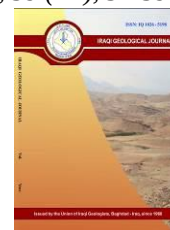




Iraqi Geological Journal

Journal homepage: <https://www.igi-iraq.org>



Evaluation of Sulfide-Induced Groundwater Pollution Using 2D Electrical Resistivity Imaging in Hit Area, Western Iraq

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Abstract

Received:
15 August 2025
Accepted:
23 April 2026
Published:
30 June 2026

The purpose of this study was to use 2D Electrical Resistivity Imaging to assess groundwater pollution by sulfides in Hit area, western Iraq. The Dipole-Dipole array was used to perform six profiles with different electrode spacing (a). An a-spacing of 2m for the profile (H1), 3m for profiles H2 and H6 as well, whereas 5m for profiles H3, H4, and H5 were set out. RES2DINV software was used to process the data. Zones with significant electrical resistivity values as (60–225 Ω m) were found in the results, suggesting that sulfide-contaminated groundwater may exist at depths between 1 and 18 m. Low resistivity values in several locations were interpreted as partially saturated rocks or gypsum layers. The inversion models showed a clear relationship between the contaminated distribution and the nearby geological and tectonic features, namely Al-Fatha Formation, which is characterized by a lithological composition of inter-bedded clay, marl and gypsum layers. The analysis confirmed the effectiveness of resistivity imaging in locating polluted areas, and determining their extent and direction of spreading.

Keywords: Electrical Resistivity; Groundwater Contamination; Sulfide Pollution; Hit Area; Subsurface Imaging

1. Introduction

The electrical resistivity method was used to investigate areas that impacted by hydrocarbon contamination, because of its importance from both an economic and environmental perspective. When choosing proper locations for well drilling, this method economically aids in locating and avoiding contaminated water zones (Airen and Emenim, 2021). Additionally, it facilitates implementing appropriate controls to prevent the spread of contamination. This method is used to map the spatial distribution of sulfur dioxide pollution from an environmental perspective and assess its effects on human health, wildlife, and vegetation (Shevnin et al., 2003). Using geophysical methods for detecting hydrogen sulfide contamination in groundwater has been one of the primary focus areas in recent decades (Loke, 2024). The electrical resistivity method is still the most widely used geophysical technique because their dependable and efficient approach in the subsurface investigations and produces images of underlying conditions that are almost realistic (Lech et al., 2020). The electrical resistivity technique has been used in numerous studies to examine groundwater and contaminants, for instance:

Al-Menshed (2011) used Wenner, Schlumberger, and Dipole-Dipole arrays in Karbala Governorate, Iraq, in which three distinct resistivity measurement methods as (1D, 2D, and 3D) in nearly six hydrocarbon-contaminated wells were utilized. The 3D approach offered the clearest and most detailed imaging compared to both 1D and 2D methods, in the same, 2D imaging method produced better outcomes than the 1D methodology. Thabit and Khalid (2016) provide the 2D imaging method as a dependable and efficient way to identify contaminated and uncontaminated zones as well as to determine their extent and direction of subterranean seepage in the southeast of Karbala. Uhlemann et al. (2017) used electrical resistivity imaging (ERI) to investigate how surface groundwater interactions are impacted by variations in mud layer thickness. The findings revealed a thickness variation ranging from 0 to 25 m, which has an impact on the aquifer's vulnerabilities. Mud breaks encourage surface water infiltration, raising the possibility of contamination, according to the geochemical data. (Hussien et al., 2020) highlighted a significant connection between the continuous emission of sulfur dioxide and its sources, including sulfur springs and sewage, in the city of Hit. Salman et al. (2020) considered the electrical resistivity method as a cost-effective way to examine subterranean weak zones. In this study, 2D inverse modeling indicates that the subsurface consists of secondary and recrystallized white gypsum, inter-bedded horizontally with claystone, siltstone and sandstone layers. Capillary processes within these layers promote the movement of contaminated water, resulting in the formation of contaminant lenses, particularly within the clay-rich interlayers. (Mohammed et al., 2021) found that the 2D imaging resistivity technique worked better than the VES survey when mapping the distribution of subsurface contamination when worked in the Hit area. The outcomes showed how the method may be used to identify and pinpoint subsurface voids in complex geological settings.

The groundwater in west Al-Ramadi was investigated using 2D electrical resistivity approach. The findings demonstrated that the water saturation depths (1.5–9.5 m) matched the water levels in Al-Anbar University wells, where the maximum saturated layer thickness in gypsum and mudstone soils was approximately 10.5 m.

The current study aims to ascertain the degree of sulfide contamination to the subterranean water in the Hit area using the electrical resistivity imaging method.

2. Materials and Methods

2.1. Location and Geology of the Site

The study area is situated within the Hit area in western Iraq. The study area lies between latitudes (33°62'59" and 33°64'19" North) and longitudes (42°80'74" to 42°82'58" E) (Fig. 1).

Al-Fatha Formation (Middle Miocene) constitutes the main geological outcrop in the study area. According to Buday (1980), this formation was subdivided into several informal units; It consists of anhydrite, gypsum, salt and fine-grained clastic rocks. The classification of its informal units is based on the quantity and interrelation of these rock types:

- a. Transition Beds, primarily composed of anhydrite, are interspersed with thin limestone and mudstone layers.
- b. Saliferous Beds, consists mainly of rock salt and anhydrite with some siltstone and mudstone, along with occasional limestone intercalations.
- c. Seepage Beds - made up of anhydrite inter-bedded with siltstone, mudstone and limestone layers.
- d. Upper Red Beds- composed of reddish mudstone and siltstone, with relatively Frequent limestone intercalations and some anhydrite (Jassim and Goff, 2006) (Fig. 2).

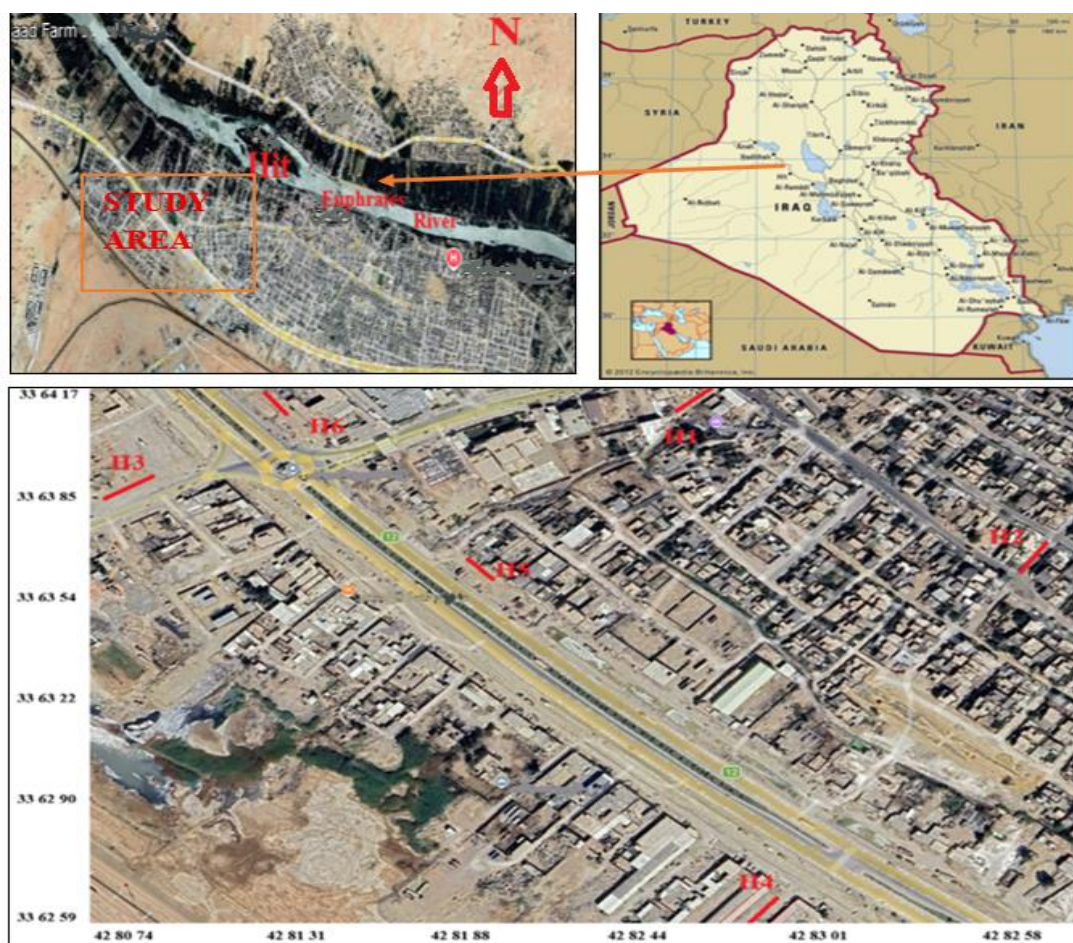


Fig. 1. Location map of the Study area

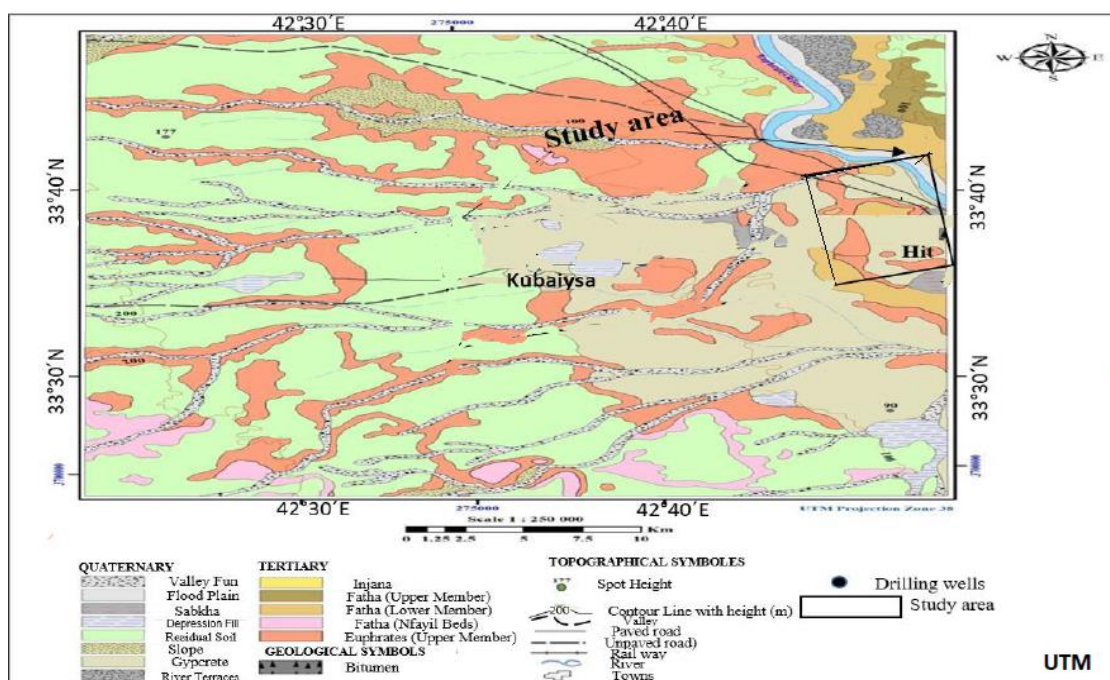


Fig. 2. The geological formations within the study area (Jassim and Goff, 2006)

(Al-Ghreri, 2007), however, divided and classified the stratigraphic sequence of Al-Fatha Formation in the Hit area into interbedded clay, siltstone, Marl and thick gypsum rocks (Fig. 3).

AGE	FORMATION	THICKNESS (m)	LITHOLOGY	DESCRIPTION
Middle Miocene	Fatha	4		Massive gypsum, white in colour
		2		Greenish to yellowish marl with intercalation of anhydrite weathered in places.
		6		Silty claystone with intercalation of siltstone, yellowish to redish in colour, with thin bed of gypsum.

Fig. 3. Lithological setting of the Fatha Formation in the Hit area. (Al-Ghreri, 2007)

2.2. Acquisition Data

Six profiles (H1–H6) were conducted across the study area using a Dipole–Dipole array in a 2D electrical resistivity survey. Profile H1 was carried out with an electrode spacing (a) of 2 m, whereas profiles H2 and H6 were performed with an a -spacing of 3 m. Profiles H3, H4, and H5 were conducted using an electrode spacing (a) of 5 m. The raw data were processed and interpreted using RESEDINV software. At each profile, 20 electrodes are used with an n -factor of 6.

2D inverse modeling was carried out using RES2DINV x64 ver. 4.8.9 software- The total reading points of the Dipole-Dipole array are 138.

3. Processing and Results

3.1. Data Processing

The RES2DINV software was utilized to produce a 2D resistivity inversion model (Loke, 2024).

In the initial stage, poor-quality data were eliminated using two approaches. The first approach involved manually identifying and removing unreliable data by setting up configuration files for the corresponding data points as shown in Fig. 4.

In the second one, an automatic filtering method was applied by utilizing the RMS error option to remove unreliable data points, thereby enhancing the overall RMS error values, as illustrated in Fig. 5. The 2D inversion model, which was produced using robust inversion constraints, Robust inversion algorithms for 2D electrical resistivity modeling, commonly based on the L_1 -norm or other robust constraints, improve subsurface imaging by reducing the influence of noise and outliers. This approach produces sharper, blockier and higher-contrast boundaries, offering a more realistic representation compared to the conventional smooth (least-squares) inversion methods (Loke and Barker, 1996).

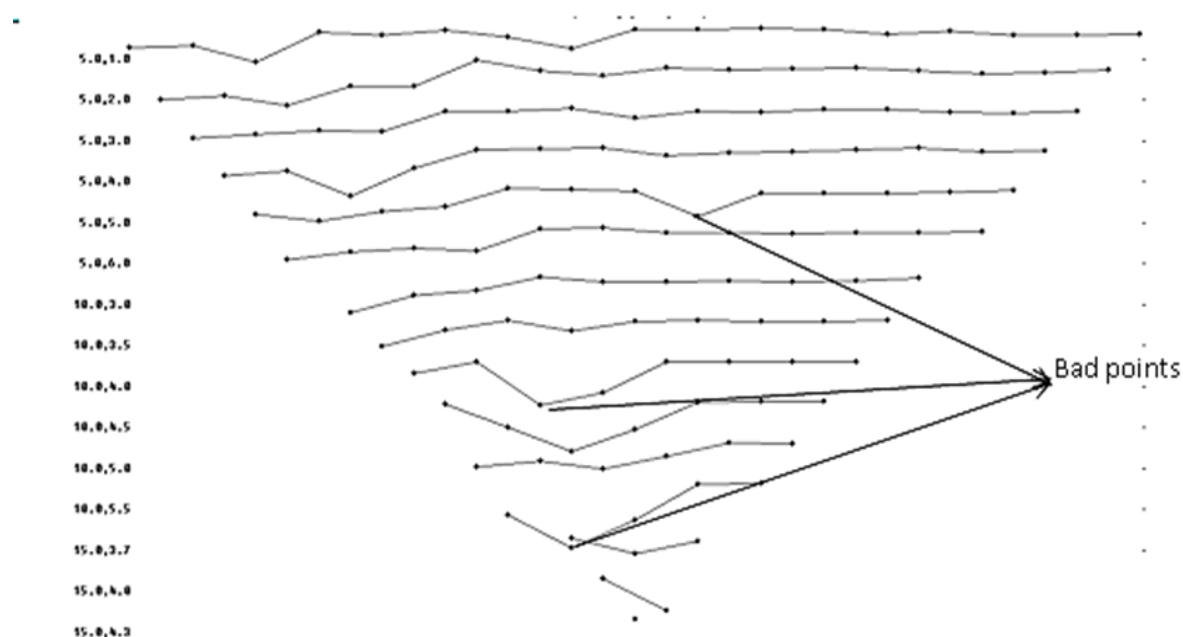


Fig. 4. The bad points in the plotting for 2D, profile H5

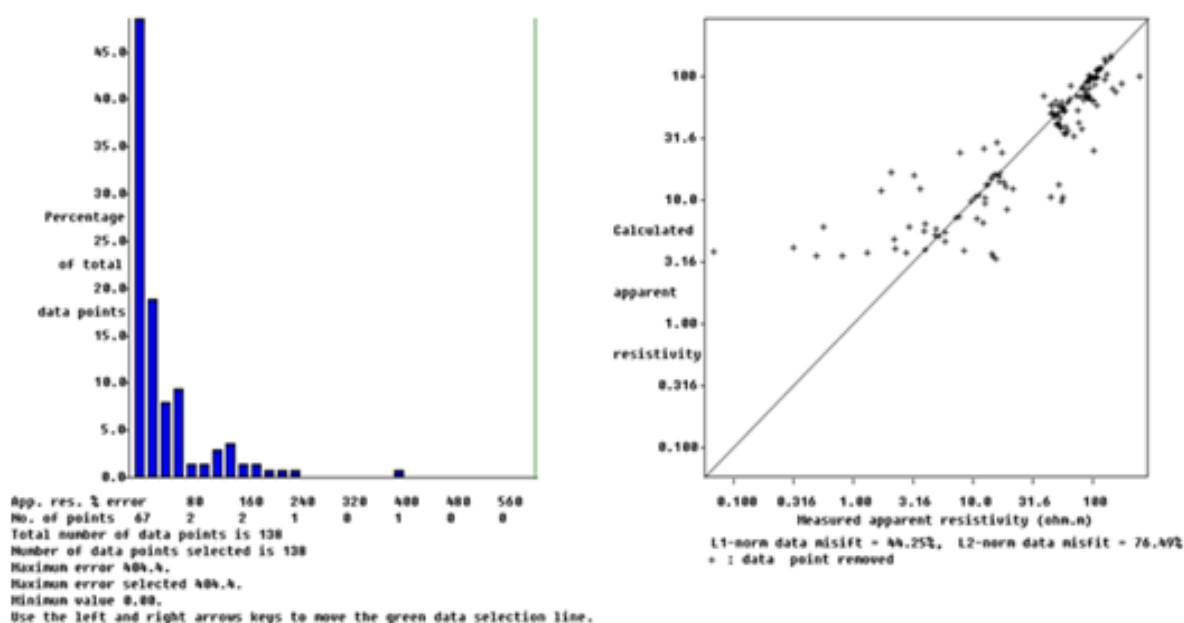


Fig. 5. RMS analysis windows for 2D, profile H5

3.2. The Results

3.2.1. H1 ERI profile

Fig. 6 illustrates the 2D inverse model of the first profile with an (Abs error) of 8.6% after (4) iterations. The high resistivity values, ranging between 137-301 Ωm , indicate the presence of sulfide groundwater (bituminous) at depths of approximately 0.5-2.50 m. This suggests that the sulfide groundwater may exist at this depth. At 2.5 to 9.5 m depths, lower resistivity values (1.25-13.9) Ωm are observed, indicating that these layers might be the gypsum of the Al-Fatha Formation.

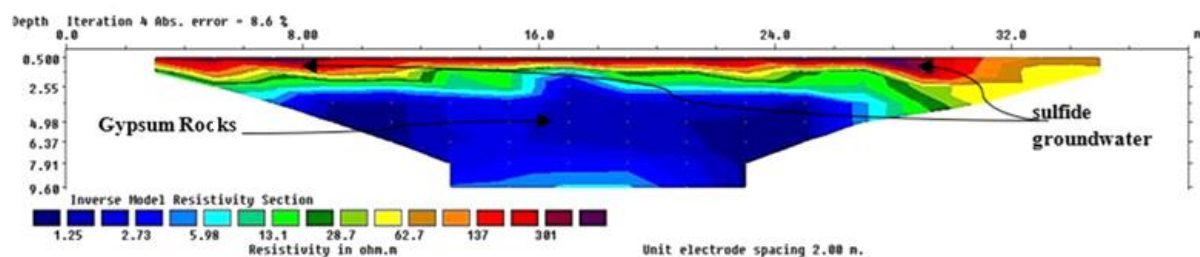


Fig. 6. 2D inverse model section of the profile H1

3.2.2. H2 ERI profile

Fig. 7 illustrates the 2D inverse model of the second profile with an (Abs error) of 8.9% after (4) iterations. The high-resistivity zones, with values more than $85.6 \Omega\text{m}$, indicate the presence of sulfide groundwater. These zones occur at depths of 0.5–2.7 m, concentrated primarily within the central section to the lower boundaries. This suggests the presence of an aquifer or a sulfide groundwater recharge zone. The low resistivity regions as 1.0–5.6 Ωm , 3.0–12.5 m depth range is characterized by gypsum and partially saturated rock formations.

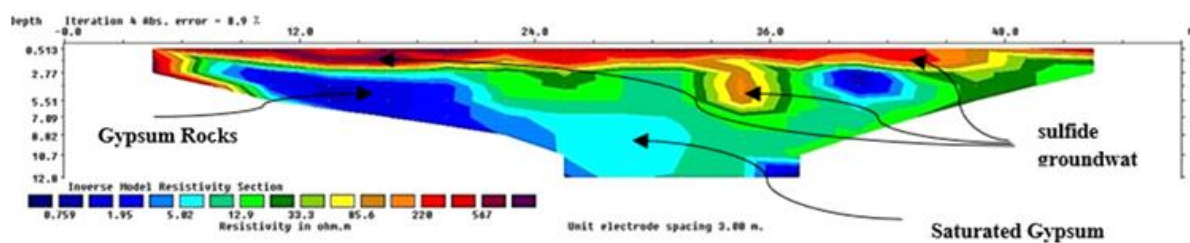


Fig. 7. 2D inverse model section of the profile H2

3.2.3. H3 ERI profile

Fig. 8 presents the 2D inverse model of the third profile with an (Abs error) of 9.3% after 4 iterations. The high-resistivity values, ranging from 62 to $150 \Omega\text{m}$, indicate sulfide water-saturated zones. These zones are concentrated in the right section of the profile at depths ranging from approximately 1.25 to 6.2 m.

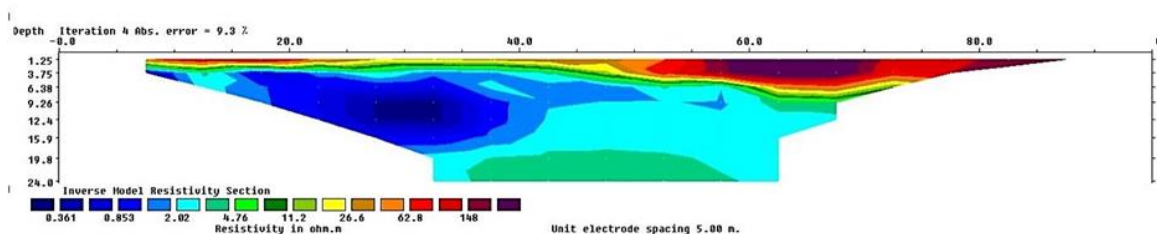


Fig. 8. 2D inverse model section of the profile H3

3.2.4. H4 ERI profile

Fig. 9 represents a 2D inverse model of the fourth profile with an (Abs error) of 5.6% after four iterations. The high resistivity values indicate sulfide groundwater saturated zones, which are located at a depth of approximately 1.25 to 4 m and extend along both sides of the section. The low resistivity values, on the other hand, represent the saturated fracture rocks.

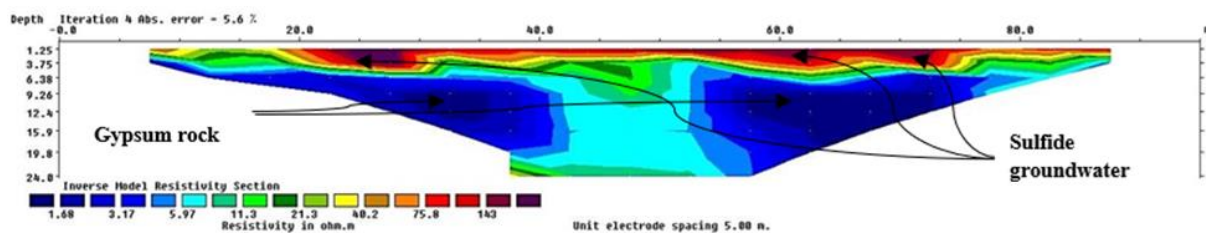


Fig. 9. 2D inverse model section of the profile H4

3.2.5. H5 ERI profile

Fig. 10 represents the 2D inverse model of the fifth profile with an (Abs error) of 9.17% after six iterations. The high resistivity values were appeared at the center of the section, ranging between 65 and 220 Ωm at a depth of approximately 0.8–16 m, indicate the presence of sulfurous water.

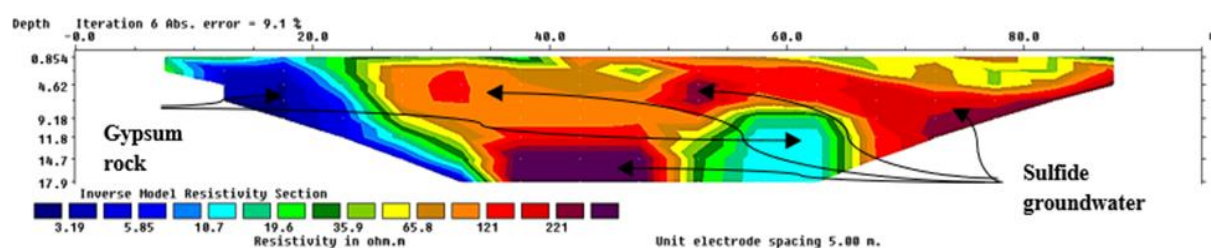


Fig. 10. 2D inverse model section of the profile H5

3.2.6. H6 ERI profile

Fig. 11 represents the 2D inverse model of the sixth profile with an (Abs error) of 11.4% after four iterations. The high resistivity values, ranging between 66 and 225 Ωm , are concentrated in the section at a depth range of 0.5 to 10.5 m. This specific depth suggests the occurrence of sulfide-bearing groundwater.

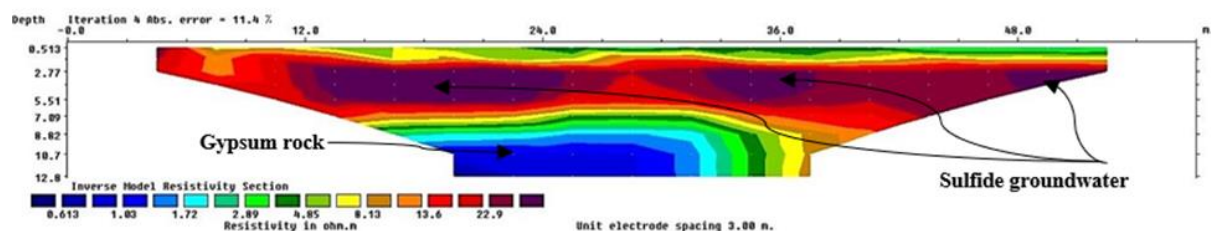


Fig. 11. 2D inverse model section of the profile H6

4. Discussion

The results of the two-dimensional electrical resistance imaging showed high efficiency in the detection and delimitation of groundwater contamination zones in the study area. Geophysical interpretations were further supported by field tests in which a depth of 1 m was drilled near profile H1, revealing that contamination by sulfide solutions was limited to shallow depths of 0.4–0.7 m. This agreement between direct observation and geophysical data increases the reliability of the resistivity method for identifying contamination near the surface of the ground. The reverse model showed that relatively high resistance values of 60–225 Ωm are associated with areas contaminated with sulfur-contaminated groundwater. This analysis is consistent with the geological environment along the H1 profile, where the subsurface is dominated by clay, green marl, and marl units. These compounds

have a high capacity to hold water and act as conduits and traps for contaminant migration via capillary processes.

In the study area, the depth of the contaminated zone varied significantly in space, generally between 1 and 6.7 m. The H5 profile went much deeper from 1 to 18 m. This variation shows heterogeneity of subsurface conditions and indicates that contamination is not uniformly distributed; rather, it is strongly controlled by stratigraphic layers and local hydrogeological factors. In contrast, it is highly controlled by stratigraphic layers and local hydrogeological factors such as the existence of relatively impermeable or semi-impermeable layers which would restrict the vertical movement of fluids and influence the lateral spread of pollutants. These findings are consistent with many other studies, but most importantly with those of Mohammed et al. (2021) who found contamination of soil water in the Hit area and related its distribution to the northeast as that of groundwater flow. These studies further prove that resistance anomalies observed in all models are an indication that the dynamics of groundwater flow, together with geological configurations in controlling the transport and accumulation of pollutants, as evidenced by the resistance abnormalities observed in all models.

5. Conclusions

Two-dimensional resistivity imaging was successful in mapping and identifying zones of groundwater contamination. Invasions bearing sulfide are generally shallow (0.4–0.7 m in section H1) and indicate a near-surface source or recent pollution. The clay and marl strata are barriers that prevent the vertical and lateral migration of the contaminants by capillary action. Contamination levels during the survey were variable, frequently ranging from 1 to 6.7 m, although an 18-m level was recorded in section H5, reflecting variation in the underlying strata. Thus, the distribution of pollutants is very irregular and related to specific hydrogeological features and geological strata, in particular the presence of impermeable or semi-permeable strata. These results draw attention to the importance of integrating geophysical imaging with field observations and hydrogeological analyses to enable a proper assessment of groundwater contamination in environments of complex geology.

Author contributions: CRediT

¹ Data Curation, Formal Analysis, Investigation, Visualization, Writing – Original Draft

² Conceptualization, Methodology, Software, Validation, Writing – Review & Editing

³ Conceptualization, Software, Supervision, Writing – Review & Editing

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

Acknowledgement

The authors would like to thank the head and members of the Department of Applied Geology for the valuable geological information they provided to support this research. Likewise, they would like to thank the Dean of the College of Science (University of Anbar) for providing the SAS-4000 tool, electrodes, electrical cables, etc., that were necessary in conducting the field survey.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request

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