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INVESTIGATION OF HYDROCARBON POLLUTION IN THE OIL TERMINAL CONSTANȚA AREA USING ELECTRICAL RESISTIVITY METHODS AND HYDROSTATIC REGIME ANALYSIS

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Abstract

Soil and groundwater contamination with hydrocarbons represents a major environmental issue in port–industrial areas, with direct impacts on agricultural ecosystems and the quality of life of local populations. This study investigates the degree of pollution in the Oil Terminal Constanța North area, located outside the industrial enclosure, within a residential zone where the persistent smell of hydrocarbons indicates active contamination. Geophysical investigations were carried out using the Vertical Electrical Sounding (VES) method along four electrical profiles (P1, P2, P3, and P4), with a spacing of 10 m between measurement points. The main objective was to determine the geological structure, identify the groundwater table, and highlight its relationship with the hydrocarbon pollution plume. The inverted geoelectrical sections, characterized by low RMS values, reveal low-resistivity anomalies associated with hydrocarbon-saturated materials, predominantly located at the groundwater level. Correlation of the geoelectrical results with the hydrostatic level map indicates a groundwater flow direction oriented toward the Black Sea, facilitating pollutant migration. The results confirm the presence of active hydrocarbon pollution, with potential impacts on agricultural soils and the coastal environment.

Key words*: coastal environment, electrical resistivity sounding, groundwater migration, hydrocarbon contamination, pollution plume.*

INTRODUCTION

One of the most persistent and difficult-to-control forms of environmental contamination is soil and groundwater pollution with hydrocarbons, particularly in port-industrial areas and in the vicinity of petroleum storage and transfer facilities. Hydrocarbons can persist in the environment for long periods, affecting groundwater quality, the physicochemical properties of soils, and consequently agricultural land use, food safety, and ecosystem health.

Hydrocarbon pollution presents an additional risk in coastal areas due to the direct interaction between continental hydrogeological systems and the marine environment. The groundwater table plays a key role in contaminant transport, as hydrocarbons preferentially migrate at this level in the direction of groundwater flow, forming a pollution plume (Ali et al., 2025). Under such conditions, contamination does not remain localized but can spread over large areas, affecting both agricultural soils and the receiving marine environment.

One of the most important industrial hubs for handling and storing petroleum products in Romania is the Oil Terminal Constanța area. Over time, long-term industrial activities have generated significant environmental contamination risks, particularly in areas adjacent to the industrial enclosure. Outside the site boundary, in the northern part of the Oil Terminal, a residential area characterized by apartment buildings and green spaces has developed, where the persistent smell of hydrocarbons indicates the presence of major subsurface pollution sources.

In this context, assessing the degree of contamination and the mechanisms of hydrocarbon migration becomes essential for the sustainable management of land with agricultural potential, as well as for environmental protection in the vicinity of industrial areas. Electrometric methods represent efficient, non-destructive tools for investigating subsurface structure, identifying the groundwater table, and delineating contaminated zones through electrical resistivity

contrasts (Alao et al., 2025). Vertical Electrical Sounding (VES) is frequently used in environmental studies aimed at characterizing hydrocarbon-saturated environments, which are typically associated with lower electrical resistivity values compared to unaffected materials. The correlation of geoelectrical results with hydrogeological data allows for the delineation of the pollution plume and the determination of contaminant migration direction.

The present study aims to investigate the degree of hydrocarbon pollution in the Oil Terminal Constanța North area by applying the Vertical Electrical Sounding method along multiple electrometric profiles (Figure 1), correlated with hydrostatic regime analysis.



Figure 1. Acquisition of electrometric data using an AGI MiniSting system

The objective is to determine the geological structure of the area, highlight its relationship with the movement of the pollution plume, and identify the groundwater level, with particular emphasis on migration toward the Black Sea and its implications for the environment and soils.

MATERIALS AND METHODS

In the northern area of the Oil Terminal Constanța, geophysical investigations were carried out outside the industrial enclosure, within a residential area characterized by apartment buildings and green spaces, where persistent hydrocarbon odors were identified. The area is located in close proximity to the port zone and is influenced by the historical activities of storage and transfer of petroleum products.

The Vertical Electrical Sounding (VES) method was used to assess the subsurface structure and the degree of pollution, this electrometric method being well established in environmental and hydrogeological studies (Goldman & Neubauer, 1994). Measurements were performed along four electrical profiles, labelled P1, P2, P3, and P4 (Figure 2), arranged in the northern extremity of the Oil Terminal, both parallel and perpendicular to the main structural directions and to the estimated groundwater flow direction. To validate the geoelectrical interpretation, two control boreholes (F1 and F2), each reaching a depth of 4 m, were drilled at representative locations within the study area (Figure 2). The borehole information was used to correlate the interpreted electrical resistivity anomalies with the local lithology and groundwater table depth, thereby increasing the reliability of the geophysical interpretation.



Figure 2. Profile layout map

A spacing of 10 m between VES points was applied in order to achieve adequate spatial resolution for identifying lateral variations in electrical resistivity (Eze & Chinemelu, 2025). The electrode configuration was designed to allow investigation of the upper meters of the subsurface, where the groundwater table develops and where the presence of a hydrocarbon pollution plume is assumed. To characterize the saturated zone, the investigation depth reached approximately 4-5 m.

Two-dimensional electrical resistivity inversion was applied to process the field data, resulting in inverted geoelectrical sections for each measured profile (Figures 3-6). The quality of the inversion was assessed using the root mean square (RMS) error, which showed low values of 3.1% for Profile 1, 4.53% for Profile 2, 5.9%

for Profile 3, and 7.07% for Profile 4. These values indicate a good agreement between the measured and calculated apparent resistivity data. Overall, the obtained RMS errors confirm the stability of the inversion solutions and the reliability of the geoelectrical interpretation. For all four profiles, the obtained RMS values confirm the stability of the inversion solutions and the reliability of the geoelectrical interpretation (Loke, 2010).

The interpretation of the geoelectrical sections involved correlating local lithology with electrical resistivity values, borehole information, and hydrogeological conditions. Zones characterized by low resistivity values were interpreted as electrically conductive materials, which may represent water-saturated fine-grained sediments, saline groundwater, wastewater infiltration, and/or hydrocarbon-contaminated horizons. The anomalies detected in this study were interpreted as hydrocarbon-affected zones only where they spatially coincide with the groundwater table, the groundwater flow direction, and the known history of petroleum-related activities in the Oil Terminal Constanța area. Higher resistivity values generally correspond to drier, coarser-grained, or more compact deposits. Particular attention was given to identifying the groundwater table and its lateral variations. Particular attention was given to identifying the groundwater table and its lateral variations.

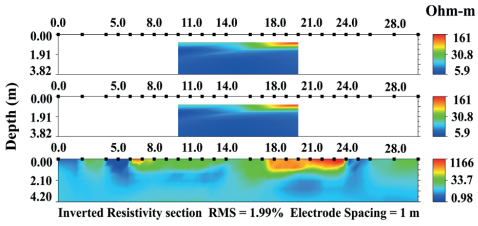


Figure 3. Inverted resistivity section - Profile 1

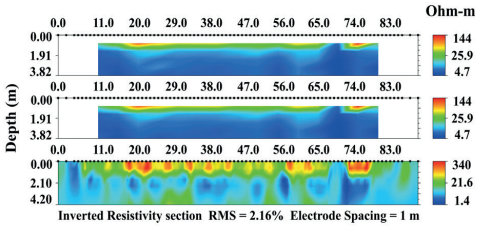


Figure 4. Inverted resistivity section - Profile 2

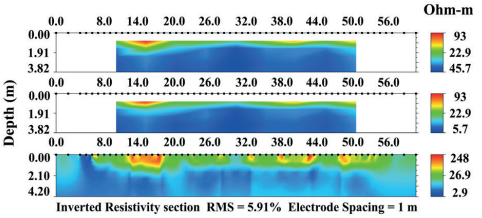


Figure 5. Inverted resistivity section - Profile 3

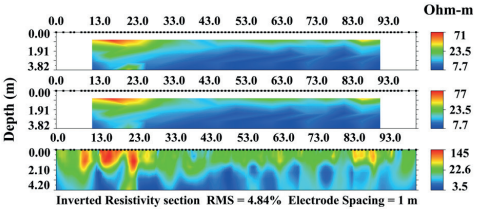


Figure 6. Inverted resistivity section - Profile 4

The analysis of pollutant migration direction was based on correlating the electrometric results with the hydrostatic level map, developed using available piezometric measurements. This correlation allowed the relationship between groundwater table position and resistivity anomaly distribution to be defined, as well as the identification of the dominant groundwater flow direction, oriented toward the coastal area of the Black Sea.

The study, based on electrometric methods and hydrostatic analysis, enabled a detailed assessment of subsurface structure and hydrocarbon transport pathways, providing a solid basis for interpreting the degree of pollution and its potential impact on the environment and on residential land use in the investigated area.

RESULTS AND DISCUSSIONS

During the interpretation stage of the inverted geoelectrical sections obtained for the four Vertical Electrical Sounding (VES) profiles (P1, P2, P3, and P4), detailed information was obtained regarding the subsurface geology and the surface distribution of electrical resistivity anomalies within the investigated area. The results reveal significant lateral and vertical variations in resistivity values, which are related to lithological changes, hydrocarbon contamination, and groundwater distribution (Ali et al., 2025).

Zones represented by red shades, corresponding to high electrical resistivity values, are observed on all profiles and are predominantly located in the upper parts of the sections (Atekwana et al., 2000). These zones are associated with unsaturated soils, more compact deposits, and anthropogenic fill materials characteristic of residential environments. Such units are characterized by low moisture conditions and a low degree of contamination. Beneath these layers, zones represented by blue shades, corresponding to low electrical resistivity values, are systematically identified at depths ranging from approximately 1.5 to 4-5 m. These low-resistivity anomalies coincide with the groundwater table and are interpreted as water-saturated horizons contaminated with hydrocarbons. Similar geoelectrical responses have been reported in hydrocarbon-contaminated environments, where contamination may modify the electrical properties of saturated sediments through physicochemical and biogeochemical processes (Abdel Aal et al., 2004). The interpretation obtained in the present study is also consistent with the findings of Eze and Chinemelu (2025), who demonstrated that electrical resistivity techniques provide reliable information for identifying groundwater contamination and delineating the spatial extent of hydrocarbon-affected zones. Similar to their observations, the low-resistivity anomalies detected in the investigated area coincide with the saturated zone and reflect the influence of contaminant migration on the electrical properties of the subsurface. This agreement further confirms the applicability of the Vertical Electrical Sounding (VES) method as an effective tool for preliminary environmental investigations and hydrocarbon contamination assessment in petroleum-impacted areas. The inverted apparent resistivity sections corresponding to profiles P1, P2, and P3 display laterally continuous low-resistivity anomalies (blue shades), indicating the presence of a pollution plume developed over a large area along the groundwater table. The spatial extent of these anomalies suggests that contamination is not localized but distributed throughout the investigated area, following natural groundwater flow pathways. The low RMS values obtained for these profiles confirm the reliability of the inversion models and the accuracy of the geoelectrical interpretation. In the case of profile P4, a similar resistivity structure is observed, but with variations in the thickness and intensity of the low-resistivity zones (blue shades). These variations may reflect differences in permeability, local lithological heterogeneities, or hydrocarbon concentration. Extremely low resistivity values are interpreted as sectors where hydrocarbons are mixed with fine-grained sediments and groundwater, resulting in a marked increase in electrical conductivity. The geoelectrical results correlate well with the hydrostatic level map, revealing a clear relationship between the position of the groundwater table and the distribution of low-resistivity anomalies. The hydrostatic gradient indicates (Fetter, 2001) a dominant groundwater flow direction oriented toward the Black Sea (Figure 7).

According to the hydrogeological principles described by Fetter (2001), groundwater flow is primarily controlled by hydraulic gradients, which govern the transport of dissolved and free-phase contaminants within saturated porous media. The groundwater flow direction identified in the present study therefore provides a logical explanation for the observed distribution of low-resistivity anomalies and supports the interpretation that the hydrocarbon plume is migrating from the industrial area toward the coastal environment.

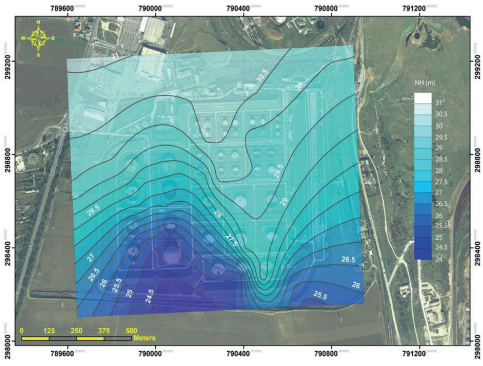


Figure 7. Hydrostatic water level map based on borehole data and piezometric studies

Consequently, the hydrocarbon pollution plume, highlighted by the low-resistivity zones (blue shades), is interpreted as migrating along the

groundwater flow direction from the industrial source area toward the coastal zone.

The migration of the pollution plume represents a significant environmental risk, as it facilitates the transport of hydrocarbons into residential areas, potentially affecting soils used for agricultural purposes as well as the coastal marine environment.

The integrated interpretation of the geoelectrical sections and the hydrostatic level map provides a consistent conceptual model of hydrocarbon migration in the investigated area. The spatial coincidence between the low-resistivity anomalies and the groundwater table indicates that contaminant transport is primarily controlled by the local hydrogeological regime rather than by isolated leakage points. The lateral continuity of the anomalies observed along profiles P1, P2, and P3 suggests the development of an extensive pollution plume migrating in the direction of groundwater flow toward the Black Sea. These findings confirm that the integration of electrical resistivity investigations with hydrogeological information represents a reliable approach for identifying hydrocarbon contamination pathways and provides valuable support for environmental monitoring and remediation planning in coastal industrial areas. These findings are consistent with previously reported geoelectrical models of hydrocarbon plumes in saturated sediments (Sauck, 2000). Furthermore, the migration pattern identified in the present study agrees with observations reported for other hydrocarbon-contaminated coastal and industrial sites, where groundwater acts as the dominant transport pathway and geoelectrical methods effectively delineate contamination plumes (Alao et al., 2025; Ali et al., 2025). The integration of VES data with hydrogeological information also reduces the ambiguity of geophysical interpretation by distinguishing lithological variations from contamination-related anomalies, thereby improving the reliability of environmental assessments and supporting remediation prioritization in complex industrial environments. The geoelectrical response observed in the investigated area is also consistent with previous studies reporting that hydrocarbon contamination modifies the electrical properties of subsurface materials, particularly within the saturated zone where contaminant migration is closely controlled by groundwater dynamics (Atekwana et al., 2000; Abdel Aal et al., 2004). In addition, the relatively low RMS errors obtained for all investigated profiles increase confidence in the inversion models and support the interpretation of the detected anomalies as environmentally significant features rather than inversion artefacts. Similar approaches have been successfully applied in contaminated industrial sites, demonstrating that electrical resistivity techniques provide reliable information on the geometry and lateral continuity of pollution plumes while minimizing environmental disturbance compared with intrusive investigation methods (Goldman & Neubauer, 1994; Loke, 2010). Consequently, the integrated application of geoelectrical investigations and hydrogeological analysis represents a robust methodology not only for contamination assessment but also for planning future monitoring campaigns and evaluating the effectiveness of remediation measures in areas affected by long-term petroleum-related activities.

CONCLUSIONS

The Vertical Electrical Sounding (VES) investigations successfully characterized the shallow geological structure and identified the groundwater table within the investigated area.

Low electrical resistivity anomalies indicate the presence of hydrocarbon-contaminated saturated horizons, confirming active contamination in the northern part of the Oil Terminal Constanța area.

Correlation between the geoelectrical results and the hydrostatic level map demonstrates that contaminant migration is controlled by groundwater flow toward the Black Sea.

The integration of electrical resistivity investigations with hydrogeological analysis provides an effective approach for identifying hydrocarbon migration pathways and supporting environmental monitoring and remediation activities.

ACKNOWLEDGEMENTS

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