

An Integrated Hydrogeological and Hydrogeochemical Approach for Distinguishing Point-Source Contamination from Natural Background Levels at a Landfill Site: The La Silva Case, Cassano Allo Ionio (Southern Italy)

Giulio Riga¹, Vincenzo De Matteis², Francesco Petrone²

¹Independent Researcher, Lamezia Terme, Italy

²Waste and Water Authority of Calabria, Catanzaro, Italy

Email: giulio.riga@tin.it, vincenzo.dematteis@arrical.it

How to cite this paper: Riga, G., De Matteis, V., & Petrone, F. (2026). An Integrated Hydrogeological and Hydrogeochemical Approach for Distinguishing Point-Source Contamination from Natural Background Levels at a Landfill Site: The La Silva Case, Cassano Allo Ionio (Southern Italy). *Journal of Geoscience and Environment Protection*, 14, 312-349.
<https://doi.org/10.4236/gep.2026.1410013>

Received: September 7, 2026

Accepted: October 27, 2026

Published: October 30, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

The report presents an integrated hydrogeological, geochemical, and geophysical investigation of a municipal solid waste landfill area located in Cassano allo Ionio (CS), Southern Italy. The study aimed to characterize the local subsurface, assess groundwater quality, and determine whether the elevated concentrations of iron (Fe) and manganese (Mn) are attributable to landfill-related contamination or to naturally occurring geogenic processes. The investigation identified a deep aquifer hosted within Pliocene conglomeratic deposits, characterized by low intrinsic vulnerability and groundwater flow predominantly toward the southeast, although locally complex piezometric conditions were observed. Although iron and manganese concentrations exceeded regulatory contamination thresholds in several monitoring wells, their spatial distribution, the prevailing redox conditions, their occurrence at upgradient locations, and comparison with surface waters and a nearby agricultural well indicate that these anomalies are more consistent with natural water-rock interactions and reductive dissolution processes within sandy-conglomeratic layers containing silty-clayey lenses than with the presence of a landfill-derived leachate plume. Geophysical investigations also contributed to delineating the geometry of the landfill and estimating the depth of the waste deposits, thereby supporting a more comprehensive characterization of the site.

Keywords

Groundwater, Landfill, Iron, Manganese, Natural Background Levels, Redox

1. Introduction

This study aims to summarize the hydrogeological, hydrogeochemical, and geophysical investigation conducted in the area of the municipal solid waste landfill located in the hamlet of Lauropoli, in the “La Silva” district, within the municipality of Cassano allo Ionio.

This report was prepared with the primary objective of defining the local geological and hydrogeological model, assessing groundwater quality using the piezometric monitoring network, assessing the origin of anomalous concentrations of iron and manganese relative to contamination threshold concentrations, and acquiring geophysical data useful for reconstructing the waste deposits and the depth of the landfill cells.

The approach adopted is integrated and multidisciplinary. It includes a critical analysis of previous geological and hydrogeological data, lithostratigraphic reconstruction based on data from the piezometers and surveyed wells, measurement of static groundwater levels, mapping of the piezometric surface and flow directions, physicochemical sampling of groundwater and surface water, including water from an agricultural well, as well as the execution and interpretation of electrical resistivity tomography. This approach allows for the correlation of geological structure, water circulation patterns, hydrochemical facies, and the spatial distribution of the key parameters of concern (SNPA, 2018; APAT-IRSA-CNR, 2003).

Particular emphasis is placed on the interpretive framework aimed at distinguishing between anomalous values due to natural geochemical conditions and possible anthropogenic inputs. In this context, the assessment of background values and redox conditions is essential for correctly interpreting exceedances of iron and manganese concentrations (SNPA, 2018; APAT-IRSA-CNR, 2003; Italia, 2006).

2. Materials and Methods

2.1. Geographical, Topographical, and Climatic Context

The site in question is located northeast of the town of Cassano allo Ionio, specifically in the La Silva district, at an average elevation of approximately 125 meters above sea level. The area is shown on the “Francavilla Marittima” map sheet (221 II NE) of the Geological Map of Italy and is identified in the cadastral records as sheet 21, parcels 141, 142, 145, 147, 99, and 138. Access to the landfill is via the La Silva district road, which runs along the northwestern side of the site.

From a geomorphological perspective, the central area of the landfill is nearly flat, with slopes less than 10%. In contrast, the northern sector has steeper slopes ranging from 10% to 30%. The topography is influenced by erosion processes in the small ditches located east of the facility and by the nearby Raganello Stream.

Overall, the area takes the form of a narrow, flat ridge, characterized by small

drainage depressions and secondary ridges oriented roughly along a north-south axis, which facilitate stormwater drainage toward the Raganello hydrographic network.

The local climate is Mediterranean, characterized by relatively cold and humid winters and hot, dry summers. The rainfall series from the Cassano allo Ionio station, updated through 2025 and covering the period 1921-2025, records an average annual rainfall of 726.1 mm.

The highest precipitation occurs in December, with an average of 98.2 mm, while the lowest is recorded in July, with only 19.6 mm. The average annual temperature is 16.5°C, with monthly averages ranging from 7.6°C in January to 25.3°C in July and August. The concentration of precipitation in the autumn and winter months promotes groundwater recharge through both vertical and lateral infiltration. High temperatures and low summer rainfall, on the other hand, reduce fluctuations in the water table, a factor further compounded by the considerable depth of the aquifer itself.

2.2. Geological, Stratigraphic, and Hydrogeological Setting

The subsurface of the site consists of a lithostratigraphic complex of Pleistocene marine sediments, predominantly reddish-yellow sands and sands with rounded pebbles, characterized by clinostratification and cross-bedding, with sporadic clay interbeds (**Figure 1**). This complex rests on well-cemented, coarsely stratified, polygenic conglomerates of the Upper Pliocene, composed of rounded calcareous and arenaceous pebbles, associated with coarse sands and lenses of silty clay. The surface formation, which serves as the foundation for the landfill, has an average thickness not exceeding 40 m and is characterized by generally high permeability, although this is limited by the clay interbeds.

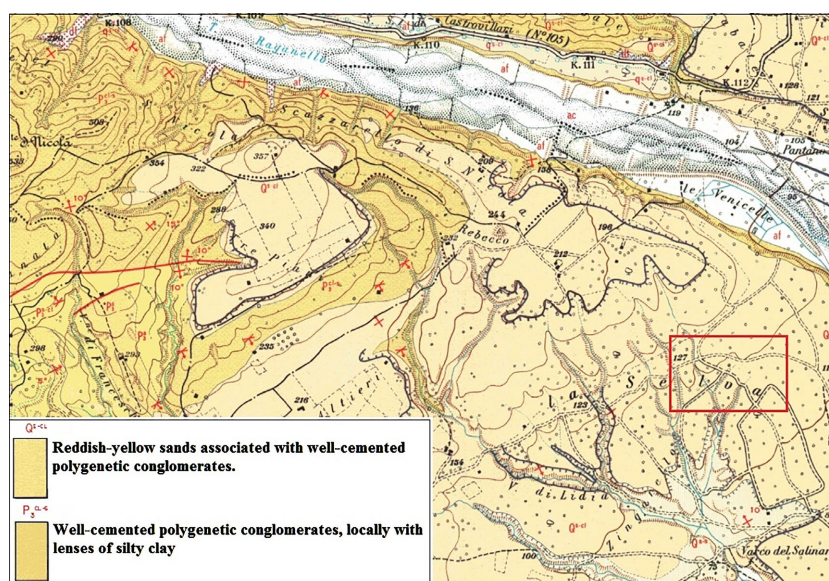


Figure 1. Excerpt from the geological map of Calabria at a scale of 1:25,000. The red box indicates the location of the landfill.

Stratigraphic investigations conducted using piezometers (Pz7 - Pz12) and surveyed wells reveal a subsoil that is heterogeneous both laterally and vertically, dominated by alternating layers of polygenic conglomerates, cemented grayish sands, and silty clays. The average stratigraphic profile is divided into two main units: a Pleistocene formation, from 0 to approximately 32 meters, consisting of polygenic conglomerates and grayish sands with clay interbeds; and a Pliocene formation, from approximately 32 to 120 meters, composed of well-cemented polygenic conglomerates with lenses of silty clays.

The structural setting is monoclinical, with strata trending SW-NE and dipping toward the SE at an angle of less than 10°.

Hydrogeologically, the reddish-yellow sands and polygenic conglomerates constitute the main permeable layers due to their porosity, while the silty clays represent low-permeability layers or local hydraulic discontinuities. The first aquifer is located on average at a depth of 50 - 53 meters below ground level and is hosted within the polygenic conglomerates, which constitute the main reservoir. Its recharge depends on precipitation and watercourses, with vertical infiltration mechanisms and predominant flow toward the southeast, consistent with the monoclinical structure. Deeper aquifers are also present in sandy and conglomeratic sediments, separated by fine-grained layers of moderate thickness (Freeze & Cherry, 1979).

The intrinsic vulnerability of the aquifer was assessed using the SINTACS method, which indicated a low potential risk of contamination in the event of surface or lateral inflows. However, the quantitative vulnerability index (Iv), equal to 97, classifies the area as having low vulnerability. This result is justified by the depth of the aquifer, the thickness of the unsaturated zone, the presence of clayey-silty layers, and the moderate permeability of the overlying strata, all of which contribute to attenuating the vertical transport of pollutants (Civita & De Maio, 2000).

2.3. Stratigraphic Data

Information regarding the stratigraphy and lithological characteristics of the study area was obtained by analyzing the stratigraphic profiles of several piezometers belonging to the existing monitoring network, for which subsurface data are available.

Observations conducted on outcrops confirmed that the stratigraphic sequences identified in the piezometers can be considered representative of the area under examination. The boreholes traversed the entire thickness of the sequence, which consists of polygenic conglomerates alternating with layers of silty clay.

Based on the available data, the area of interest exhibits moderate lithological variability, both horizontally and vertically.

It was therefore possible to reconstruct the following average stratigraphic profile:

- from 0.00 to 120.00 m below ground level: alternating layers of polygenic conglomerate and silty clay.

Tables 1-7 provide a summary of the stratigraphic profiles recorded at some of the piezometers in the monitoring network.

Table 1. Piezometer Pz5, diameter = 160 mm, filter 1 from –51.0 to –99.0 m.

Layer No.	Depth (m)	Classification
1	2.5	Fill soil consisting of loose sand and gravel ranging in color from ochre yellow to brown, with heterometric and heterogeneous clasts
2	10.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular
3	37.0	Brown silty clays interbedded within the sandy conglomerate layers
4	45.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular
5	51.0	Brown silty clays interbedded within the sandy conglomerate layers
6	100.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular

Table 2. Piezometer Pz7, diameter = 160 mm, filter 1 from –60.0 to –70.0 m, filter 2 from –80.0 to –90.0 m, filter 3 from –93.0 to –100.0 m, filter 4 from –105.0 to –115.0 m.

Layer No.	Depth (m)	Classification
1	2.0	Topsoil
2	9.0	Well-cemented polygenic conglomerate, generally consisting of heterometric pebbles that are partly rounded and partly angular
3	35.0	Brown silty clays. These are generally interbedded within the sandy conglomerate layers
4	48.0	Well-cemented polygenic conglomerate
5	55.0	Brown silty clays. These are generally interbedded within the sandy conglomerate layers
6	74.0	Grayish, sometimes ochre-colored, cemented sands
7	80.0	Brown silty clays. These are generally interbedded within the sandy conglomerate layers
8	85.0	Well-cemented polygenic conglomerate
9	87.0	Brown silty clays. These are generally interbedded within the sandy conglomerate layers
10	90.0	Well-cemented polygenic conglomerate
11	93.0	Gray silty clays
12	100.0	Well-cemented polygenic conglomerate
13	105.0	Alternating silty clays and conglomerates
14	115.0	Well-cemented polygenic conglomerate
15	120.0	Gray silty clays

Table 3. Piezometer Pz8, diameter = 160 mm, filter 1 from –48.0 to –68.0 m, filter 2 from –70.0 to –77.0 m, filter 3 from –80.0 to –90.0 m.

Layer No.	Depth (m)	Classification
1	3.0	Overlying and fill material

Continued

2	25.0	Well-cemented polygenic conglomerate, generally consisting of heterometric pebbles that are partly rounded and partly angular
3	30.0	Brown silty clays. These are generally interbedded within the sandy conglomerate layers
4	32.0	Grayish, sometimes ochre-colored, cemented sands
5	40.0	Well-cemented polygenic conglomerate
6	41.0	Well-cemented polygenic conglomerate, generally consisting of rounded pebbles
7	48.0	Brown silty clays. These are generally interbedded within the sandy conglomerate layers
8	68.0	Grayish, sometimes ochre-colored, cemented sands
9	70.0	Brown silty clays. They are generally interbedded within sandy-conglomeratic layers
10	73.0	Grayish, sometimes ochre-colored, cemented sands
11	76.0	Grayish, sometimes ochre-colored, cemented sands. They contain clay interbeds
12	77.0	Well-cemented polygenic conglomerate
13	80.0	Brown silty clays
14	90.0	Well-cemented polygenic conglomerate, generally consisting of rounded pebbles
15	97.0	Brown silty clays. They are generally interbedded within the sandy conglomerate layers
16	98.0	Well-cemented polygenic conglomerate, generally consisting of rounded pebbles
17	120.0	Gray silty clays

Table 4. Piezometer Pz9, diameter = 160 mm, filter 1 from –65.0 to –69.0 m, filter 2 from –80.0 to –95.0 m.

Layer No.	Depth (m)	Classification
1	2.0	Overlying and fill material
2	40.0	Well-cemented polygenic conglomerate, generally consisting of heterometric pebbles that are partly rounded and partly angular
3	50.0	Well-cemented polygenic conglomerate
4	52.0	Brown silty clays. These are generally interbedded within the sandy conglomerate layers
5	69.0	Well-cemented polygenic conglomerate
6	71.0	Brown silty clays
7	75.0	Well-cemented polygenic conglomerate
8	79.0	Brown silty clays
9	95.0	Well-cemented polygenic conglomerate
10	100.0	Brown silty clays. They are generally interbedded within the sandy conglomerate layers

Table 5. Piezometer Pz10, diameter = 160 mm, filter 1 from –5.0 to –50.0 m, filter 2 from –55.0 to –80.0 m.

Layer No.	Depth (m)	Classification
1	2.0	Topsoil
2	4.5	Fill soil consisting of loose sand and gravel ranging in color from ochre yellow to brown, with heterometric and heterogeneous clasts
3	51.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular
4	53.0	Brown silty clays interbedded within the sandy conglomerate layers
5	82.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular
6	85.0	Brown silty clays interbedded within the sandy conglomerate layers
7	100.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular

Table 6. Piezometer Pz11, diameter = 160 mm, filter 1 from –5.0 to –55.0 m, filter 2 from –65.0 to –80.0 m.

Layer No.	Depth (m)	Classification
1	2.0	Topsoil
2	3.0	Fill soil consisting of loose sand and gravel ranging in color from ochre yellow to brown, with heterometric and heterogeneous clasts
3	57.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular
4	60.0	Brown silty clays interbedded within the sandy conglomerate layers
5	100.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular

Table 7. Piezometer Pz12, diameter = 160 mm, filter 1 from –5.0 to –45.0 m, filter 2 from –55.0 to –80.0 m.

Layer No.	Depth (m)	Classification
1	2.0	Topsoil
2	4.5	Fill soil consisting of loose sand and gravel ranging in color from ochre yellow to brown, with heterometric and heterogeneous clasts
3	47.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular
4	49.0	Brown silty clays interbedded within the sandy conglomerate layers
5	100.0	Well-cemented polygenic conglomerate generally consisting of heterometric pebbles, some rounded and some angular

2.4. Hydrogeological Characteristics of the Area

Based on data provided by the stratigraphic logs of wells used for agricultural and

drinking-water purposes (Source: ISPRA) and by the piezometers installed in the study area, a more detailed analysis of the local geological and hydrogeological conditions was carried out. The available information confirms the presence of multiple aquifers with moderate yield potential.

The reddish-yellow sands and polygenic conglomerates are highly permeable due to their porosity, whereas the interbedded silty clays are impermeable or poorly permeable. Their hydrogeological role, both in groundwater recharge and as a basal layer, depends on their position in the stratigraphic sequence, their dip, and the extent of their outcrop.

Water from direct and indirect inputs accumulates in the sands and polygenic conglomerates, which have an approximately monoclinical structure dipping about 10° toward the southeast; flowing above the silty clays, groundwater drains toward the southeast.

The deep wells drilled in the study area intercepted a first aquifer at approximately 53 m below ground level, hosted in the polygenic conglomerates, which represent the main reservoir in the area. The aquifer is supplied exclusively by rainfall over the area and by watercourses.

Water reaches the aquifer predominantly by vertical infiltration, with medium-to-high infiltration rates. Well productivity values (Q/s) are less than 10 L/s.

Overall, the hydrogeological structure of the area can be attributed to a multi-aquifer system, in which the conglomerates constitute the main aquifers, while the intercalated fine-grained layers regulate circulation and communication between the various hydrogeological units.

2.5. Piezometer Network and Groundwater Dynamics

The groundwater monitoring network consists of 12 piezometers (**Figure 2**), located both along the perimeter and within the landfill and classified as upstream, downstream, and intermediate piezometers. The boreholes were lined with PVC pipes with a nominal diameter of DN 140 - 160 mm, slotted up to the terminal section, and reach maximum depths of approximately 130 m below ground level.

The locations and elevations of the piezometers in the monitoring network were determined using a portable global positioning system (GPS). The geographic coordinates, georeferenced in the WGS 84 reference system, are shown in **Table 8**.

In May 2025-2026, a survey campaign was conducted to measure static piezometric levels (**Table 9** and **Table 10**) using an acoustic-signal water level meter, with the aim of reconstructing the piezometric surface and identifying the main flow paths of the aquifer (APAT-IRSA-CNR, 2003).

The piezometric data were processed using the Kriging interpolation method, with the Surfer software from Golden Software Inc. The measured static water levels were processed to reconstruct the isopiezometric curves, expressed in meters above sea level (m.a.s.l.), using a contour interval of 0.20 m.

Data interpolation made it possible to define the geometry of the aquifer's piezometric surface and to identify the main directions of underground flow, which

were inferred from the trend of the isopiezometric curves and, under isotropic conditions, are oriented perpendicular to those curves, in the direction of decreasing piezometric heads.

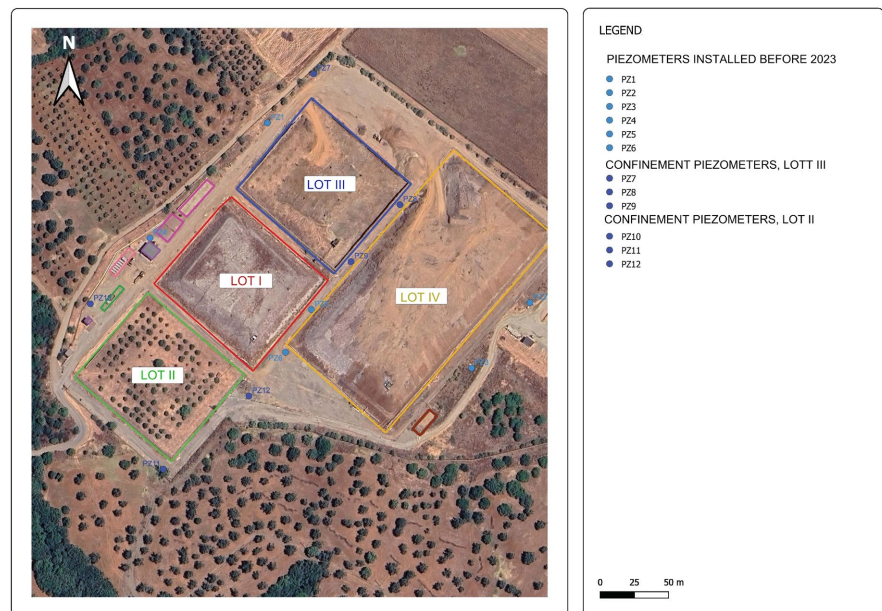


Figure 2. Site plan of the current piezometric monitoring network. Google Maps, 2025, <https://maps.google.com/>.

Table 8. Locations and coordinates of the piezometers.

Piezometer No.	Piezometer Location	Latitude	Longitude
Pz1	Upstream	39°47.500208	16°22.755257
Pz2	Downstream	39°47.429752	16°22.890120
Pz3	Downstream	39°47.403769	16°22.859808
Pz4	Upstream	39°47.455113	16°22.695532
Pz5	Intermediate	39°47.426923	16°22.778097
Pz6	Intermediate	39°47.410277	16°22.765000
Pz7	Upstream	39°47.521234	16°22.785835
Pz8	Intermediate	39°47.470529	16°22.825057
Pz9	Intermediate	39°47.443827	16°22.794899
Pz10	Upstream	39°47.429040	16°22.665235
Pz11	Intermediate	39°47.364113	16°22.704650
Pz12	Intermediate	39°47.393084	16°22.741615

Table 9. Piezometric levels, May 2025.

Piezometer No.	Elevation measured at the piezometer inlet (m.a.s.l.)	Groundwater level at piezometer mouth (m)	Absolute groundwater level (m)	Depth piezometer (m)	Diameter (mm)	Pipe thickness (mm)
Pz1	135.953	58.53	77.423	130	140	6

Continued

Pz2	124.268	50.07	74.198	93	140	6
Pz3	123.280	49.66	73.620	78	140	6
Pz4	133.430	56.02	77.410	80	140	6
Pz5	125.733	48.53	77.247	100	160	7.7
Pz6	125.243	47.93	77.313	80	140	6
Pz7	136.111	58.73	77.381	120	160	7.7
Pz8	127.825	50.62	77.205	120	160	7.7
Pz9	126.773	49.55	77.223	100	160	7.7
Pz10	131.739	54.30	77.439	100	160	7.7
Pz11	124.149	46.99	77.159	100	160	7.7
Pz12	124.948	47.37	77.578	100	160	7.7

Table 10. Piezometric levels, May 2026.

Piezometer No.	Elevation measured at the piezometer inlet (m.a.s.l.)	Groundwater level at piezometer mouth (m)	Absolute groundwater level (m)	Depth piezometer (m)	Diameter (mm)	Pipe thickness (mm)
Pz1	135.953	57.56	78.393	130	140	6
Pz2	124.268	49.42	74.848	93	140	6
Pz3	123.280	48.89	74.390	78	140	6
Pz4	133.430	55.22	78.210	80	140	6
Pz5	125.733	47.55	78.183	100	160	7.7
Pz6	125.243	47.13	78.113	80	140	6
Pz7	136.111	57.61	78.501	120	160	7.7
Pz8	127.825	50.05	77.775	120	160	7.7
Pz9	126.773	48.54	78.233	100	160	7.7
Pz10	131.739	53.56	78.179	100	160	7.7
Pz11	124.149	46.30	77.849	100	160	7.7
Pz12	124.948	47.01	77.938	100	160	7.7

The resulting piezometric reconstruction is considered representative of the equilibrium hydraulic head of the multilayer aquifer system, consisting of poly-genic conglomerates interbedded with silty clays present in the subsoil of the area affected by the landfill. This representation therefore allows for a regional-scale description of the hydrogeological configuration of the aquifer and the possible pathways of groundwater migration.

The interpolation revealed a piezometric surface characterized by a complex geometry, as illustrated in **Figure 3** and **Figure 4**. The trend of the piezometric contours highlights different hydraulic configurations within the study area:

- In the southern sector of the landfill, a converging radial structure is observed.

This configuration generates an increase in the piezometric gradient, which causes groundwater flow directed toward piezometer Pz3, altering the local groundwater flow pattern.

The groundwater flow is therefore directed from piezometers Pz11, Pz12, Pz5, Pz6, Pz8, and Pz9 toward Pz3. Near Pz3, the spacing between the isopiezometric contours decreases, indicating a steeper hydraulic gradient.

- In the area between piezometers Pz4, Pz5, and Pz6, however, a divergent structure is observed, associated with a rise in the piezometric surface.
- A main drainage axis extends from the northwest to the southeast, located between piezometers Pz5 and Pz3. The main groundwater flow paths indicate that groundwater recharge is supplied predominantly by water from the northern sector.

The hydraulic gradient is approximately 3% in the areas corresponding to Lots IV and I, while it drops to less than 1% in Lots I, II, and III.

To examine the temporal evolution of the piezometric surface, a comparative analysis was conducted between the map prepared by the Calabria Region (**Figure 3(a)**) and the piezometric maps constructed based on data measured in May 2025 and 2026 (**Figures 3(b)** and **Figures 3(c)**).

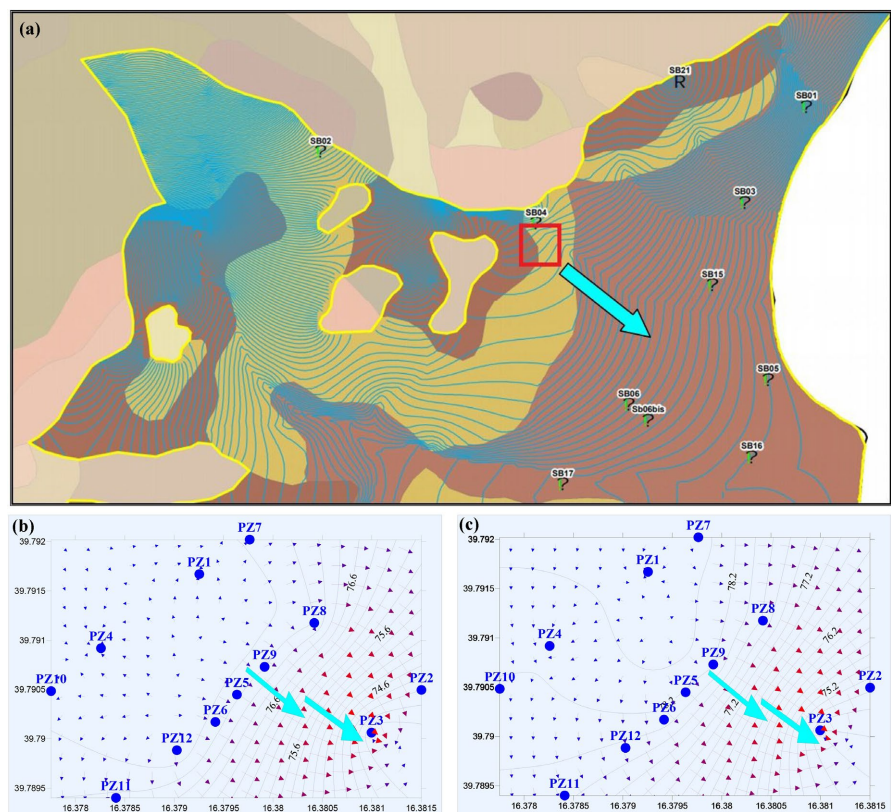


Figure 3. Isopiezies and groundwater flow directions: (a) reconstruction of the Sibari hydrogeological basin based on data from the Calabria Region; (b) and (c) reconstructions developed, respectively, in the supplementary studies of May 2025 and 2026. The red and blue vectors indicate the flow directions. The light blue vectors indicate the main drainage axis.

The trend of the isopiezometric curves indicates groundwater flow directed toward piezometer Pz3. The flow is oriented from the northwest toward the southeast, with an increase in the spacing between the isopiezometric contours toward piezometer Pz3, indicating a reduction in the hydraulic gradient in that sector.

During the monitoring period under consideration, the minimum depth to groundwater was recorded in the southwestern sector of the landfill, at 46.98 m below ground level, while the maximum depth to groundwater was measured in the northern sector, at 59.11 m below ground level.

The depth-to-groundwater values recorded in the various piezometers are shown in **Table 11**, while **Figure 5** shows the map of groundwater depth relative to ground level in May 2025.

Table 12 lists the main characteristics of the aquifer, which are useful for a more in-depth understanding of the hydrogeological dynamics in the area of interest. **Table 13** shows the univariate statistics for: a) Isopiezes 2025, b) Isopiezes 2026.

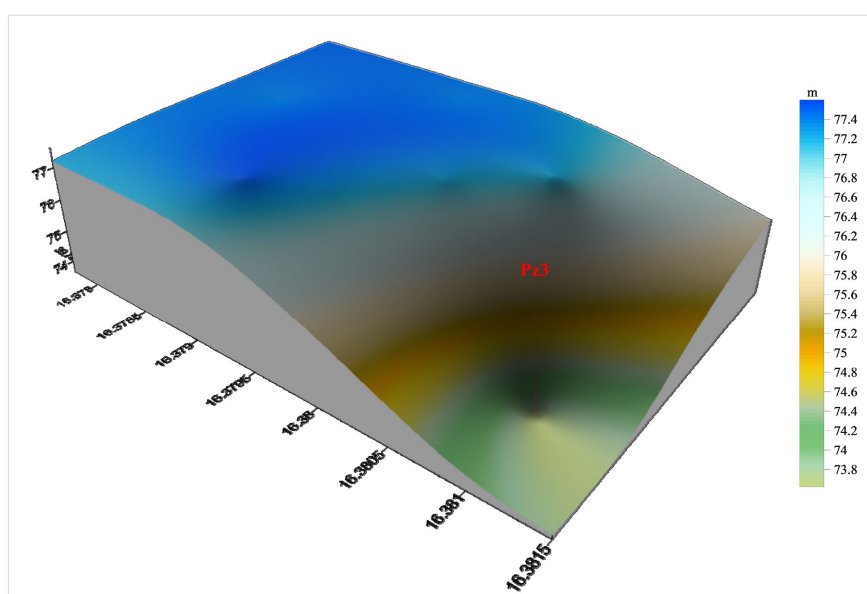


Figure 4. Three-dimensional model of the piezometric surface reconstructed in the supplementary study.

Table 11. Water table depth in May 2025.

Piezometer No.	Elevation measured at the piezometer inlet (m.a.s.l.)	Ground level (m.a.s.l.)	Groundwater level at piezometer mouth (m)	Water table depth (m)
Pz1	135.953	135.774	58.53	58.351
Pz2	124.268	124.135	50.07	49.937
Pz3	123.280	123.248	49.66	49.514
Pz4	133.430	133.134	56.02	55.724
Pz5	125.773	125.963	48.05	48.280
Pz6	125.243	125.100	47.93	47.787

Continued

Pz7	136.111	136.495	58.73	59.114
Pz8	127.825	128.104	50.62	50.899
Pz9	126.773	126.975	49.55	49.752

Table 12. Summary of aquifer characteristics.

Parameter	Value/Range	Technical Meaning	Remarks
Depth to groundwater	46.891 - 59.114 m below ground level	Deep aquifer with substantial depth to groundwater	Minimum at Pz11; maximum at Pz7
Piezometric elevations	73.620 - 77.578 m above sea level	Piezometric surface with a gentle gradient	Lowest elevations in Pz3 - Pz5
Predominant flow	NW-SE, with drainage axis Pz5 - Pz3	Consistent with the morphological and stratigraphic structure	Convergent radial structure in Pz3
SINTACS vulnerability	Iv = 97, low class	Attenuation due to groundwater depth and fine-grained layers	Remains sensitive to localized inputs

Table 13. Univariate statistics: a) Isopiezes 2025, b) Isopiezes 2026.

a	X	Y	Z
Minimum:	16.3778	39.7894	73.62
25%-tile:	16.379	39.7902	77.205
Median:	16.3796	39.7905	77.313
75%-tile:	16.3804	39.7912	77.423
Maximum:	16.3815	39.792	77.578
Midrange:	16.3796	39.7907	75.599
Range:	0.00375	0.00262	3.958
Interquartile range	0.00139	0.001	0.218
Median Abs. Deviation:	0.00078	0.00043	0.11
Mean:	16.3795	39.7906	76.7663
Trim Mean (10%):	16.3795	39.7906	76.9998
Standard Deviation:	0.00106	0.00071	1.28826
Variance:	1.1E-06	5.1E-07	1.65962
Coef. of Variation:		0.01678	
Coef. of Skewness:		-1.79109	
b	X	Y	Z
Minimum:	16.3778	39.7894	74.390
25%-tile:	16.379	39.7902	77.849
Median:	16.3796	39.7905	78.179
75%-tile:	16.3804	39.7912	78.233
Maximum:	16.3815	39.792	78.501

Continued

Midrange:	16.3796	39.7907	76.4455
Range:	0.00375	0.00262	4.111
Interquartile range	0.00139	0.001	0.384
Median Abs. Deviation:	0.00078	0.00043	0.241
Mean:	16.3795	39.7906	77.551
Trim Mean (10%):	16.3795	39.7906	77.7721
Standard Deviation:	0.00106	0.00071	1.32939
Variance:	1.1E-06	5.1E-07	1.76728
Coef. of Variation:		0.01714	
Coef. of Skewness:		1.72036	

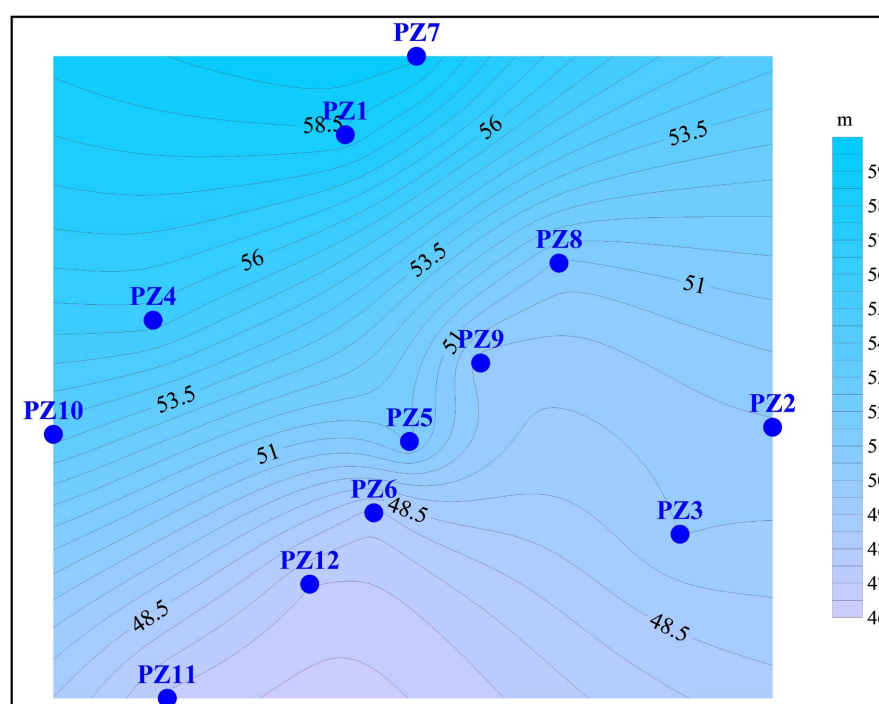


Figure 5. Map of groundwater depth relative to ground level in May 2025.

3. Results

3.1. Hydrogeochemical Characteristics of Groundwater

The sampling conducted in May 2025 was preceded by the purging of the piezometers, aimed at removing stagnant water that was not representative of the actual conditions of the aquifer. At nearly all monitoring points, at least three well volumes were purged. Samples were subsequently collected using a low-flow submersible pump, working from upgradient to downgradient piezometers, in order to minimize potential interference between sampling points and ensure the representativeness of the hydrochemical characteristics of the groundwater (APAT-IRSA-CNR, 2003).

Official methods recognized at the national and/or international level and in accordance with the most advanced techniques in general use were applied to determine all analytical parameters. The procedures adopted ensure adequate levels of accuracy, reliability, and reproducibility of the results.

The data obtained were validated by the Supervisory Authority, both for the fieldwork and for the laboratory analyses.

The major cations and anions Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , Cl^- , HCO_3^- , and NO_3^- were analyzed to characterize the hydrochemical facies of the waters and to identify the main geochemical processes that govern their composition. In particular, analysis of the data allows for an assessment of the role of water-rock interaction, any mixing processes between waters of different origins, and possible spatial variations in the aquifer's chemical characteristics.

The ionic composition of the water can, in fact, reveal whether the samples belong to a single homogeneous hydrochemical body or whether they exhibit trends that can be correlated with the sampling area, the varying lithology traversed, or the presence of portions of the aquifer characterized by specific local conditions. These include, for example, deep water inflows, geothermal phenomena, processes of mineral dissolution or precipitation, and anthropogenic or agricultural inputs, which are particularly significant with regard to the presence of nitrates.

The definition of the geochemical facies of each sample is based on the relative distribution of the main dissolved components: Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , Cl^- , and HCO_3^- , supplemented, where available, by CO_3^{2-} , F^- , and NO_3^- . These species derive primarily from the interaction between water and the geological formations it passes through, via processes of dissolution of common mineral phases in sedimentary, igneous, and metamorphic rocks. The relative ratio of ions thus allows for the recognition of different facies, as well as the identification of any changes in chemical composition along the underground flow path.

The analytical quality of the data was verified by calculating the ion balance, expressed in milliequivalents per liter (meq/L). This verification is based on the principle of solution electroneutrality, according to which the sum of positive charges must be balanced by the sum of negative charges. The ion balance index was calculated using the following expression:

$$B = 100 \times \frac{\sum \text{meqCationi} - \sum \text{meqAnioni}}{\sum \text{meqCationi} + \sum \text{meqAnioni}} \quad (1)$$

Under ideal conditions, the IB value should be close to zero. Generally, values within $\pm 5\%$ are considered acceptable; however, depending on the hydrochemical matrix and the completeness of the analytical profile, a range of up to $\pm 10\%$ may be permitted.

All analyzed samples exhibit ion balance values within the $\pm 10\%$ range. This result indicates overall consistency among the determined concentrations of the major cations and anions and confirms the reliability of the analytical data for hydrochemical characterization. The subsequent interpretation of the ionic distribution thus allows for an assessment of whether the samples belong to the same

facies, the identification of possible evolutionary processes along the aquifer system, and the detection of local anomalies attributable to specific geochemical inputs or processes.

The main physicochemical parameters determined for the water samples collected from the monitoring network are shown in **Table 14**. The groundwater in the study area has temperatures ranging from 18.6 to 23.8 °C, with the lowest value recorded in sample Pz10 and the highest in sample Pz5.

Table 14. Summary statistics for physicochemical parameters and major constituents in groundwater samples.

Parameter	Minimum	Maximum	Average	Standard deviation
T (°C)	18.6	23.8	20.36	1.3604
pH	7.11	7.60	7.45	0.1454
Electrical conductivity (µS/cm at 20 °C)	710	958	789.5	88.47
Dissolved oxygen (mg O ₂ /L)	1.45	5.72	3.24	1.204
Redox (mV)	36.0	278.0	203.8	60.37
Mg (mg/L)	38.0	54.0	42.63	4.769
Ca (mg/L)	85.3	122.1	97.792	12.302
Na (mg/L)	30.0	48.0	37.8	5.46
K (mg/L)	2.3	3.0	2.75	0.215
Cl (mg/L)	49.0	118.0	75.21	22.13
HCO ₃ (mg/L)	383.03	566.76	423.77	50.7453
SO ₄ (mg/L)	20.81	42.09	36.731	4.5601
NO ₃ (mg/L)	0	4.31	1.966	1.409
Fluoride (µg/L)	170	251	216.5	25.19
Iron (µg/L)	0	596.5	127.67	216.82
Manganese (µg/L)	0	565.7	174.46	171.07
Arsenic (µg/L)	0	3.2	0.65	1.2

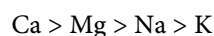
All samples are slightly alkaline, with pH values ranging from 7.11 to 7.60 and a mean of 7.45. These values are consistent with those generally found in water circulating within sandy formations. The lowest pH value was measured in sample Pz6, while the highest was recorded in sample Pz2; in the other samples, the pH averages around 7.5.

The redox potential (Eh) is generally similar across most samples, with Pz3 showing the lowest value, 36 mV. Electrical conductivity ranges from a minimum of 710 µS/cm, measured in sample Pz4, to a maximum of 958 µS/cm, recorded in sample Pz3. Dissolved oxygen concentrations range from 1.45 mg/L in sample Pz3 to 5.72 mg/L in sample Pz4.

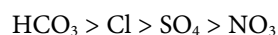
Nitrate concentrations are generally low, indicating the absence of significant anthropogenic sources of contamination. Sodium, potassium, magnesium, and chlorides are present in low-to-moderate concentrations, while bicarbonates and

calcium show moderate-to-high values.

The geochemical composition of the groundwater is characterized by the predominance of calcium among the major cations, in the following order:



In terms of average concentration, the cations are ranked as follows: calcium, at 97.792 mg/L; magnesium, at 42.63 mg/L; sodium, at 37.8 mg/L; and potassium, at 2.75 mg/L. Among the anions, bicarbonates predominate, followed by chlorides, sulfates, and nitrates:



The average concentrations are 423.77 mg/L for bicarbonates, 75.21 mg/L for chlorides, 36.731 mg/L for sulfates, and 1.966 mg/L for nitrates. Overall, almost all of the major ions show limited variability among the different samples.

The relatively low nitrate content indicates the absence of significant inputs attributable to agricultural or domestic contamination and suggests a limited influence of anthropogenic nitrogen sources on the monitored aquifer (Appelo & Postma, 2005).

Manganese concentrations exceeded the contamination threshold concentration (CSC) in 8 of the 12 samples. The values range from 0.0 to 565.7 µg/L, with an average concentration of 174.46 µg/L. Iron concentrations range from 0.0 to 596.5 µg/L, with an average value of 127.67 µg/L.

Finally, a concentration of 0.3 µg/L of Trichloromethane was detected in sample Pz1, which exceeds the limit of 0.15 µg/L. This value was attributed to a possible sampling artifact.

The Piper and Schoeller diagrams (Piper, 1944; Schoeller, 1962) are widely used to interpret the geochemical evolution of groundwater and to classify its hydrogeochemical facies.

The Piper diagram consists of three distinct fields: two triangular diagrams, which represent the relative compositions of the major anions and cations, respectively, and a central diamond-shaped field. The overall composition of the water is represented in the diamond-shaped field by projecting the points identified in the two triangular diagrams.

The Piper diagram shown in Figure 6 represents the hydrochemical facies of the samples collected on May 5, 2025. The results show that the groundwater samples collected from the piezometers fall predominantly within the calcium-bicarbonate hydrochemical facies. This classification indicates the predominance of the bicarbonate ion among the anions and the calcium ion among the cations, delineating a relatively homogeneous hydrogeochemical facies.

Schoeller's semilogarithmic diagram, shown in Figure 7, is particularly effective for comparing waters with different chemical compositions. Analysis of the results from the same sampling campaign shows nearly identical trends for the samples collected from the piezometers. This similarity confirms what was already observed in the Piper diagram and indicates the predominance of a calcium-bicarbonate facies, with limited compositional variations among the different sampling points.

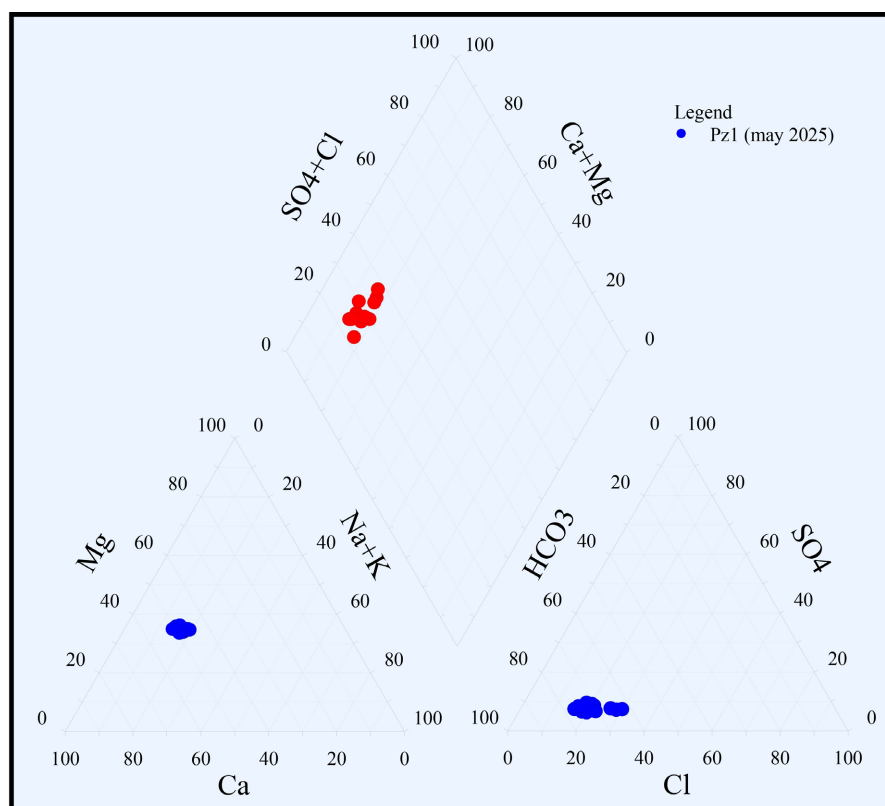


Figure 6. Piper diagram for groundwater samples collected in May 2025.

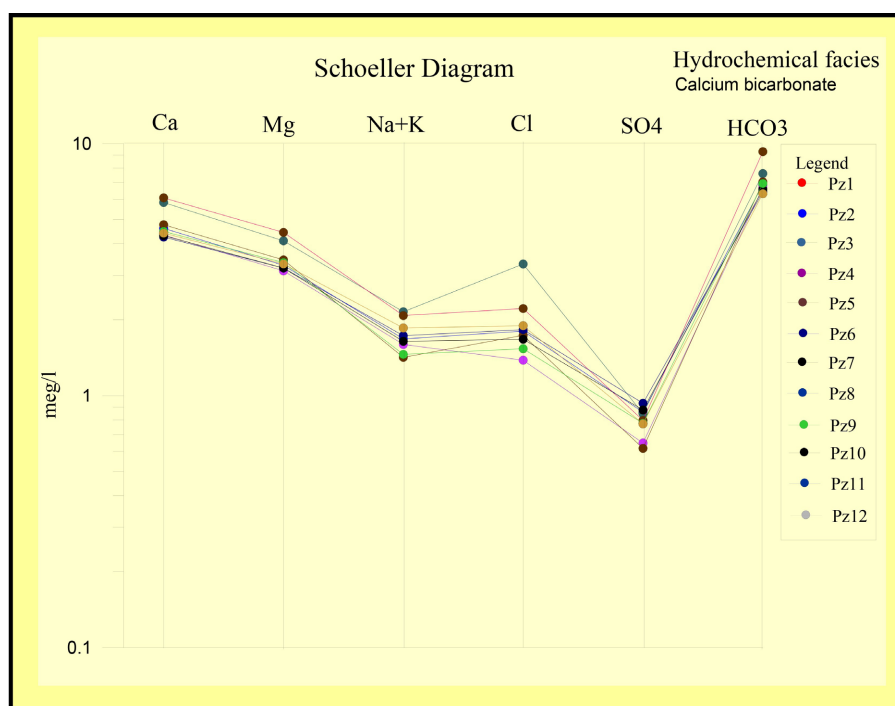


Figure 7. Schoeller diagram for groundwater samples collected in May 2025. In this type of graph, the concentration values of the main ionic constituents, expressed in meq/L, are plotted on the y-axis, and each individual water sample is represented by a dashed line that forms the sample's "hydrochemical profile".

3.2. Temporal Trends of Manganese and Iron Ions

A summary of the data obtained from analyses conducted during the monitoring campaigns carried out between 2021 and 2025 for iron and manganese ions is presented in **Tables 15-26**.

The results of the analyses conducted during the observation period show that iron concentrations exceeded the contamination threshold concentration (CSC) in piezometers Pz4, Pz5, Pz10, Pz11, and Pz12, while both iron and manganese were present in samples collected from piezometers Pz1, Pz2, Pz6, Pz7, Pz, and Pz9.

Overall, throughout the entire observation period (**Table 27**), the trend in ions exceeding the limit shows increasing concentrations only in piezometer Pz10 for manganese and in piezometer Pz11 for iron, while the trend in piezometer Pz3 remains flat.

The maximum concentration of iron (1724 µg/L) was recorded in piezometer Pz1, located upstream in the hydrogeological system, in 2024, while the maximum concentration of manganese (2523 µg/L) was recorded in piezometer Pz6, located in the middle section of the landfill, in 2023.

Based on the results of the chemical analyses performed, it is clear that the highest values were recorded in the years 2023-2024.

Table 15. Groundwater at piezometer Pz1 (L.max = Maximum Limit, U.M. = Unit of Measurement).

DATE	L.max.	U.M	06/01/20	11/07/22	02/18/23	08/10/23	12/06/23	02/16/24	05/07/24	08/30/24	09/19/24	12/18/24	03/28/25	05/05/25
Iron	200	µg/L	<0.12	258	1060	283	7.5	8.2	6.1	1724	143	35	28	0.0
Manganese	50	µg/L	0.5	12	965	<0.04	11.0	13.4	8.5	0.50	10.0	0.9	0.30	0.0

Table 16. Groundwater at piezometer Pz2.

DATE	L.max.	U.M	06/01/20	11/07/22	02/27/23	08/10/23	12/06/23	02/16/24	05/07/24	08/30/24	09/19/24	12/27/24	05/05/25
Iron	200	µg/L	<0.12	287	869	797	471	602	577	817	759	788	563.4
Manganese	50	µg/L	1055	422	966	293	988	97	1083	41	319	344	338.4

Table 17. Groundwater at piezometer Pz3.

DATE	L.max.	U.M	06/01/20	11/07/22	02/27/23	08/10/23	12/06/23	02/16/24	05/07/24	08/30/24	09/19/24	12/18/24	05/05/25
Iron	200	µg/L	7.7	974	208	708	4.36	505	407	500	545	375	596.5
Manganese	50	µg/L	329	645	<0.04	894	988	984	1013	28	814	785	565.7

Table 18. Groundwater at piezometer Pz4.

DATE	L.max.	U.M	07/28/21	11/11/21	02/15/22	05/17/22	08/10/22	12/30/22	02/16/23	05/07/23	08/30/23	09/19/23	12/27/23	03/19/24	05/05/24
			1	1	2	2	3	3	4	4	4	4	4	5	5
Iron	200	µg/L	10.8	8.8	<0.12	<0.12	174	22.3	22.0	19.5	22	24	32	14	0.0
Manganese	50	µg/L	20.6	18.0	0.40	0.88	45.0	54.8	37.0	45.3	48	43	48	146	0.0

Table 19. Groundwater at piezometer Pz5.

DATE	L.max.	U.M	07/28 /21	11/11/2 1	02/15/2 2	05/17/2 2	08/10/2 3	12/30/2 3	02/16/2 4	05/07/2 4	08/30/2 4	09/19/2 4	12/27/2 4	03/19/2 5	05/05/2 5
Iron	200	µg/L	0.30	0.22	<0.12	<0.12	118	176	122	163	129	172	154	22	0.0
Manganese	50	µg/L	16.6	18.4	886	721	103	948	884	977	844	826	796	230	21.2

Table 20. Groundwater at piezometer Pz6.

DATE	L.max.	U.M	07/28 /21	11/11/2 1	02/15/2 2	05/17/2 2	08/10/2 3	12/30/2 3	02/16/2 4	05/07/2 4	08/30/2 4	09/19/2 4	12/27/2 4	03/19/2 5	05/05/2 5
Iron	200	µg/L	3.2	2.6	---	---	353	188	188	178	144	151	143	13	0.0
Manganese	50	µg/L	13.6	15	915	843	2523	974	1122	1031	978	739	696	235	78.6

Table 21. Groundwater at piezometer Pz7.

DATE	L.max.	U.M	02/15/24	05/07/24	08/30/24	09/19/24	12/18/24	03/19/25	05/05/25
Iron	200	µg/L	96	94	427	12	41	78	0.0
Manganese	50	µg/L	6.3	5.3	63	25	55	33	22.8

Table 22. Groundwater at piezometer Pz8.

DATE	L.max.	U.M	02/15/24	05/07/24	08/30/24	09/19/24	12/18/24	03/19/25	05/05/25
Iron	200	µg/L	502	405	1199	66	53	67	46.8
Manganese	50	µg/L	1815	2519	608	261	107	123	152.6

Table 23. Groundwater at piezometer Pz9.

DATE	L.max.	U.M	02/15/24	05/07/24	08/30/24	09/19/24	12/18/24	03/19/25	05/05/25
Iron	200	µg/L	505	446	854	180	58	168	136.7
Manganese	50	µg/L	2112	2486	666	271	307	299	263.3

Table 24. Groundwater at piezometer Pz10.

DATE	L.max.	U.M	12/27/24	03/19/25	05/05/25
Iron	200	µg/L	32	20	0.0
Manganese	50	µg/L	67	61	303.6

Table 25. Groundwater at piezometer Pz11.

DATE	L.max.	U.M	12/27/24	03/19/25	05/05/25
Iron	200	µg/L	98	103	114.7
Manganese	50	µg/L	194	182	187

Table 26. Groundwater at piezometer Pz12.

DATE	L.max.	U.M	12/27/24	03/19/25	05/05/25
Iron	200	µg/L	82	74	73.8
Manganese	50	µg/L	191	182	160.3

Table 27. Hypothetical short-term trend.

Piezometer No.	Trend Iron	Trend Manganese
Pz1	Descending	Descending
Pz2	Descending	Descending
Pz3	Horizontal	Descending
Pz4	Descending	Descending
Pz5	Descending	Descending
Pz6	Descending	Descending
Pz7	Descending	Descending
Pz8	Descending	Descending
Pz9	Descending	Descending
Pz10	Descending	Ascending
Pz11	Ascending	Descending
Pz12	Descending	Descending

3.3. Iron, Manganese, and Redox Conditions

The most critical parameters are iron and manganese (**Table 28**). Iron exceeded the Contamination Threshold Concentration (CSC) in 2 out of 12 samples, with a maximum value of 596.5 µg/L and an average concentration of 127.67 µg/L. Manganese, on the other hand, exceeded the CSC in 8 out of 12 samples, reaching a maximum value of 565.7 µg/L and an average concentration of 174.46 µg/L. The highest concentrations of iron were detected in piezometers Pz2 and Pz3, where low levels of dissolved oxygen limit the oxidation and precipitation of the metal, causing it to remain in solution.

Table 28. Summary of key parameters and CSC exceedances.

Parameter	CSC	Minimum	Maximum/Average	Exceedances
Iron	200 µg/L	0 µg/L	596.5/127.67 µg/L	2/12 samples
Manganese	50 µg/L	0 µg/L	565.7/174.46 µg/L	8/12 samples
Arsenic	10 µg/L	0 µg/L	3.2/0.65 µg/L	0/12 samples
Dissolved oxygen	-	1.45 mg/L	5.72/3.24 mg/L	-

To interpret the variations in iron and manganese concentrations measured in the piezometers, it was necessary to consider the geochemical behavior of these elements in groundwater. To this end, the Eh-pH diagrams shown in **Figure 8** and **Figure 9** were used, which allow for the identification of the thermodynamically most stable chemical species as a function of pH and electrochemical potential.

The diagram for Iron shows the stability ranges of the main species of this element (Hem, 1985; Gao et al., 2019). The upper and lower limits of the diagram represent, respectively, strongly oxidizing conditions associated with water oxidation and oxygen evolution and strongly reducing conditions, in which hydrogen

evolution is favored. The Iron species are distributed within this range.

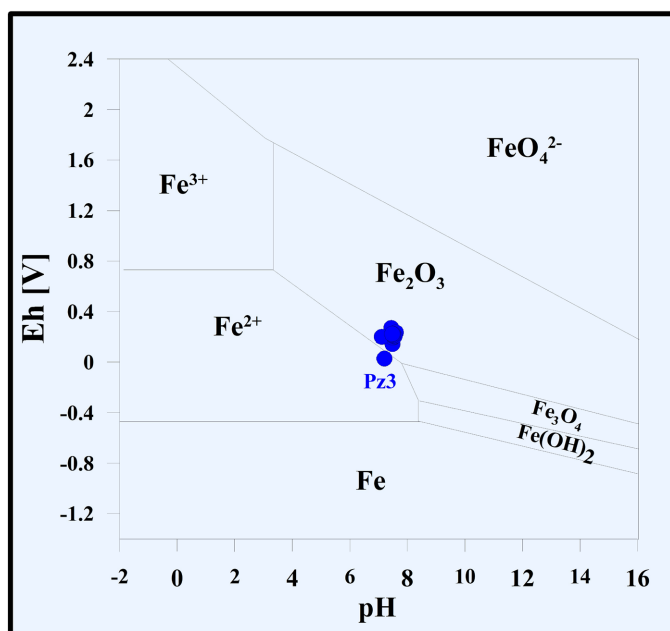


Figure 8. Redox potential and pH diagram (simplified pourbaix diagram).

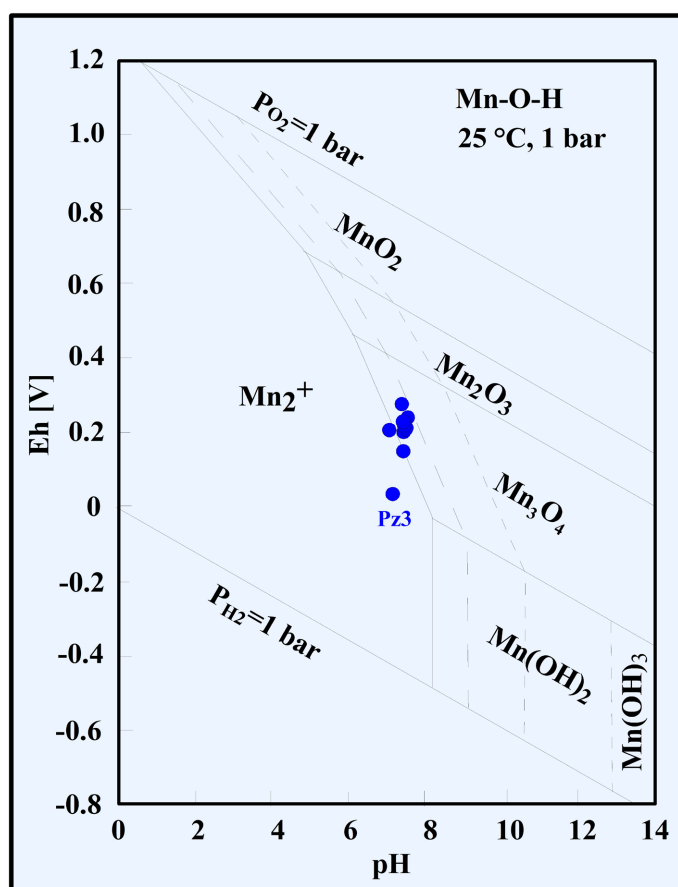


Figure 9. Diagram of Mn as a function of Eh and pH values.

The upper portion of the central region of the diagram is dominated by ferric species, characterized by the Iron (III) oxidation state, while the lower portion is dominated by ferrous species, characterized by the iron (II) oxidation state. In practical terms, ferric species are typical of well-aerated systems, while ferrous species prevail under anaerobic and reducing conditions.

Ferrous iron, Fe^{2+} , is soluble over a wide pH range, from strongly acidic to weakly alkaline conditions. Ferric iron, Fe^{3+} , on the other hand, is soluble only under strongly acidic conditions generally at a pH below 3 and in oxidizing conditions, with an Eh greater than approximately 0.77 V. Outside this stability range, iron tends to precipitate. In the absence of other complexing anions, at room temperature it can form ferric oxide, Fe_2O_3 , or, under alkaline and reducing conditions, ferrous hydroxide, $\text{Fe}(\text{OH})_2$.

The narrow stability range of ferric iron in solution, located in the upper left portion of the diagram, indicates that dissolved iron can be removed relatively easily by oxidizing it to iron (III), followed by adjusting the pH to values above approximately 3. Under these conditions, iron rapidly precipitates as ferric hydroxide. However, the actual course of the process can be influenced by kinetic factors, including temperature, reaction time, and the rate of pH change.

Iron concentrations varied among the sampled piezometers. The values are close to the boundary between Fe^{2+} and ferric oxides, highlighting the system's sensitivity to even moderate changes in redox conditions. The highest concentrations were detected in piezometers Pz2 and Pz3, where low concentrations of dissolved oxygen limit the oxidation of ferrous iron and promote its retention in solution.

Variations in manganese concentrations were detected among the various piezometers in the landfill's monitoring network, with values exceeding the Contamination Threshold Concentration (CSC). The Eh-pH diagram (Evgeny, 2023; Noda et al, 2019) indicates that the water in some piezometers falls near the boundary between the dissolved species Mn^{2+} and hausmannite (Mn_3O_4), an insoluble manganese oxide.

In particular, in piezometer Pz3, oxygen concentrations of 1.45 mg/L and Eh values close to 0 V were measured. These conditions are not sufficiently oxidizing to promote a significant decrease in Mn^{2+} concentrations, which therefore remain predominantly in solution.

The high levels of manganese and iron detected in the piezometers of the monitoring network may be related to the circulation of groundwater through sandy and conglomeratic layers, as well as to the presence of clay layers in the subsoil. Clays can, in fact, contribute to the release of manganese and iron, in addition to promoting reducing conditions and limiting oxygen circulation.

An additional source of manganese may come from the waterways in the area surrounding the landfill, including the Raganello Stream. Concentrations of iron and manganese close to the CSC have been detected in these water bodies, likely attributable to surface water flowing over clayey soils and the resulting leaching of elements present in the geological matrix.

Given the number of samples analyzed, the frequency of occurrence of the var-

ious measured values was evaluated in order to obtain information on the structure and possible subdivision of the aquifer.

Under ideal conditions, an approximately Gaussian distribution of the data may indicate that the analyzed samples originate from the same aquifer or from an area characterized by relatively homogeneous hydrochemical conditions. The presence of two or more distinct clusters, on the other hand, may suggest the existence of different aquifers or of sectors characterized by different hydrogeological or geochemical conditions. If no distinct clusters are recognizable, this may be attributed to the presence of numerous aquifers or different zones, or to marked variability in the system's characteristics.

In addition to traditional line graphs, used to represent trends in concentrations, and bar charts, used to describe frequencies, the data were represented using Raincloud plots (Allen et al., 2021; Mumiyo Team, 2026). These charts allow for the simultaneous visualization of data distribution, density, variability, and key statistical indicators, providing a transparent and minimally distorted representation of summary statistics and raw data.

For the study area, diagrams were prepared for iron and manganese, as shown in Figure 10 and Figure 11. In both cases, the distributions exhibit positive skewness (a right-skewed distribution), characterized by a higher concentration of values on the left side of the distribution and a long tail extending toward higher values. Furthermore, a bimodal distribution is observed, marked by the presence of two distinct peaks.

This pattern may reflect the presence, in the subsoil beneath the landfill area, of multiple aquifers or different hydrogeological zones, characterized by varying geochemical conditions and, consequently, by different concentrations of iron and manganese.

The ion exchange diagrams (Figure 12) also confirm the predominant role of

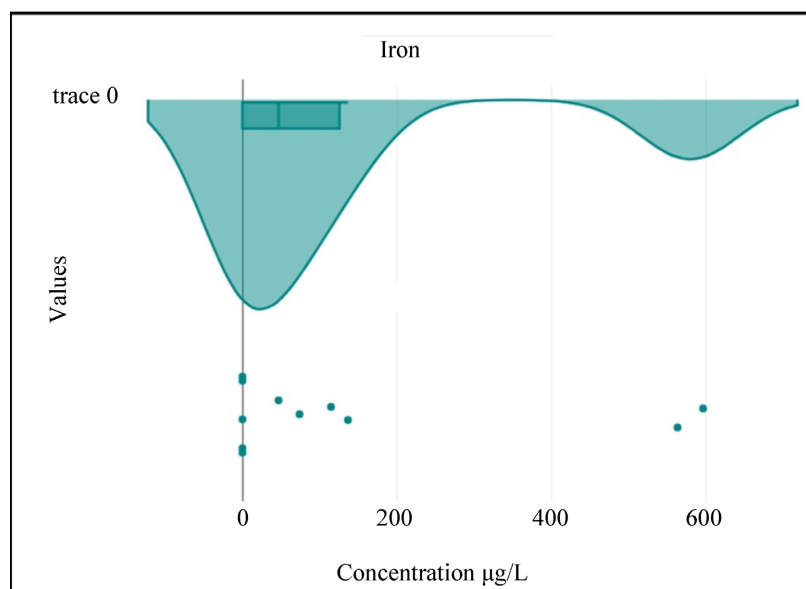


Figure 10. Raincloud plot for iron.

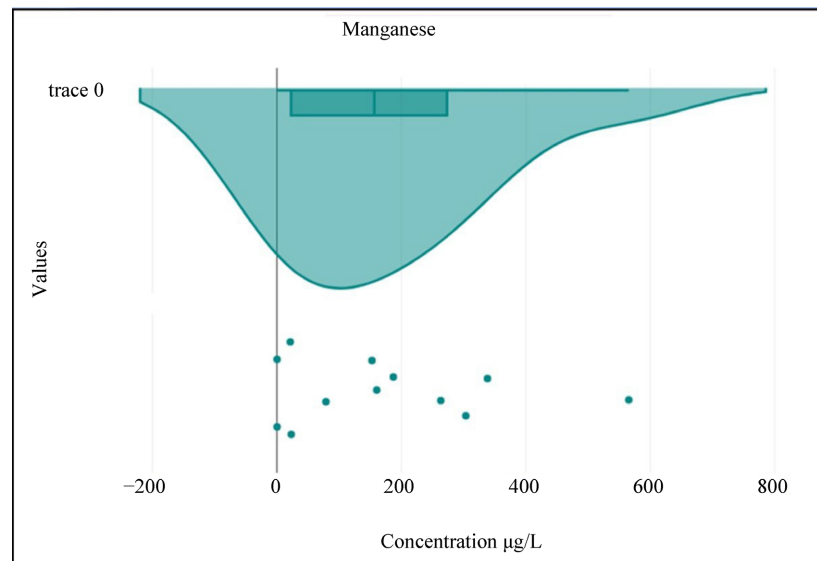


Figure 11. Raincloud plot for manganese.

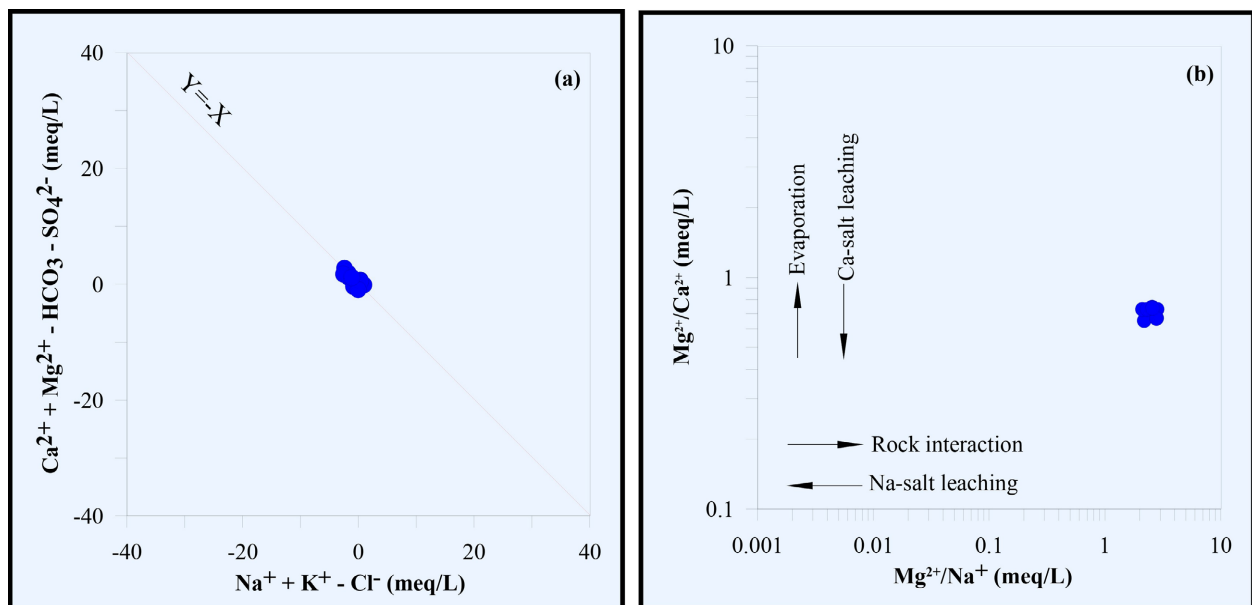


Figure 12. Graphs showing (a) $\text{Ca}^{2+} + \text{Mg}^{2+} - \text{HCO}_3^- - \text{SO}_4^{2-}$ versus $(\text{Na}^+ + \text{K}^+ - \text{Cl}^-)$ and (b) $\text{Mg}^{2+}/\text{Ca}^{2+}$ versus $\text{Mg}^{2+}/\text{Na}^+$.

water-rock interaction processes in controlling the chemical composition of groundwater and in the formation of the main hydrochemical facies (SNPA, 2018; Hem, 1985; Gao et al., 2019).

3.4. Chemical and Physical Characteristics of Groundwater

3.4.1. Piezometer Flushing for Sampling

Before sampling the groundwater, the piezometers were flushed. The purging operations removed the stagnant groundwater contained within the piezometers, which cannot be considered representative of the aquifer and therefore unsuitable for sampling.

Taking into account the static water level in the piezometers, the aquifer's flow rate, and the recharge of the piezometers, the minimum volume of water purged was equal to three well volumes (**Table 29**).

Table 29. Sampling conditions, May 2025.

Piezometers n°	Method	Pre-treatment	Storage	Methods of Analysis
1 - 12	Low-Flow Pump	Field filtration using a 0.45 µm filter	Glass containers	National and/or International

3.4.2. Groundwater Sampling

Once the flushing operations were completed, groundwater samples were collected for chemical laboratory analysis.

Sampling began at the piezometers located upstream of the site in the hydrogeological system and was subsequently extended, in a stepwise manner, to the piezometers located downstream, in order to reduce the risk of cross-contamination between the various monitoring points.

To ensure the samples were representative of the aquifer conditions, water was collected using a low-flow submersible pump, employing operating procedures designed to minimize water agitation and the volatilization or alteration of analytical parameters as much as possible. The samples collected in this manner were subsequently subjected to the chemical analyses specified in the monitoring plan (**Table 30**).

Table 30. Chemical and physical data measured in the field.

Piez. N°	T (°C)	pH (20°C)	Dissolved oxygen mg O ₂ /L	Conductivity µs/cm (20°C)
Pz1	19.24	7.44	4.08	853
Pz2	19.93	7.60	3.43	868
Pz3	21.2	7.20	1.45	1093
Pz4	20.70	7.48	5.72	815
Pz5	23.80	7.49	3.61	869
Pz6	20.82	7.11	2.53	1138
Pz7	19.70	7.54	2.57	840
Pz8	20.90	7.56	1.91	825
Pz9	19.83	7.51	2.32	842
Pz10	18.60	7.51	4.67	985
Pz11	20.10	7.49	3.50	998
Pz12	20.50	7.47	3.09	842

3.5. Spatial Distribution and Interpretation of the Plume

Based on the values of the analyzed chemical parameters (**Table 31**), the spatial distribution of certain ions was reconstructed by generating specific geochemical

maps. The data were represented as isolines to facilitate the interpretation of the spatial variability of individual concentrations.

Table 31. Parameters of interest, May 2025.

Piezometer No.	Iron $\mu\text{g/L}$ Maximum limit 200 $\mu\text{g/L}$	Manganese $\mu\text{g/L}$ Maximum limit 50 $\mu\text{g/L}$
Pz1	0.0	0.0
Pz2	563.4	338.4
Pz3	596.5	565.7
Pz4	0.0	0.0
Pz5	0.0	21.2
Pz6	0.0	78.6
Pz7	0.0	22.8
Pz8	46.8	152.6
Pz9	136.7	263.3
Pz10	0.0	303.6
Pz11	114.7	187.0
Pz12	73.9	160.3

The analysis was performed using the Kriging interpolation method with Surfer software, developed by Golden Software Inc. This procedure made it possible to estimate the distribution of the parameters even in areas not directly covered by the sampling points, ensuring a continuous representation of their spatial variability.

For the spatial distributions shown in **Figures 13-15**, a color scale was adopted to highlight the areas characterized by the highest concentrations. Specifically, areas where values exceed the respective threshold values are delineated by red contour lines, allowing them to be immediately identified on the maps.

The maps indicate that the so-called iron and manganese plume is not consistent with the groundwater flow field, whose predominant flow is oriented from the northwest to the southeast.

In fact, the isoconcentration lines exhibit concentric or semi-concentric geometries centered on specific piezometers, with maximum values distributed in both the upstream and downstream sectors. This pattern is not consistent with the presence of a point source of contamination associated with the landfill and subsequently transported along the direction of groundwater flow. Instead, the pattern is more consistent with local contributions controlled by the lithological characteristics of the aquifer, attributable to the presence of clayey-silty layers and groundwater flow paths characterized by longer residence times, in which geochemical conditions favorable to the mobilization of iron and manganese can develop (Freeze & Cherry, 1979; Appelo & Postma, 2005).

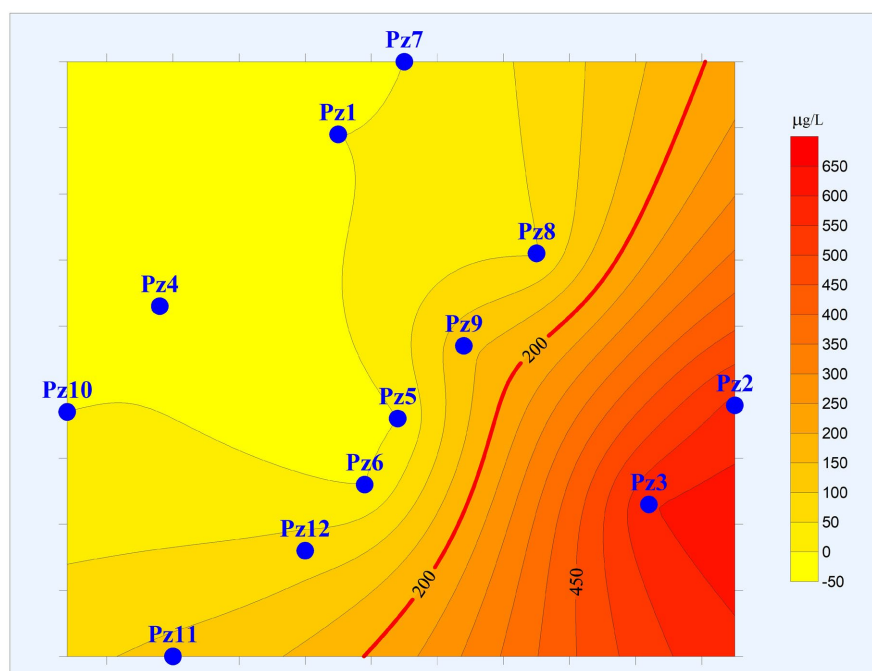


Figure 13. Spatial distribution of iron concentrations. The thick red line indicates the CSC.

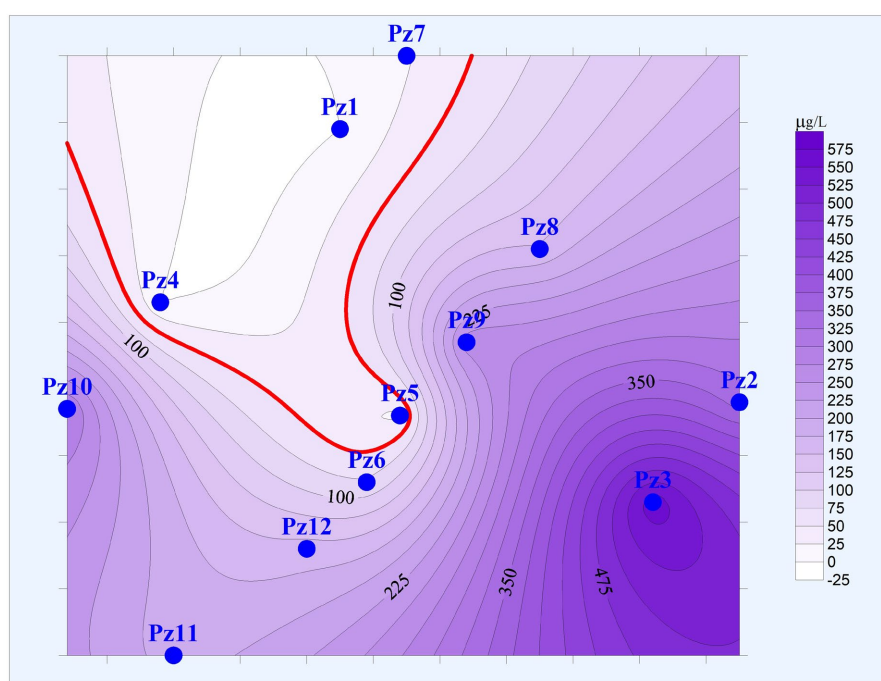


Figure 14. Spatial distribution of manganese concentrations. The thick red line indicates the CSC.

With regard to Trichloromethane, the contamination threshold concentration (CSC) was exceeded only in piezometer Pz1 during the sampling on May 5, 2025, while in piezometer Pz5 the substance was found only in trace amounts, at concentrations below the CSC. Given that Pz1 is located hydrogeologically upstream

of the site and represents an upgradient hydrogeological background point, and considering that the subsequent sampling on June 6, 2025, showed a concentration below the limit of quantification ($<0.02 \mu\text{g/L}$), the anomaly is attributed to accidental contamination or a procedural artifact that occurred during the sampling operations. In particular, contamination resulting from the use of a PVC pipe previously employed for biogas sampling or other field activities is considered plausible. The May 2025 result is therefore considered unrepresentative of groundwater quality and not significant for characterizing the chemical status of the aquifer (APAT-IRSA-CNR, 2003).

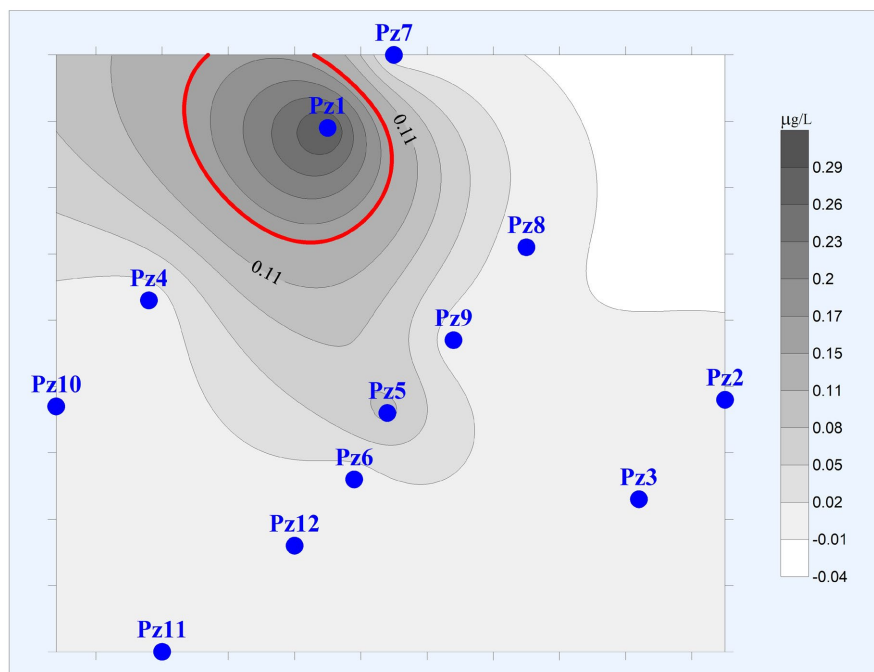


Figure 15. Spatial distribution of Trichloromethane concentrations (anomalous sampling result from 05/05/2025). The thick red line indicates the CSC.

3.6. Surface Water and the Upstream Agricultural Well

Surface water characterization was conducted by collecting a sample from the Raganello Stream (Figure 16) to assess the possible contribution of surface water to the chemical composition of the aquifer. The analyses revealed an iron concentration of $198.7 \mu\text{g/L}$, close to the Contamination Threshold Concentration (CSC) of $200 \mu\text{g/L}$, a manganese concentration of $27.3 \mu\text{g/L}$, which is below the corresponding CSC of $50 \mu\text{g/L}$, and an aluminum concentration of $504.0 \mu\text{g/L}$, which exceeds the CSC of $200 \mu\text{g/L}$. These results indicate that the surface drainage network can transport significant quantities of metals, likely related to soil leaching processes and the lithological characteristics of the watershed, particularly the presence of clay-rich formations (Appelo & Postma, 2005; Hem, 1985).

Upstream of the landfill, an agricultural well was also identified (P2), approximately 180 m deep, with a static groundwater level of about 90 m below ground level and an estimated flow rate of approximately 8 L/s (Table 32 and Table 33).

Samples collected on May 5 and June 6 showed concentrations of iron and manganese exceeding their respective CSC. However, the second round of sampling, conducted after more prolonged purging of the well, showed a significant reduction in the measured concentrations: iron decreased from 7892 to 365 µg/L, while manganese decreased from 486.8 to 88.2 µg/L. This pattern suggests that the initially observed values may have been influenced by stagnation and reducing conditions within the well. The presence of iron and manganese in concentrations exceeding the CSC at a point located hydrogeologically upstream of the landfill nevertheless represents significant evidence supporting a natural origin for the observed anomalies or the existence of external contributions independent of the landfill. However, diffuse anthropogenic inputs—such as those associated with agricultural practices and the use of fertilizers or soil conditioners containing manganese—may also contribute (Appelo & Postma, 2005; Hem, 1985).

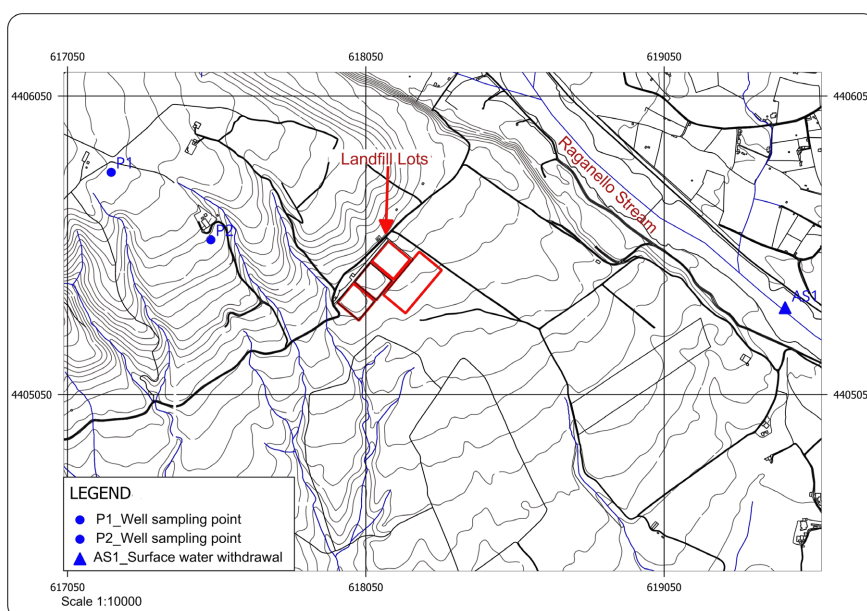


Figure 16. Location of external control points.

Table 32. Data for Well No. 2 (data source: ISPRA <https://sgi2.isprambiente.it/viewersgi2/>).

Piezometer No.	Ground Level (m)	Water Table Level	Maximum Flow Rate (l/s)	Well Diameter (mm)	Presence of Aquifer (m)	Filter Location
P2	179	90	78.393	320	130 - 160	110 - 170

Table 33. Stratigraphic profiles.

Layer No.	Depth (m)	Classification
1	5.0	Reddish clays
2	120.0	Conglomerates with fine sand and layers of fine to coarse sand
3	180.0	
		Loose sand

Abnormal levels of iron and manganese have been detected in the soils of various areas of Calabria, corresponding to specific outcrop lithological units, including metamorphic rocks and alluvial or basin-derived deposits belonging to the Apennine mountain range.

Figure 17 and **Figure 18** show the official maps of the distribution of iron and

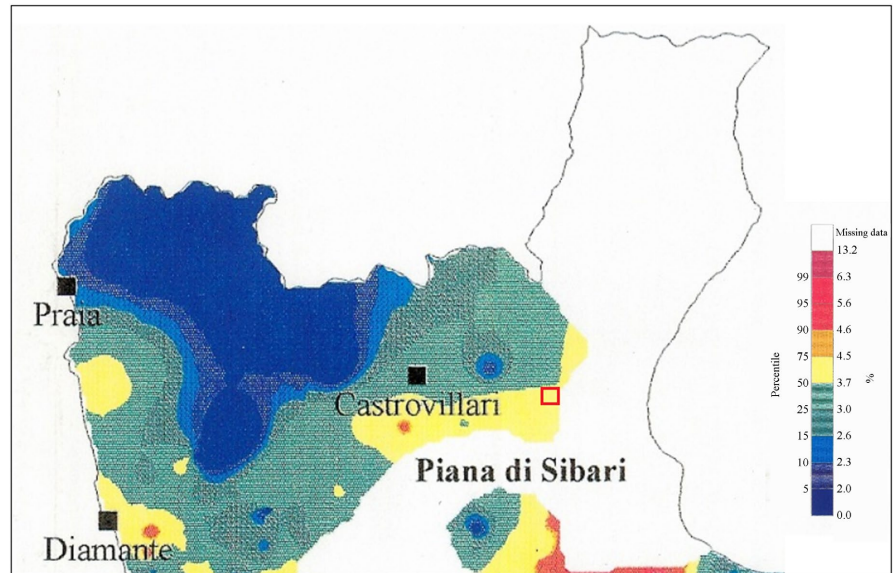


Figure 17. Geochemical map of iron (data source: ISPRA

<https://www.isprambiente.gov.it/it/pubblicazioni/periodici-tecnici/memorie-descrittive-della-carta-geologica-ditalia/cartografia-geochimica-ambientale-2013-primi-esempi-di-applicazione-calabria-monti-peloritani-sardegna-e-toscana-meridionale>).

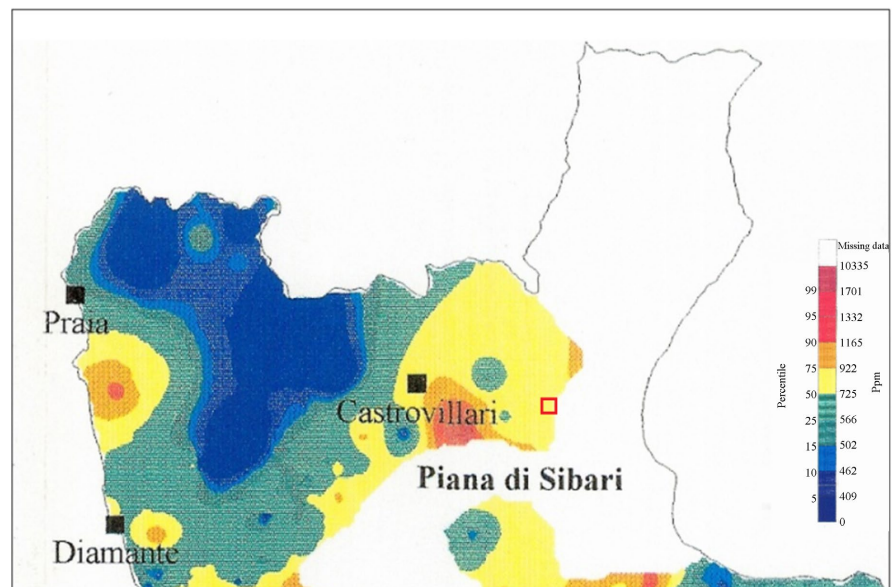


Figure 18. Geochemical map of manganese (data source: ISPRA

<https://www.isprambiente.gov.it/it/pubblicazioni/periodici-tecnici/memorie-descrittive-della-carta-geologica-ditalia/cartografia-geochimica-ambientale-2013-primi-esempi-di-applicazione-calabria-monti-peloritani-sardegna-e-toscana-meridionale>).

manganese in the northern part of Calabria, compiled as part of the Geochemical Maps published in 1998 by the National Geological Service, now ISPRA. The cartographic analysis shows that the landfill area, outlined in red in the figures, lies near the edge of zones characterized by average concentrations of both elements.

This location highlights the possible influence of the local geological and lithological context on the natural distribution of iron and manganese in the area's soils.

3.7. Geophysical Surveys and Geometry of the Landfill Cells

The geophysical survey involved conducting four electrical resistivity tomography (ERT) surveys (**Figure 19**), one for each landfill lot, using a dipole-dipole configuration with 81 electrodes and an inter-electrode spacing of 3 m. Data acquisition was performed using a Terrameter LS2 system, while data processing and inversion were carried out using Res2DInv software. The RMS error values obtained, all below 5%, attest to the good overall reliability of the reconstructed geoelectric models. The ERT results (**Figures 20-23**) were also integrated with available previous surveys, conducted in 2023, including seismic refraction tomography and earlier electrical resistivity tomography surveys (Loke, 2004; Reynolds, 2011).

The landfill is divided into four lots (**Figure 24, Figure 25**), each equipped with a multilayer basal liner system consisting, from bottom to top, of a layer of compacted clay at least 1.0 m thick, a bentonite geocomposite, an HDPE geomembrane, and a drainage layer for collecting leachate approximately 0.50 m thick. The total thickness of the lining and drainage system is therefore assumed to be approximately 1.50 m. The final cover of each lot has an average thickness of approximately 1.0 m.

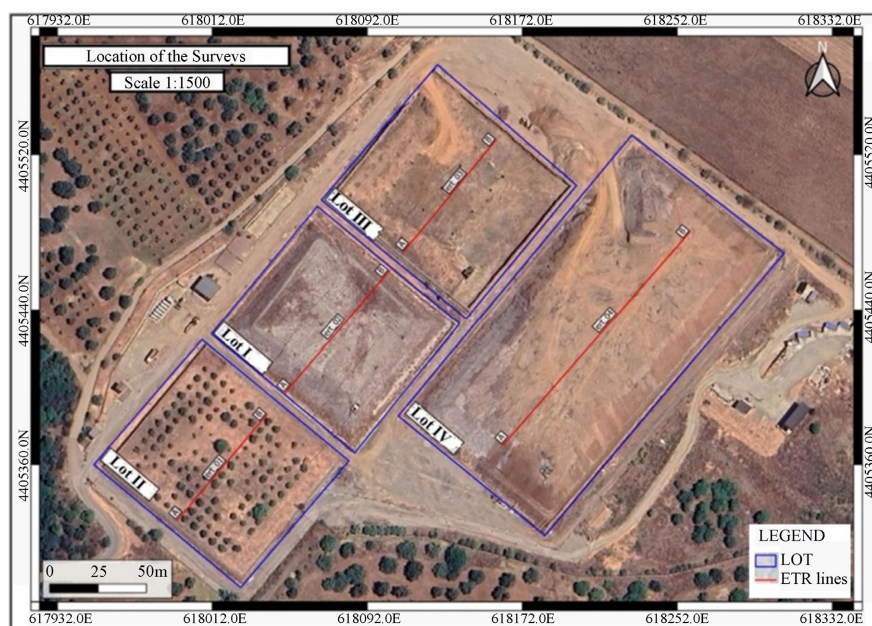


Figure 19. Location of the electrical tomography measurements. Google Maps, 2025, <https://maps.google.com/>.

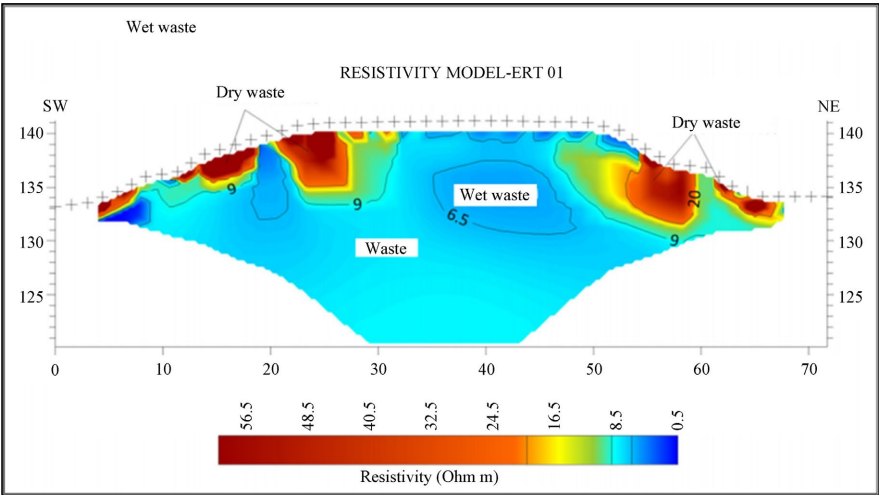


Figure 20. ERT 04 resistivity model (Lot I).

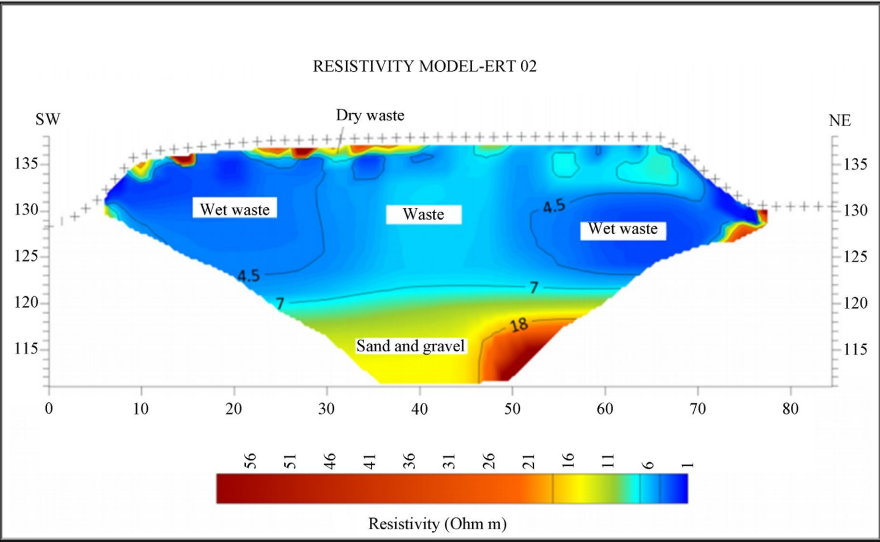


Figure 21. ERT 04 resistivity model (Lot II).

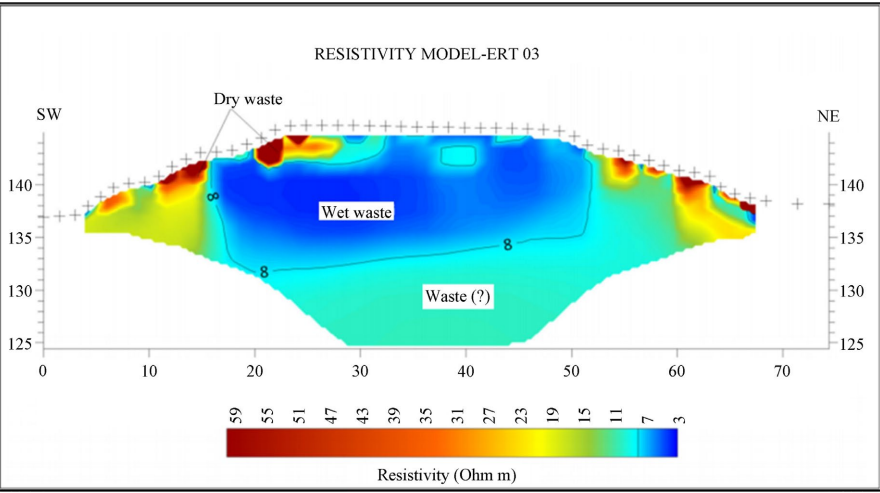


Figure 22. ERT 04 resistivity model (Lot III).

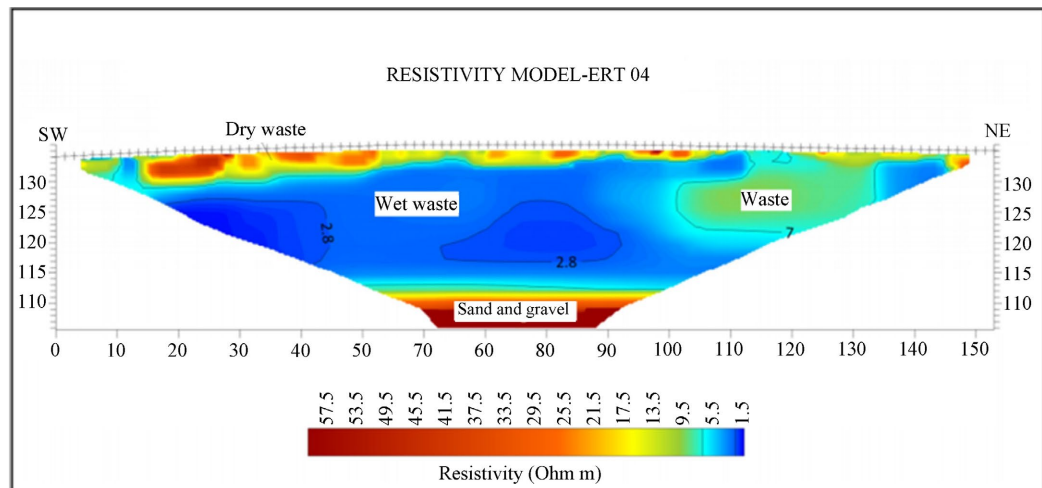


Figure 23. ERT 04 resistivity model (Lot IV).

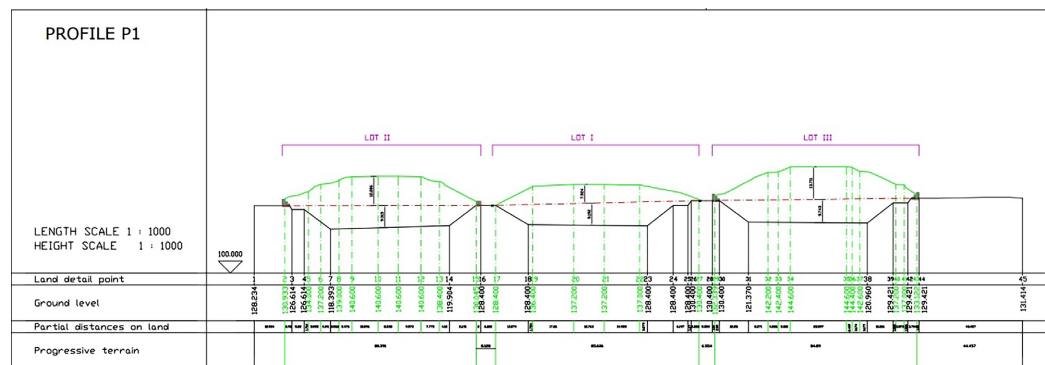


Figure 24. Topographic cross-section of Lots I, II, and III.

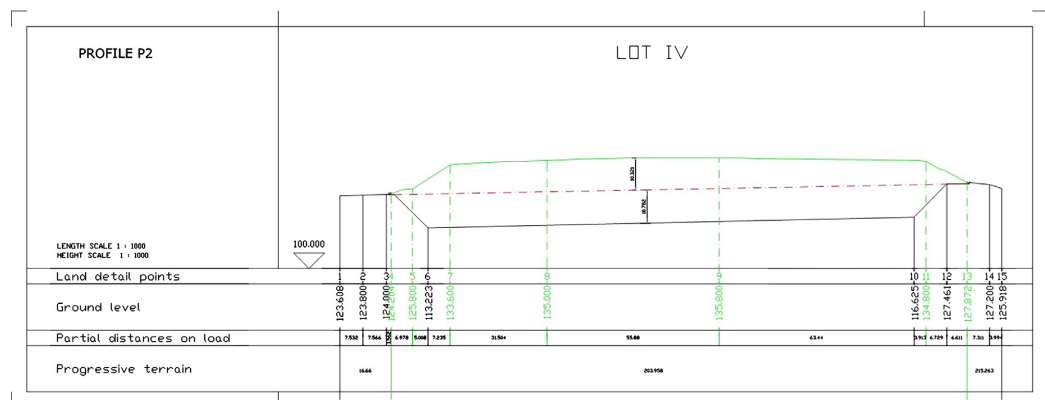


Figure 25. Topographic cross-section of Lot IV.

The geological substrate of the area consists of sands and conglomerates with clayey-silty interlayers. The aquifer is located at elevations significantly lower than the base of the landfill lots, at depths ranging from 46.891 m to 59.114 m below ground level.

The investigations revealed maximum thicknesses of the waste body (Table 34) of approximately 14.6 m in Lot I and approximately 21.0 m in Lot III. In Lots II

and IV, the presence of interfaces characterized by low resistivity allowed for a more reliable reconstruction of the base of the landfill, identified at depths of approximately 18 - 19 m and 20.82 m (average value) from the top surface, respectively. In Lots I and III, however, the interpretation is more cautious: in Lot I, the depth of investigation reached does not allow the bottom interface to be identified with sufficient certainty, while in Lot III, the low-resistivity body detected at a depth of approximately 14 m could correspond either to the bottom of the waste body or to an internal discontinuity associated with layers having different moisture content (Loke, 2004; Reynolds, 2011).

Table 34. Summary of landfill lot characteristics.

Lot	Maximum thickness at center of lot	Cover plus barrier	Maximum waste thickness	Average depth to groundwater
I	17.12 m	2.50 m	14.62 m	51.00 m
II	21.60 m	2.50 m	19.10 m	49.00 m
III	23.45 m	2.50 m	20.95 m	52.50 m
V	21.10 m	2.50 m	18.60 m	49.50 m

3.8. Seismogenic Sources and Active Faults

To identify active faults and seismogenic sources, the “Database of Individual Seismogenic Sources (DISS)”, version 3.2.1, was consulted, supplemented with bibliographic data available from recognized agencies and institutions and with the results of direct field surveys.

The resulting map (Figure 26) shows, to the north of the area affected by the landfill, the presence of a normal-fault system, identified as the “Lauropoli Fault”, with a length of approximately 10.2 km. This structure must be adequately taken into account in the hydrogeological and geochemical studies of the area, as its activity and relative structural configuration could favor the establishment of preferential pathways for water flow and, potentially, mixing phenomena between deep and surface waters.

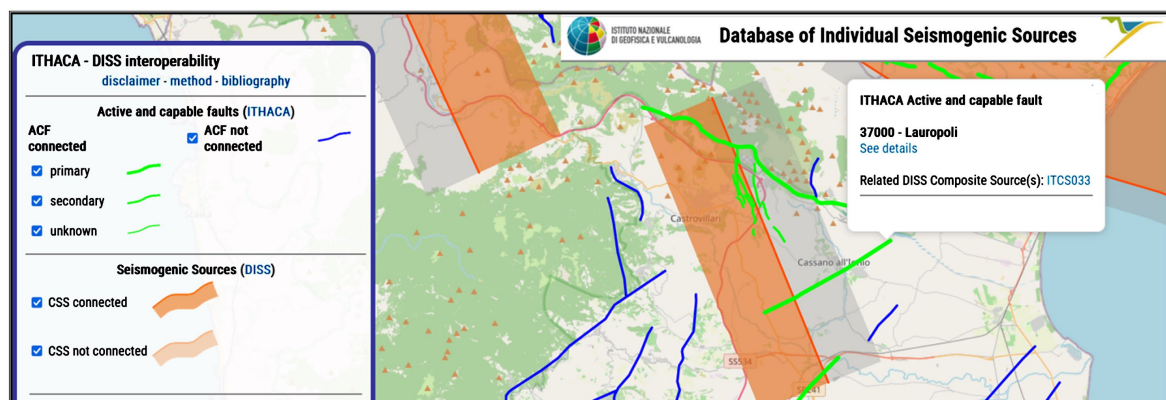


Figure 26. Laupoli fault (green line). The study area is indicated within the red box. Source: Catalog of Italian Seismogenic Sources DISS 3.2.1. <https://diss.ingv.it/ithdiss/#>.

In support of this assessment, the chemical analyses conducted revealed concentrations of iron and manganese exceeding their respective “Contamination Threshold Concentrations (CSC)”. Considering the exceedances detected in both the piezometer and surface waters, the depth of the piezometers and the monitored well, and the structural configuration of the area, it is not possible to rule out the occurrence of mixing between deep and surface waters, with potential negative effects on groundwater quality.

This hypothesis will need to be verified through further hydrogeological and geochemical investigations, including long-term piezometric and chemical monitoring, analysis of environmental isotopes, and characterization of the main tracers of deep and surface origin.

4. Conclusions

The hydrogeological conceptual model developed describes a site characterized by a succession of alternating sandy-conglomeratic and clayey-silty layers, with a first aquifer located at a considerable depth, fed both by precipitation and by interaction with surface watercourses. Groundwater flow is predominantly directed toward the southeast, while the presence of a multilayer aquifer system results in locally complex hydrodynamic conditions. From a geochemical perspective, the exceedances observed for iron and manganese represent the aspects of greatest environmental concern. However, the spatial distribution of concentrations, the presence of these same elements even in upstream areas and in an agricultural well outside the study area, the lack of correspondence between the presumed plume and the direction of groundwater flow, as well as the hydrochemical characteristics of the water attributable to a calcium-bicarbonate facies under low-oxygen conditions suggest a predominantly natural origin for the observed phenomena, closely related to water-rock interaction processes and the lithological characteristics of the aquifer. A diffuse anthropogenic contribution to the manganese content potentially linked to agricultural practices and the use of fertilizers in areas upstream of the site remains technically plausible; however, the investigations conducted do not reveal evidence sufficient to identify a primary source directly attributable to the landfill.

From an operational standpoint, the report identifies as priorities the permanent installation of low-flow pumping systems in all piezometers, riser pipes, electrical panels, sampling valves, devices for monitoring static and dynamic water levels, and adequate protective structures. These measures are essential for improving sampling representativeness, reducing hydrodynamic interpretive uncertainty, and ensuring the repeatability and reliability of monitoring over time.

Overall, the study provides a coherent and scientifically robust interpretive framework for the groundwater flow and water quality at the site. The most critical issue does not appear to be the existence of a contamination plume clearly attributable to the landfill, but rather the need to distinguish more reliably, through continuous and methodologically controlled monitoring, among natural

background values, local anomalies linked to the lithological characteristics of the aquifer, and possible diffuse anthropogenic inputs. In this regard, continued monitoring, with particular attention to the area between piezometers Pz2 and Pz3 and systematic comparison with surface waters and wells located upgradient of the site, appears essential to consolidate the conceptual model of the site and provide adequate support for future technical and administrative assessments.

Author Contributions

Riga, G., writing original draft preparation and writing review.

Mattieis, V., supervision and critical revision of the manuscript.

Petrone, F., data organization and correction of the manuscript.

All authors have read and agreed to the published version of the manuscript.

Acknowledgements

The authors would like to express their sincere thanks to geologist Alessandro Cittadino for his dedicated collaboration and for conducting the topographic survey of the lot profiles and piezometers.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- Allen, M., Poggiali, D., Whitaker, K., Marshall, T. R., van Langen, J., & Kievit, R. A. (2021). Raincloud Plots: A Multi-Platform Tool for Robust Data Visualization. *Wellcome Open Research*, 4, 63. <https://doi.org/10.12688/wellcomeopenres.15191.2>
- APAT-IRSA-CNR (2003). *Metodi analitici per le acque. Manuali e Linee guida 29/2003*. <https://www.isprambiente.gov.it/it/pubblicazioni/manuali-e-linee-guida/metodi-analitici-per-le-acque>
- Appelo, C. A. J., & Postma, D. (2005). *Geochemistry, Groundwater and Pollution* (2nd ed.). Amsterdam. <https://it.scribd.com/document/459059791/Geochemistry-Groundwater-and-Pollution-Appelo-and-D-Postma-Second-Edition-1-50>
- Civita, M., & De Maio, M. (2000). *Valutazione e cartografia automatica della vulnerabilità degli acquiferi all'inquinamento con il sistema parametrico SINTACS R5*. Pitagora Editrice.
- Evgeny, K. (2023). *Electrochemical Contributions: Marcel Pourbaix (1904-1998)*. Electrochemical Science Advances (ELSA).
- Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice-Hall. (in Italian) <https://fc79.gw-project.org/italiano/>
- Gao, Z. J., Liu, J. T., Feng, J. G., Wang, M., & Wu, G. W. (2019). Hydrogeochemical Characteristics and the Suitability of Groundwater in the Alluvial-Diluvial Plain of Southwest Shandong Province, China. *Water*, 11, Article 1577. <https://doi.org/10.3390/w11081577>
- Hem, J. D. (1985). *Study and Interpretation of the Chemical Characteristics of Natural Water*. U.S. Geological Survey Water-Supply Paper 2254. <https://pubs.usgs.gov/wsp/wsp2254/pdf/wsp2254a.pdf>

- Italia (2006). Decreto legislativo 3 aprile 2006, n. 152. Norme in materia ambientale. *Gazzetta Ufficiale della Repubblica Italiana*, n. 88.
https://www.bosettiegatti.eu/info/norme/statali/2006_0152_allegati.htm
- Loke, M. H. (2004). *Tutorial: 2-D and 3-D Electrical Imaging Surveys*. Geotomo Software.
https://www.researchgate.net/publication/264739285_Tutorial_2-D_and_3-D_Electrical_Imaging_Surveys
- Mumiqo Team (2026). Mumiqo: Online Statistics Calculator. *numiqo*.
<https://numiqo.com>
- Noda, N., Imamura, S., Sekine, Y., Kurisu, M., Fukushi, K., Terada, N. et al. (2019). Highly Oxidizing Aqueous Environments on Early Mars Inferred from Scavenging Pattern of Trace Metals on Manganese Oxides. *Journal of Geophysical Research: Planets*, 124, 1282-1295. <https://doi.org/10.1029/2018je005892>
- Piper, A. M. (1944). A Graphic Procedure in the Geochemical Interpretation of Water Analyses. *Transactions, American Geophysical Union*, 25, 914-928.
- Reynolds, J. M. (2011). *An Introduction to Applied and Environmental Geophysics* (2nd ed.). Wiley-Blackwell.
- Schoeller, H. (1962). *Les eaux souterraines*. Masson.
- SNPA (2018). Linee guida per la determinazione dei valori di fondo per i suoli e per le acque sotterranee. *Sistema Nazionale per la Protezione dell'Ambiente*.
<https://www.snambiente.it/pubblicazioni/linee-guida-snpa/linee-guida-per-la-determinazione-dei-valori-di-fondo-per-i-suoli-e-per-le-acque-sotterranee/>