPH), pH, organic carbon content, and heavy metal concentrations, further validating geophysical findings.

This integrated hydrogeophysical approach not only precisely delineated the affected area but also improved the understanding of contaminant infiltration, retention, and dispersion processes in the subsurface environment. The obtained results are crucial for developing efficient remediation strategies, supporting the recovery of affected land, and facilitating its reintegration into sustainable agricultural use (Anghel, 2024).

Furthermore, the study contributes to optimizing hydrocarbon pollution monitoring methodologies and enhancing predictive capabilities regarding contaminant evolution in similar environments, thereby offering valuable insights for environmental protection and land management policies.

MATERIALS AND METHODS

Study Area

This area, located a short distance from the Mamaia resort, is notable for its sandy soils alternating with clay, presenting a strong flow of groundwater but also of contaminating substances. The spillage of petroleum products through pipelines in the area bordering the locality of VADU was the main motivation in choosing the investigation area. Thus, geophysical mapping allowed for the determination of the thickness and extension of the petroleum products' settling area (Alimohammadi & Butt, 2020).

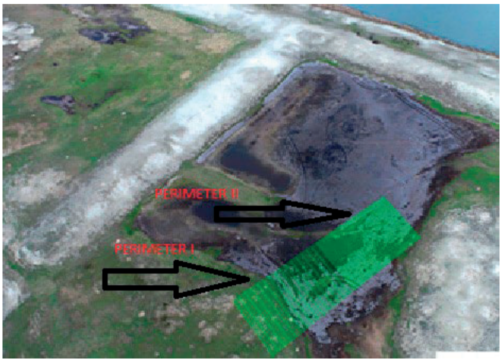

Figure 1. Network of profiles related to perimeters I and II investigated with two antennas (100MHz and 500MHZ)

Data Acquisition

Methodology of using the GPR - NOGGIN system

First of all, it can be said that there is a perfect similarity between GPR and seismic refraction. Thus, the radar transmitter located on the antenna emits a short-duration pulse characterized by high frequency, which can vary in the range of 10 MHz - 10 GHz. The propagation of the electromagnetic wave through the ground occurs at a speed that depends on the characteristics of the terrestrial electric field.

Propagating in the investigated environment, the electromagnetic wave can encounter an object or surface characterized by different electrical properties, so that part of its energy is reflected to the surface, and the remaining energy continues to penetrate deeper into the investigated environment (Figure 1).

The GPR reception system captures the reflected wave, which is subsequently recorded by the NOGGIN 500 system (Figure 2). The travel time of the pulse from the surface to the reflective interface and back is analyzed based on these recordings. Water content is an important element in determining the electrical properties of geological structures. The volume of water from the pores of rocks can influence the electrical properties of the investigated terrain.

The type of rock, the material, or the water that fills the existing mini-fractures played an essential role in determining the accuracy of the GPR (Ground penetrating radar) system.

These variations in electrical properties cause partial reflection of the transmitted signal.

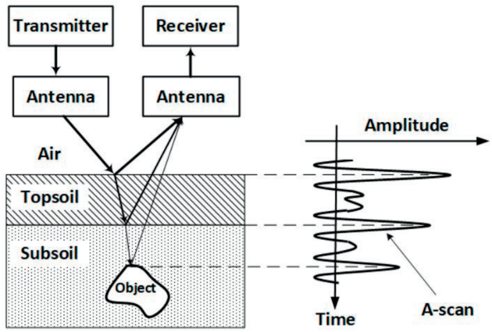

Figure 2. Synthetic scheme regarding the propagation of electromagnetic waves in the subsoil - shape and amplitude intensity (after Ukaegbu et al., 2019)

The propagation of high-frequency radio waves in the soil is based on two essential factors: velocity, which quantifies how fast the wave propagates through the soil, and attenuation, which gives us an image of the weakening of the signal as it propagates through the investigated medium. The conductivity of the material and the dielectric properties can characterize the speed and attenuation of electromagnetic waves in the investigated medium. The dielectric constant (relative permittivity) is a term used to describe the response of the material at high frequencies (10-1000 MHz) and can be characterized by the relative permittivity, in this case, two frequencies,s 100 MHz and 500 MHz. At very high frequencies (10-1000 MHz), in the case of limestones where the conductivity does not exceed 10 mS/m, the propagation speed of electromagnetic waves is not dependent on frequency. To determine the extension of the pollution plume in the subsoil, its position, and its depth, we must take into account the propagation speed of the electromagnetic wave, which is dependent on the dielectric constant.

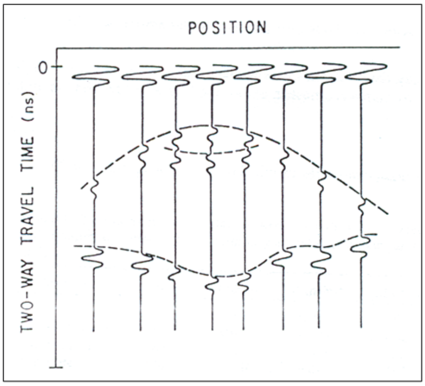

Figure 3. Generation of a radargram within the data acquisition process

The type of material can influence the speed of the electromagnetic wave and the degree of attenuation, according to Table 1.

Table 1. Dependence of Radar Wave Velocity and Attenuation on Material Type

Material	ε_r Relative Permittivity	σ (mS/m) Conductivity	V (m/ns) Velocity	α (Db/m) Attenuation
Air	1	0	0.30	0
Distilled water	80	0.01	0.033	2×10^{-3}
Freshwater	80	0.5	0.033	0.01
Seawater	80	3×10^{4}	0.01	10^{3}
Dry sand	3-5	0.01	0.15	0.01
Saturated sand	20-30	0.1-1.0	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Clay	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Dry salt	5-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

Conductivity (mS/m) – determines how much energy is absorbed by the material. High-conductivity materials, such as clay (2-1000 mS/m) or seawater (30,000 mS/m), rapidly attenuate the radar signal, limiting the penetration depth (Figure 3).

Signal attenuation (dB/m) – represents the loss of energy as the radar wave propagates through the material. For example, air and dry sand have very low attenuation (~0 dB/m and 0.01 dB/m), allowing deep penetration. In contrast, seawater (1,000 dB/m) or highly saturated clay (>300 dB/m) absorb the radar signal almost completely, significantly reducing the depth of investigation.

Materials with low permittivity and low conductivity (e.g., dry sand, ice, air, dry rock) allow deep radar signal penetration, making them ideal for geological and archaeological investigations.

Materials with high permittivity and/or high conductivity (e.g., water, wet clay, saturated sand) reduce radar signal penetration, limiting the depth of investigation and making it difficult to detect subsurface structures.

Water content and soil moisture are critical factors, as even small amounts can drastically alter the soil's electrical properties, affecting the depth and clarity of GPR surveys.

This interpretation helps in understanding how GPR can be effectively used depending on the soil and material characteristics. The GPR method measures the signal travel time, which must be determined with nanosecond precision. Resolution refers to the system's ability to distinguish between two closely spaced signals. There is always a trade-off between investigation depth and GPR resolution. Studies have shown that a 100 MHz frequency offers an optimal balance between penetration depth, resolution, and device portability. When a deeper investigation is required, a lower resolution is acceptable, whereas higher resolution demands a reduced penetration depth.

Geological surveys rely on detailed stratigraphic information to determine groundwater flow direction, especially in areas with high concentrations of dissolved salts. GPR plays a key role in defining subsurface geology and assessing the parameters that influence fluid movement through rocks.

In most cases, GPR is operated in reflection profiling or tomography mode (Figure 2), where the antennas are moved along the survey line. Determining the depth of buried bodies, their shape, size, and inclination using the speed of propagation of electromagnetic waves is a process that can also be applied in the case of seismic refraction where the elastic wave is generated mechanically. However, it is important to note that GPR equipment remains costly, and data interpretation can be challenging due to numerous interferences, particularly from power transmission networks. Additionally, the presence of clay layers, which act as natural barriers, can render the method ineffective for deep investigations.

Despite these limitations, GPR remains the geophysical method with the highest resolution capability. Georadar investigations were carried out on two designated areas using 100 MHz and 500 MHz antennas. Each survey area measured 30 meters in length and 20 meters in width. The survey grid for each perimeter consisted of both longitudinal and transverse profiles.

For the first perimeter, measurements were conducted along longitudinal profiles spaced at 0.5 meters and transverse profiles spaced at 2 meters (Figure 4). In this case, a 100 MHz antenna was used.

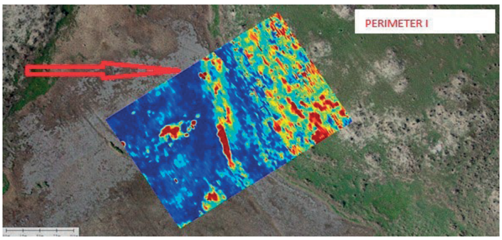

Figure 4. Ground-Penetrating Radar (GPR) Depth Section (0.5 m) - Perimeter I

In Perimeter I, investigated with the 100 MHz antenna (Figure 4), measurements followed a grid of transverse and longitudinal profiles, maintaining a spacing of 0.5 meters between longitudinal profiles and 2 meters between transverse profiles.

As shown in Figure 5, the placement of the survey area on the orthophotomap highlights that 30% of the area is located in an unpolluted zone, while 70% falls within the petroleum discharge zone.

The positioning of the perimeter was carefully selected to ensure that data acquisition captured information from both polluted and unpolluted areas. This approach enables a comparative analysis during data processing, allowing radargrams to reveal the effects of petroleum contamination more clearly. The data was positioned in real-time using the GPS integrated into the Noggin system. The preliminary processing and interpretation were carried out in the field immediately after the data acquisition phase was completed.

As part of the data processing and interpretation process, GPR sections were generated at depths of 0.5 m, 1 m, and 1.5 m. For a depth of 0.5 m, the GPR section highlights high-intensity reflections in the unpolluted area (red-yellow color) and low-intensity reflections, characteristic of the area heavily polluted with hydrocarbons (blue color). As shown in Figure 5, the section corresponding to a depth of 0.5 m highlights high-intensity reflections in the non-polluted area (red-yellow color) and low-intensity reflections, characteristic of the heavily hydrocarbon-polluted area (blue color).

Thus, in this case, a clear delineation of the heavily hydrocarbon-polluted area can be observed both at the surface and in depth.

For Perimeter II (Figure 1), investigated using the 500 MHz antenna (Figure 5), measurements were conducted along both transverse and longitudinal profiles, with a fixed spacing of 0.5 meters between them.

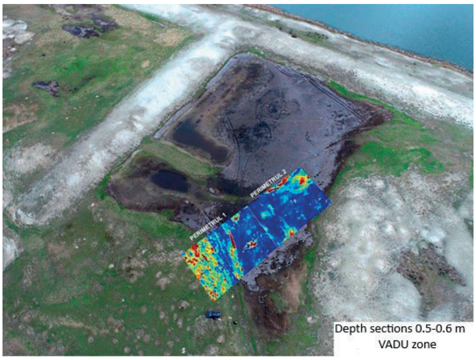

Figure. 5 GPR Depth Section (0.5 m) - Perimeter I, and (0.6 m) - Perimeter II

As shown in Figure 5, the placement of the perimeter on the orthophotomap highlights that it is located entirely (100%) within the petroleum spill zone.
The perimeter was deliberately positioned to ensure that only data from the polluted area was recorded during the acquisition process. This approach allows for a comparative analysis of the radargrams during data processing, emphasizing the impact of petroleum pollutants when investigated using the two types of antennas (Bachu & Bennion, 2009).
During the data processing and interpretation phase, it was observed that the hydrocarbon spill area, encompassed within the two perimeters, can generate low-intensity reflections on the depth sections, both when using the 100 MHz antenna and the 500 MHz antenna for data acquisition.
The analysis of the radargrams presented in Figure 6 shows that the petroleum-contaminated area produces very low-intensity reflections on the radargrams, compared to the distinct hyperbolas observed in the area with vegetated soil.

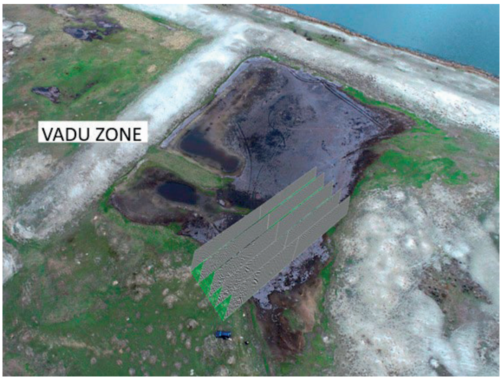

Figure 6. Positioning of the radargrams on the two perimeters was carried out with a fixed spacing of 5 meters between them

This experiment, which compares data obtained using two types of antennas under conditions of intense pollution, represents a first-of-its-kind study and highlights the crucial role that the ground-penetrating radar (GPR) method can play in investigating and identifying heavily polluted areas in depth.
Considering the thickness of the pollutant layer, approximately 1.5 meters, and the continuity of the low-reflection zone up to this depth, we can conclude that the GPR method is highly effective even when the pollutant is not present at the surface, allowing for its detection in depth in the form of a contamination plume.

Figure 7. GPR data acquisition using the 100 MHz and 500 MHz antennas

***Electrical Resistivity Measurements* (*VES*)**

The electrometric investigation (Figure 7) of the perimeter was conducted along a network of parallel profiles (Cassiani et al., 2004). Based on this analysis, it was deemed appropriate to generate apparent resistivity sections to highlight the presence of a quasi-homogeneous resistive horizon, associated with a gravelly sand layer located beneath the petroleum-contaminated horizon.
Below this resistive horizon lies a low-resistivity domain, corresponding to the aquifer level, which was also confirmed through piezometric boreholes in the area.
In the studied area affected by petroleum pollutant discharge, two shallow boreholes were drilled, and sediment samples were collected every 20 cm using a manual corer.

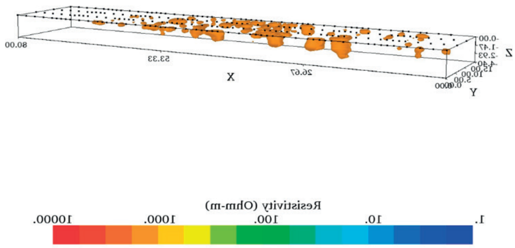

Figure 8. 3D representation of the inverted apparent resistivity section (Rez2Inv), highlighting the high-resistivity zones corresponding to the polluted areas (Loke, 2018)

The collected soil samples were analyzed using a DR 2000 analyzer (Domenico & Schwartz, 1998). In the first borehole, hydrocarbon concentrations of 1 ppm were identified down to a depth of 40 cm, while in the second borehole, similar concentrations were detected down to a depth of 1.4 m (Figure 1). These analyses contributed to the calibration of both the electrometric method and the ground-penetrating radar (GPR) method (Covaliu et al., 2024).

Figure 9. Field data acquisition using the Vertical Electrical Sounding (VES) method (McNeill, 1990)

RESULTS AND DISCUSSIONS

The investigations conducted in the hydrocarbon-contaminated area near the Petromidia refinery (Vadu zone) have highlighted the presence of pollution in both soil and subsoil, impacting land quality and its potential agricultural use. The parallel use of geophysical and hydrogeological methods led to the delineation of the polluted areas and the determination of the degree of contamination. Using the vertical electrical survey method for the determination as well as georadar profiling, significant differences (contrasts) were highlighted between the contaminated and uncontaminated perimeters. The apparent resistivity sections identified a quasi-homogeneous gravel sand horizon located below the hydrocarbon-polluted layer, which was highlighted by the apparent resistivity sections. The sudden decrease in resistivity below this layer marked the aquifer level, which was also confirmed by piezometric drilling. The pronounced hyperbolas present on the georadar sections are characteristic of areas with unaltered soil and are in contrast to the low-intensity reflections characteristic of hydrocarbon-contaminated soils. Thus, it was possible to clearly delineate the pollution plumes and their migration paths into the subsoil. The local geological structure, precipitation and active infiltration influenced the contaminant migration pathways, which were outlined by the resulting hydrogeophysical model. The sustainability of agricultural crops (Reynolds, 2011) depends largely on the degree of soil contamination. The importance of geophysical methods for detecting and monitoring soil pollution is vital for sustainable agriculture. The protection of agricultural resources and the environment depends on the data collected that provide a solid basis for remediation strategies and sustainable agricultural land management.

CONCLUSIONS

The high level of soil and subsoil contamination, with direct implications for the use of agricultural land, was highlighted by the investigations carried out in the area of oil product spillage from the Petromidia refinery in the Vadu region. Hydrogeological, GPR and electrometric investigations identified the presence of hydrocarbons infiltrated into the soil, with significant accumulations reaching depths of up to 1.4 m (Iorga et. al, 2024). These petroleum products have dispersed unevenly within the sand and gravel layer, forming an extended pollution plume. Hydrocarbon pollution significantly alters the soil's physical and chemical properties, reducing its fertility and its ability to sustain agricultural crops. The presence of hydrocarbons disrupts soil structure, hinders water and nutrient absorption, and negatively affects beneficial microorganisms essential for plant growth.

Given the high concentrations of pollutants and the persistent nature of hydrocarbons in the soil, the investigated land is not suitable for agricultural use without remediation measures. Risks to human health and local ecosystems may arise when pollutants could enter the food chain as a result of the cultivation of contaminated agricultural land (Sultan et al., 2014).

To restore the land and reintegrate it into agricultural use, urgent remediation actions are required, such as bioremediation, soil washing, or excavation of the contaminated layer.

The assessment of the evolution of contamination and the effectiveness of remediation techniques depends largely on long-term monitoring strategies (Oprea et al., 2024).

This study has demonstrated that geophysical methods are effective tools for identifying and mapping soil contamination, providing essential data for decision-making in land management. Integrating these methods into remediation programs can help mitigate the impact of contaminants on the environment and agriculture.

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