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"Development of a groundwater flow model: preliminary characterization of a contaminated site in Borgaro Torinese"

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Tables of contents

ABSTRACT

Groundwater resources are one of the most vulnerable environmental components, increasingly subjected to contamination and degradation, mainly due to human activities; the solution, in the Italian legislation framework, is represented by Human Health Risk Assessment, which helps define the intervention priorities at the affected site by evaluating the potential adverse health and environmental effects deriving from the release of a contaminant.

This thesis work was developed to support the realization of a HHRA, second phase of a broader remediation plan of a contaminated site located in Borgaro Torinese (Piedmont, Italy), focused on the assessment of groundwater quality following the detection of heavy metals and chlorinated solvents contamination. The uncertainty surrounding the conceptual site model made it necessary to improve the understanding of the local hydrogeological setting; to this end, a comparison between site-specific stratigraphic data and regional geological information was carried out, together with on-site piezometric monitoring campaigns, conducted as part of a mandatory environmental assessment prescribed by the City of Turin. Data collected from the revised monitoring network, consisting of 18 piezometers, served as input for Surfer software to generate a representative groundwater flow model via Kriging interpolation method.

The resulting model aims to assess the reliability of the current monitoring network in representing the site's hydrogeological conditions. This evaluation will support the subsequent stages of acquisition of coherent concentrations of contaminants and consequent development of an efficient remediation strategy.

1 Introduction

In an environment increasingly threatened by anthropogenic pressures such as industrial activities, improper waste disposal, and chemical usage contamination, groundwater resources stand out as one of the most critical and vulnerable components. In Italy, the assessment and remediation of contaminated sites are framed by the Legislative Decree No. 152/2006, also known as the Environmental Code, which requires the implementation of the Human Health Risk Assessment considered the most advanced scientific approach for evaluating site contamination and setting remediation priorities [1]. It develops in several stages, from site characterization, fulcrum of this analysis, to the definition of a conceptual model, determination of contaminant concentrations at the receptors and, at last, to the final risk calculation and assessment [1]. The first 2 stages, which constitute the so-called Characterization Plan, aim to gather all the available data to accurately assess and characterize the site of interest by defining 3 key factors: sources, migration pathways and receptors.

The case examined in this thesis is the site of La Siderurgica Inc. industrial activity, located in Borgaro Torinese and active since 1985. The main activities were demolition and storage of ferrous materials coming from automotive, motor vehicles and industrial plants. Both the end of the work activity, in 1997, and the site's acquisition by Ergom Inc. 3 years later, made necessary the implementation of a risk assessment of the contamination – by heavy metals, chlorinated solvent, volatile hydrocarbons – detected at the end of the work activity. Several site characterizations and piezometric monitoring campaigns were conducted over the years, leading to a final remediation project executed in 2008; after further contamination was detected, supplementary documents and relative updates were issued between the years 2020 – 2022, when the intervention was divided into 2 phases: the former based on soil remediation, ended in May 2025, while the latter, still in progress, based on groundwater quality investigation.

The present work focuses on the development of a groundwater flow model, as part of the second phase constituting the 2022 plan, to support the preliminary site characterization by comparing and combining all the available data, historical and more recent, and ultimately to assess the current piezometric network's capability to accurately represent the hydrogeological conditions of the site. Although this represents only the initial step of the full HHRA process, it is crucial for the reliable acquisition of contaminant concentration data in future stages and for the design of an effective and targeted remediation plan.

The model was developed using Surfer software, based on data collected from an updated monitoring network consisting of 18 piezometers. The methodology included several key activities: comparison of stratigraphic logs and construction of a correlated stratigraphic profile, field GPS surveys to geolocate the piezometers, internal inspections of well completions using a borehole camera and in-situ piezometric level measurements. The interpolated potentiometric surface was generated using the Kriging method, allowing for detailed visualization and analysis of groundwater flow directions and hydraulic gradients across the site.
A first qualitative assessment of the lithological and hydrogeological characteristics of Borgaro Torinese is presented in the following paragraph, using data from Geoportale Arpa Piemonte, which provides access to environmental, geological, and hydrogeological datasets used for environmental assessments and land management in the Piedmont region. Then, Chapter 2 provides a detailed overview of the site's industrial history and past remediation activities, structured in a way to reflect the logic of a preliminary characterization plan. The latter, the main phases constituting it and the relative regulatory framework guiding its implementation are then presented in Chapter 3, with the goal of providing the tools necessary to better understand the basis of this analysis. In the end, Chapters 4 and 5 are respectively dedicated to the methodologies and different steps that led to the development of a hydrogeological model and to the relative results of the study.

1.1 Geo – lithological and hydrogeological assessment

The analysis conducted in this paragraph is a preliminary step to better understand the intrinsic characteristics of Borgaro Torinese area, described then in details at the local scale in the following chapters.
For the purposes of this analysis, four different maps were examined: Geological Map 1:250.000, Lithological Deposit Map, Soil Map 1:50.000 and Piezometric Map 1.50.000.
As for the first one, it provides geological unit, age and higher-level geological units to which a specific soil belongs; the area occupied by the municipality of Borgaro Torinese falls within three geological units - P14, P16, fl1 - as shown in Figure 1, characterizing respectively the northeast (light orange), east (light blue), south and the remaining part of the municipality (white), which includes in particular the contaminated site of interest (dashed red polygon).
These three units date back to different ages, first two to middle-late Pleistocene and third one to Holocene, the epoch that comes after the Pleistocene and continues to the present day; each

of the three is described as “river deposits” which are one of the typical deposits from the Quaternary Period, consisting of the two epochs mentioned above.
The south part of the site is marked by a syncline fold (dashed gray line) of the subsoil which is a type of geological fold that forms when rock layers bend downward into a trough-like shape due to compressional forces, with the youngest rock layers lying at its core. [2]

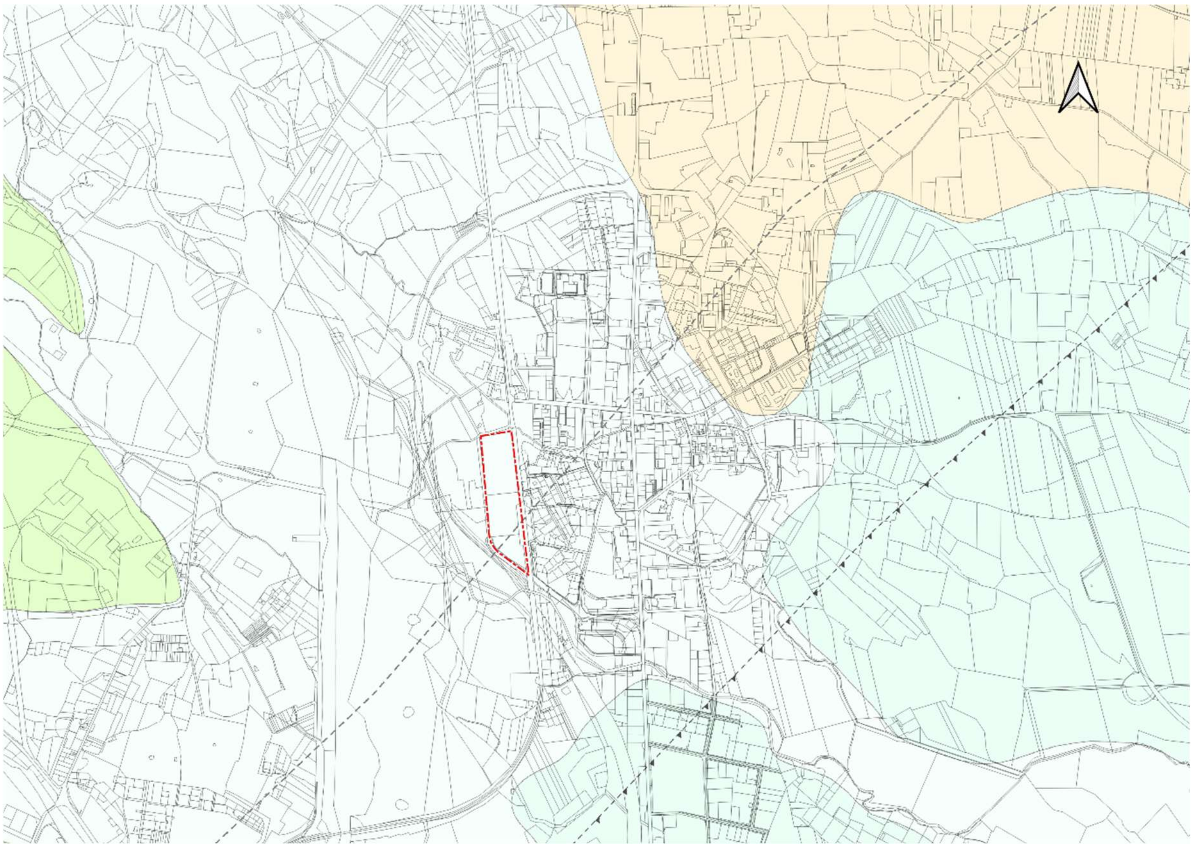


Figure 1. Geological Map 1:250.000. [3]

Then the second map, the Lithological Deposit one, describes in details the main characteristics of the deposits: “gravelly alluvial deposits, sometimes sandy and silty, ancient and terraced” [3], identify the south-west area of Borgaro while “gravelly and cobbly fluvioglacial alluvium, sometimes containing large erratics, altered into clay-rich soils” are typical of the north-east area, as shown in Figure 2.
In the Soil Map, Figure 3, the area of interest mainly falls within the cartographic unit U0401 characterized by *bellacomba* soils[4]; as reported in the soil information system, these soils are typical of the segment along the Stura di Lanzo river and they usually arose from gravelly and sandy alluvial deposits. Poor and uneven rockiness distinguish the topsoil with a stoniness class between 1-5, while the subsoil with a stoniness class of 16-35 appears to be richer in coarse texture; in its entirety it has a mediocre drainage.

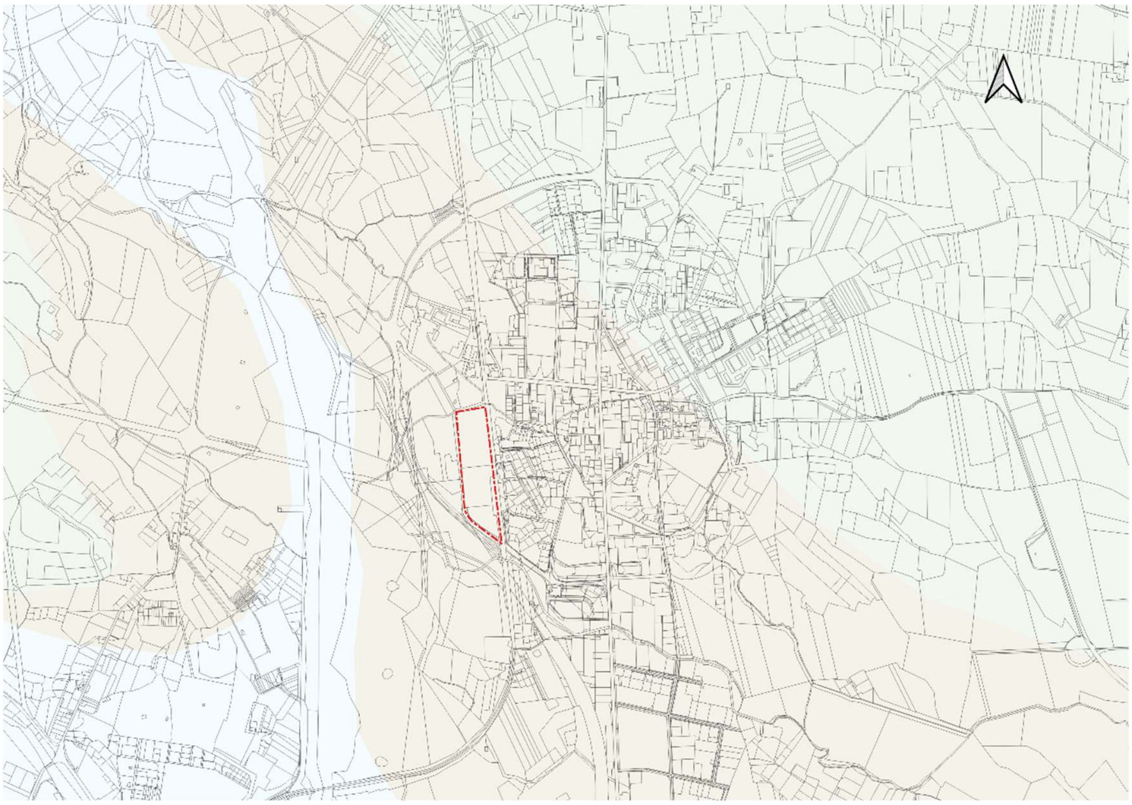


Figure 2. Lithological Deposit Map. [3]

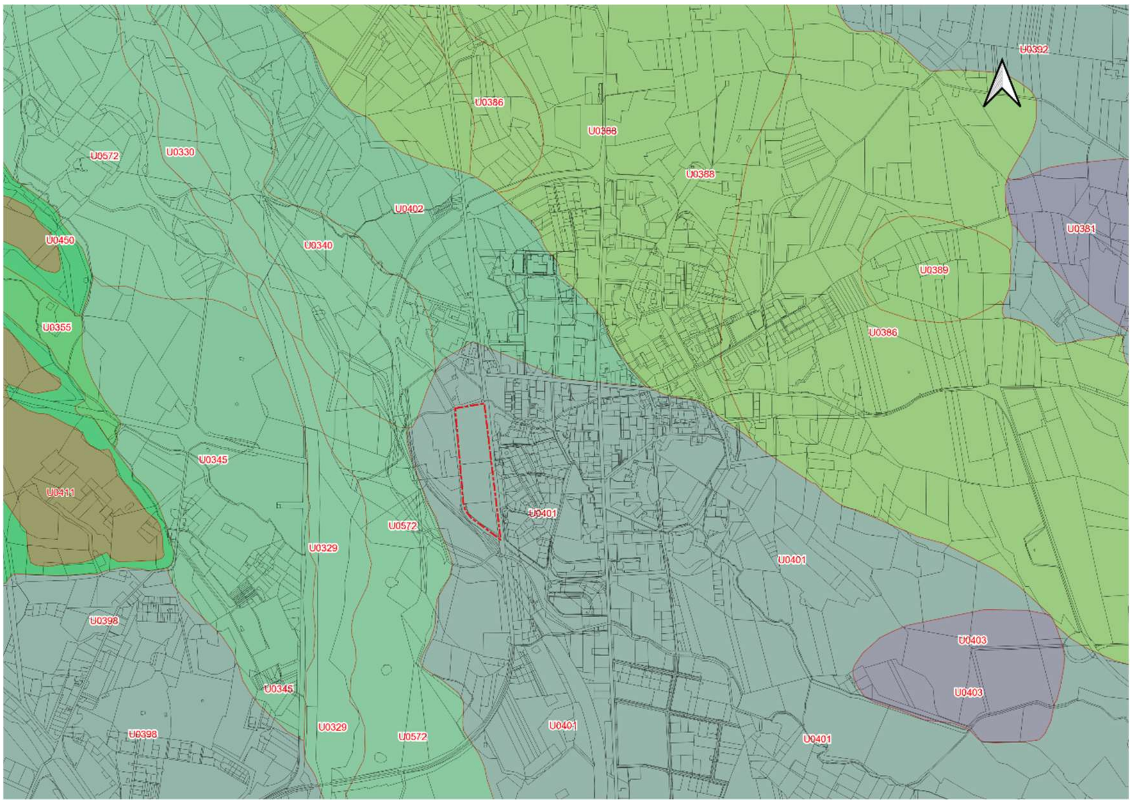


Figure 3. Soil Map 1:50.000. [3]

Lastly, Figure 4 presents the groundwater level map, showing a general flow direction from northwest to southeast. As for the Stura di Lanzo stream influence, it exerts a draining effect on the aquifer, although affected by local variations in the piezometric gradient.

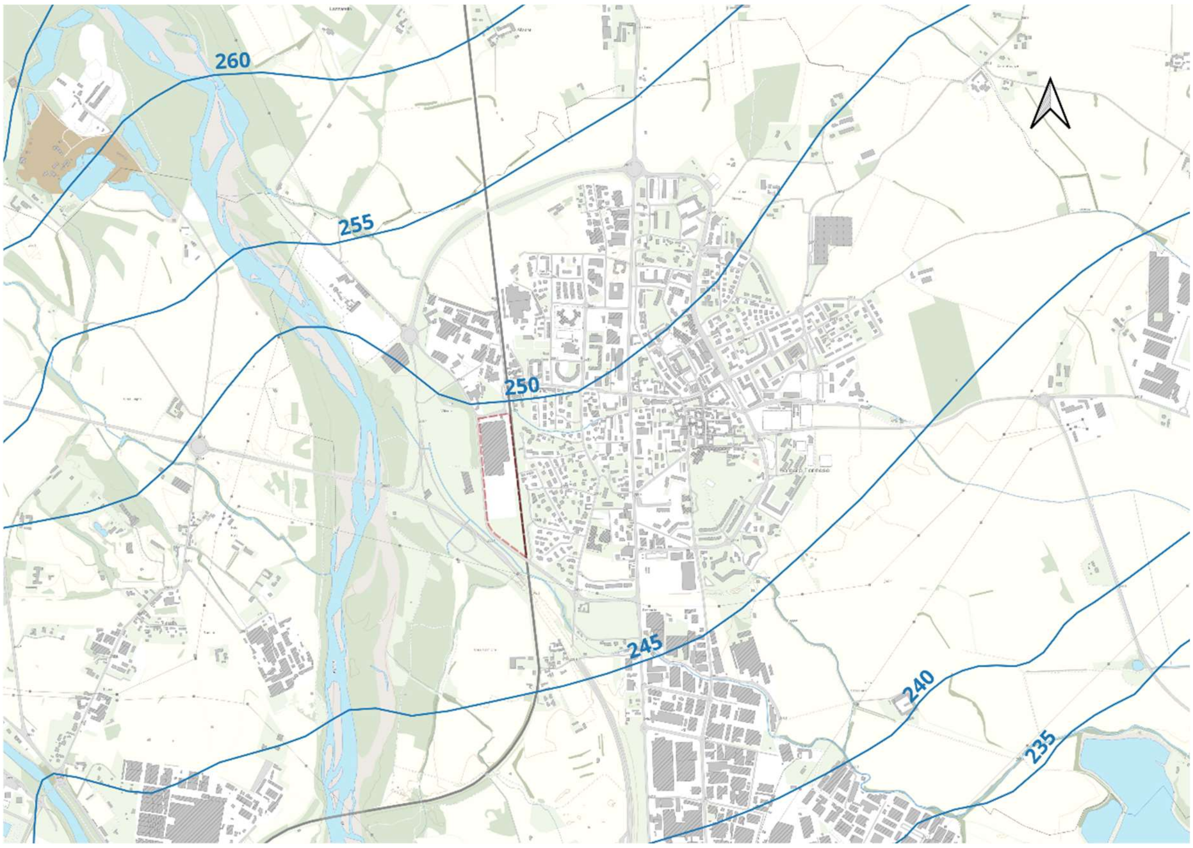


Figure 4. Piezometric Map 1:100000. [3]

2 Characterization Plan

Following the large-scale geological characterization previously conducted to outline the main features of the area, the focus is now on the process that, starting in 1999, led - after several clarifications and legislative changes - to the approval of the final remediation plan in 2008 and its subsequent updates, including the 2022 revision, whose proposed interventions are currently being implemented.

The present chapter is structured according to the various topics typically addressed in a characterization plan, whose aim is to define in details geological and hydrogeological structure of the site, past and ongoing activities conducted and the correlation between these activities and the type, location and extent of the contamination [5]. By implementing a systematization of existing data, Paragraph 2.1 outlines the geographical location of the site and provides a historical overview of the industrial activities carried out; then, following the chronological sequence of events, the subsequent paragraphs explore the characterization of the site, the final remediation plan and the following updates and additions; in particular, Paragraph 2.2 (covering 1999-2003), and 2.4 (2011-2023), are divided into three sections addressing three main topics: geological survey required for the monitoring network installation, piezometric analysis and at last the contamination itself and the soil and groundwater analysis; while, Paragraph 2.3 briefly presents the approved remediation plan of 2007, its implementation and the results obtained.

To provide context for the following analysis, a brief timeline of the key events related to the remediation plan is presented below.

After several geological and hydrogeological surveys started in 1999, the preliminary plan proposed in 2000, following the entry into force of Ministerial Decree no. 471 of 1999, led to a first final remediation plan, which - after some clarifications and, above all, the introduction of Italian Legislative Decree no. 152 of 3 April 2003, also known as Environmental Code - was possible to carry out only in 2007 and it was completed in January 2008. At the end of the remediation, a 5-year monitoring program was planned, beginning in 2011. In November 2018, after the end of the monitoring activity, and when the ownership of the area passed to Marca Ltd company, a newly identified area of soil contamination was discovered near piezometer P14 – hotspot – (ref. figure); this area was subsequently included in a proposal for remediation through permanent safety measures. A new remediation plan, revising the 2007 plan, was then approved and structured into 2 main phases: one related to the safety measures of the soil and the other to groundwater quality.

To provide a general framework of what will be discussed in the following paragraphs, Figure 5 shows the total 28 piezometers realized since the start of the remediation process, highlighting P14 piezometer location (red square) in the central part of the site, the most recently affected area by soil contamination.

For the purposes of this thesis work, the following analysis will primarily focus on groundwater-related events.

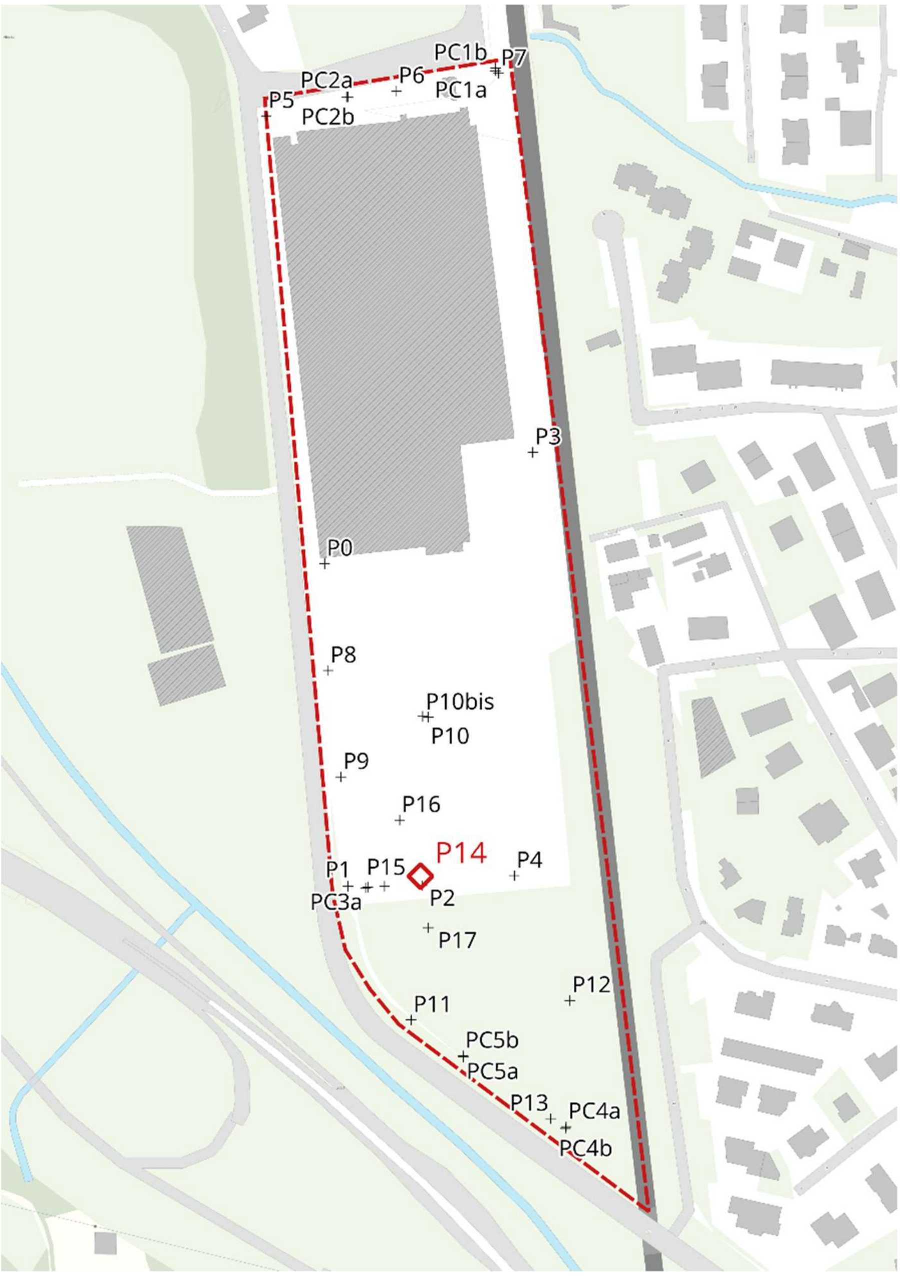


Figure 5. Piezometer location map

2.1 Site's characterization and production history

The site in question is located in the industrial area of the southwestern outskirts of Borgaro Torinese, as highlighted in red innFigure 6; it is surrounded to the west by the Stura di Lanzo stream, to the north and east by the urban area and to the south by a wooded area.

Figure 6. 1999 La Siderurgica site highlighted on a BDTRE map. [2]

Starting in 1985, the study's area was site of an industrial activity led by La Siderurgica Inc., authorized by D.PG. N° 186/ 12242/342 on 30.07.1987 to be in charge of storage activity aimed at sorting special waste and at the demolition of ferrous materials, automotive and motor vehicles and industrial plants components until 21.03.2000; nevertheless, the company's productive activity ceased in December 1997.

The interested area was about 24.000 m^2, of which 3.200 m^2 were occupied by a shed and offices. The activity started in 1985 with ferrous materials shearing and pressing and continued in 1992 with the addition of a car shredding plant. In the end, 4 main treatment cycles were carried out with different plants according to the type of scrap to be treated:

1. Pressing: volumetric reduction of bulky scraps, such as sheet metal offcuts from car manufacturing, which were reduced to packages of 40 × 50 × 80 cm.
2. Shearing: pressing and cutting of long and bulky scrap into smaller pieces with a maximum size of 60 × 60 cm.
3. Shredding: used to separate ferrous scraps from other material residues, such as glass, plastic or rubber; exclusively employed for light component, mainly cars.
4. Magnetic separation: last step, after the shredding, performed to separate metal parts from non-ferrous residues.

Pressing and magnetic separation were carried out inside the shed, the former on the west side and the latter on the east side, while the shearing and shredding plant worked side by side outside the shed; together, these 4 processes were involved in the processing of a total amount of ferrous and non-ferrous scrap of approximately 80.000 tons, to be sold back to steel plant and foundry. Batteries and used oils were also handled on-site; once removed from the vehicles, they were stored in sealed container inside the warehouse to be delivered periodically to batteries recyclers and regional consortia for waste oil recovery.

As already mentioned, the production ended in December 1997, the dismantled machinery was transferred to another La Siderurgica processing center and the area's owner, as required by the above-mentioned authorization, commissioned a first assessment of the possible contamination generated by the activity. Three years later, in early 2000, the area was acquired by Ergom Inc. which intended to expand its adjacent production facility and committed to continue the site reclamation whose preliminary analytical survey had begun in the first half of 1999.

The following paragraphs focus on the development of the aforementioned plan over the span of more than 20 years, as well as the related updates resulting from changes in the regulations governing the management of contaminated sites — from Legislative Decree No. 471/1999 to Legislative Decree No. 152/2006.

2.2 2003 preliminary remediation project

Figure 7. Location of soil sampling points related to the 1999 soil contamination.

At the end of the production activity, a characterization survey was carried out in February 1999, consisting in the collection of 12 soil samples taken at a depth of 15- 20 cm, at the points where the plants were placed and the residues materials were deposited; the parameters analyzed were heavy metals (lead, total chromium, zinc), PAHs, VOCs, chosen according to the activities conducted on site. After this first check phase, the area was declared contaminated with heavy metals in 5 main points, outlined with red squares in Figure 7. This phase was followed by a second phase of core drilling in May, during which 4 squares of ten meters per side were built around each one of the five points and the soil within the delimited areas was sampled at a depth of 40-50 cm; again, the results were that the area was contaminated just with heavy metals, while all the other parameters analyzed were found to be below the detection limits.

In the end, the contamination was assessed as superficial, affecting a depth of 15-20 cm and it covered a total surface of 600 m^2.

Then, a third phase of groundwater analysis followed in July. The well for water withdrawal was placed near the contaminated area and at a lower height than the other surface in order to be able to collect the water coming from soil percolation and runoff phenomenon and so to detect the highest contaminant concentrations; the surface groundwater was withdrawn at a 12 meters depth.

The contamination found was of halogenated aliphatic compounds (tetrachloroethylene) with values of 130 μg/L while the limit was of 30 μg/L. However, since these compounds were not detected in the soil, the contamination was established to be not related to that one.

After this preliminary survey, in November 1999 a series of geological and hydrogeological surveys started aiming at the realization of a groundwater monitoring network using piezometers.

2.2.1 Geological survey

The subsoil stratigraphy was obtained taking into account three main pre-existing wells disposed along the NW-SE profile of the interested area, as showed in Figure 8Figure 8, and 4 other piezometers realized in the site purposely in sight of the remediation. The first 3, characterized by the stratigraphies shown in Figure 9 and placed as described below, were identified with the letters A, B and C:

A. Marocchinerie Scamosc. Italiane well, placed in the southwestern outlying areas of Borgaro Torinese;
B. Royal well, placed in the center area of Borgaro Torinese;
C. Cascina Stroppiana well, south-east of Borgaro Torinese.

Figure 8. A, B, C wells from geotechnical database [3].

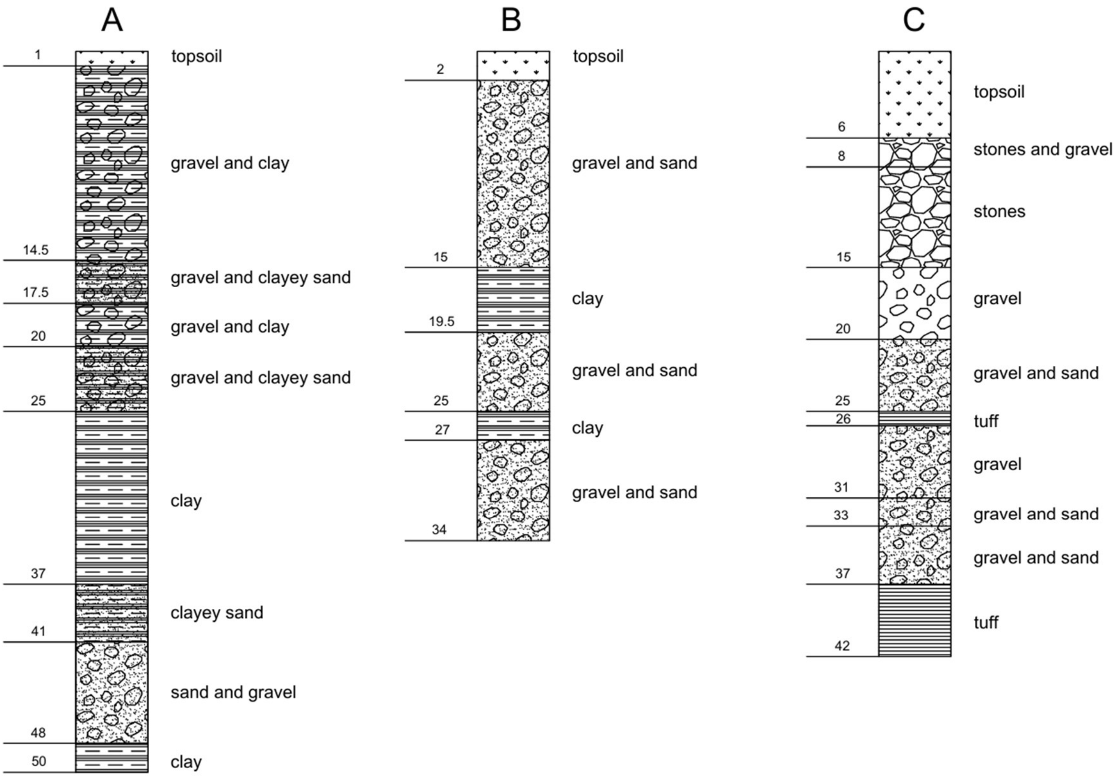


Figure 9. Reconstruction of A, B, C wells stratigraphy. [6]

As for the other 4 wells P0, P1 (later P1b), P2, P3, P4, they were realized through destructive drilling, since the purpose of the surveys was only to install the piezometers and not to analyze the soil; this drilling method consists in the breaking and removal of subsurface material to create a borehole, without preserving a continuous core sample, which eventually translates into less reliable and precise stratigraphy.

The first one to be drilled was P0 in 1999 in the NW apex of the area in upstream piezometer function, characterizing the groundwater flow before the interference with the industrial material of the activity; the production column, at first made of a metallic pipe, was later, at the end of 2002, substituted by a PVC one to avoid the water contamination by Fe and Mn and the wells screens were placed from -6 to – 18 meters from the wellhead.

Then, in March 2000, P1, P2 and P3 piezometers were realized and placed respectively south of the wastewater treatment plant, east (downstream the soil contaminated areas) and east of the industrial shed; the wells screens were placed in the lower part of the well, from -9 to -15 meters from the wellhead.

Later, by the end of 2001, a new piezometer Pb1 was installed as a substitute to the P1 which output values were abnormal due to the inappropriate designed depth and screens; it was realized at about 32 meters west to P1, 18 meters deep and with a 12 meters long screen starting from the well bottom.

In the end, in December 2000, it was realized P4, placed 16 meters east from P1 and screened from -6 to – 18 meters with respect to the wellhead.

A summary Table 1 of the characteristics of the aforementioned wells is showed below:

Table 1. Historical monitoring wells completion details [6].

Piezometer	Wellhead elevation (m)	Depth from ground level (m)	Well screens from ground level (m)
P0	258.67	18	6 - 18
P1	-	15	9-15
Pb1	258.00	18	6-18
P2	258.23	15	9-15
P3	259.53	15	9-15
P4	257.91	18	6-18

From the comparison of the stratigraphies resulted a correlation, characterized as follows:

- Ground surface to 15 meters: *water-table* or *phreatic* aquifer (Holocene alluvial sediments);

- From 15 to 40-50 meters: several aquifer layers more or less permeable, partially independent between each other but more likely hydraulically related to the phreatic aquifer;
- Up to 40-50 meters*: confined* aquifer (upper and lower boundaries are aquicludes), characterized by a substantial independence from the phreatic aquifer and captured mainly to collect potable water.

2.2.2 Piezometric survey

For the large scale piezometric reconstruction, the following data were used:

- direct piezometric measurements;
- bibiliographical data;
- topographic height of ground water surface outcrops (e.g. lakes, Stura river).

First, from the interpolation of the available data, a large-scale potentiometric surface, which is the surface representing the piezometric level [1], was obtained and it was characterized by a slightly divergent trend from NNW to SSE, result of the drainage by the Stura creek located on the western edge of the site, and a 0.7 – 0.8 % hydraulic gradient.

Regarding the piezometric trend observed from the 5 installed piezometers, 8 different monitoring campaigns were carried out over a 3-year period, from 2000 to 2003. In this context it is important to note that, to ensure accurate and consistent results, all measurements across the different points were taken on the same day. In fact, data collected during campaigns conducted in different seasons are not directly comparable due to potential seasonal variations in groundwater levels.

In Table 2 are listed the results of the monitoring campaigns conducted during the years 2000-2003, thanks to which it was possible to evaluate the differences in terms of depth to groundwater and hydraulic gradient during the different seasons.

Table 2. Piezometric trend from 2000-2003 surveys on historical wells [6].

PIEZOMETRIC SURVEY	Depth to groundwater z (m)	i (%)	Groundwater flow direction
30/03/2000	11 ÷ 12	1.1	W-E
25/09/2000	8.5 ÷ 10.5	0.4 ÷ 0.5	N-S
15/12/2000	10 ÷ 11	0.4 ÷ 0.6	NW-SE
17/01/2001	7 ÷ 9	-	NNW-ESE
10/04/2001	11 ÷ 12	0.3	NW-SE
13/12/2001	10 ÷ 11	-	NW-SE
10/01/2003	10 ÷ 11	-	NW-SE
05/08/2003	8 ÷ 9	-	NE-S

The depth to groundwater data, referenced to the wellhead elevation, was used to obtain the piezometric levels, showed in

Table 3, resulting from the difference between the wellhead elevation z_t - relative to the mean sea level - and the depth to water table h_w (see Eq. (1)):

$$h = z_t - h_w \; [L] \qquad (1)$$

while, the hydraulic gradient, variation of hydraulic head per unit of horizontal distance, indicates the direction of groundwater, always flowing from higher to lower piezometric head, and it was calculated as the ratio between the piezometric head difference between 2 measured points and the distance separating them:

$$i = \frac{\Delta h}{\Delta l} \qquad (2)$$

Table 3. Piezometric level of 2000-2003 surveys on historical wells.

PIEZOMETRIC LEVEL h [m]	P0	P1	P1bis	P2	P3	P4
30/03/2000	248.13	246.16	-	246.14	247.65	-
25/09/2000	248.86	248.32	-	248.39	249.13	-
15/12/2000	248.4	250.66	-	247.78	248.31	-
17/01/2001	247.39	247.2	-	246.8	247.53	247.18
10/04/2001	247.44	250.3	-	247.02	247.65	246.99
13/12/2001	248.29	-	247.52	247.44	248.52	247.46
10/01/2003	248.43	-	247.75	247.60	248.80	247.68
05/08/2003	249.60	-	249.04	248.99	250.15	249.01

The table above clearly shows how the piezometric measurements were consistent across the same seasons of different years, with a rise of 1.2-1.3 meters in summer compared to winter – likely due to intensive irrigation of nearby agricultural fields. Furthermore, the water table always fell within the screened intervals of the wells, ensuring the detection of any potential supernatant.

2.2.3 Soil and groundwater sampling results

Between 2000 and 2003, sampling analyses were carried out in accordance with Legislative Decree No. 152/99 - legislative reference for water pollution control - and Ministerial Decree No. 471/99 - reference in the field of contaminated site remediation - regarding contaminant threshold limits, while, as for the sampling methodologies, in those years there wasn't a unique regulation but some of them were defined in Annex 2 of Legislative Decree No.22/97.

In order to determine whether the soil was to be considered contaminated, the sampling points were selected in correspondence with the working and demolition areas, vehicle shredding locations, or material storage areas; the analyses were focused on the detection of all the parameters linked to the typical activities historically carried out in the area: heavy metals (Lead, Total Chromium, and Zinc), PAHs (Polycyclic Aromatic Hydrocarbons), Volatile Hydrocarbons, Organochlorine compounds. In summary, the soil contamination appeared to be limited to the superficial soil layers beneath the concrete slab, to a depth of a few decimetres near zones affected by past activities, caused by **lead**, **total chromium** and **volatile hydrocarbons** (ref. Figure 7. Location of soil sampling points related to the 1999 soil contamination.Figure 7).

As for the groundwater, in order to collect a representative sample from each of the available piezometers, it was first practiced a purging of at least three times the volume inside the piezometer, then the sample was placed in a virgin glass container with an airtight seal and delivered, using a cooler bag and avoiding contact with heat sources or light, to the analysis laboratory on the same day. Both purging and sampling were realized through "GRUNDFOS" pump, which allowed the regulation of the water flowrate thanks to a frequency converter; purging was about 3 minutes long to ensure getting an unaltered sample with different physico – chemical equilibria than the one characterizing the aquifer, for example for the presence of suspended silt.

From the year 2000 to 2003, 4 sampling campaigns were carried out and yielded consistent results, showed and compared in the following Table 4, Table 5, Table 6 to the threshold limits imposed by the Italian law D.M. 471/99. All three sampling campaigns revealed exceedances of the regulatory threshold limit of 1.1 μg/l for **tetrachloroethylene**: in 2000, only upstream of the site

(P0), whereas between 2001 and 2003 also downstream (P1, P1b, P2, P4); **trichloromethane** showed exceedances as well, though only during the second and third sampling campaigns.

Table 4, Table 5, Table 6. 2000-2003 sampling campaigns results [6].

25/09/2000					
2000 sample	Lead (µg/l)	Total chromium (µg/l)	Chromium VI (µg/l)	Tetrachloroethylene (µg/l)	Σ Organohalogen compounds (µg/l)
P0	<1	<10	1.7	**15.7**	<1
P1	<1	<10	5	<1	<1
P2	<1	<10	3.4	<1	<1
P3	<1	<10	3.4	<1	<1
Threshold limits D.M. 471/99	10	50	5	**1.1**	10

22/01/2001						
2001 sample	Lead (µg/l)	Total chromium (µg/l)	Chromium VI (µg/l)	Trichloromethane (µg/l)	Tetrachloroethylene (µg/l)	Σ Organohalogen compounds (µg/l)
P1	1.5	5.9	<1	**1.8**	**7.2**	9
P4	<1	8.4	<1	**1.2**	**1.2**	2.7
Threshold limits D.M. 471/99	10	50	5	**0.15**	1.1	10

10/01/2003						
2003 sample	Lead (µg/l)	Total chromium (µg/l)	Chromium VI (µg/l)	Trichloromethane (µg/l)	Tetrachloroethylene (µg/l)	Σ Organohalogen compounds (µg/l)
P0	<5	2.6	<1	**0.26**	**1.6**	1.86
P1b (*)	<5	2.6	<1	**0.98**	**5.5**	6.94
P2	<5	6	<1	**0.56**	**3.2**	4.16
P3	<5	2.3	<1	**0.46**	**2.7**	3.42
P4	<5	1.5	<1	**0.64**	**4**	5.14
Threshold limits D.M. 471/99	10	50	5	**0.15**	**1.1**	10

Relying on the fact that piezometer P0 was located hydraulically upstream of the investigation area, as showed in Figure 10, and on the absence of these contaminants on the soil samples, the conclusion was that the previous activities carried out at the site under investigation were not accountable for this contamination and that these organochlorine compounds were related to a widespread contamination of the aquifer to the northwest of Turin; this is also confirmed by a document issued by the Piedmont Region, prepared between 2000 and 2002 for the development of the water protection plan, in compliance with Legislative Decree 152/99. [7]

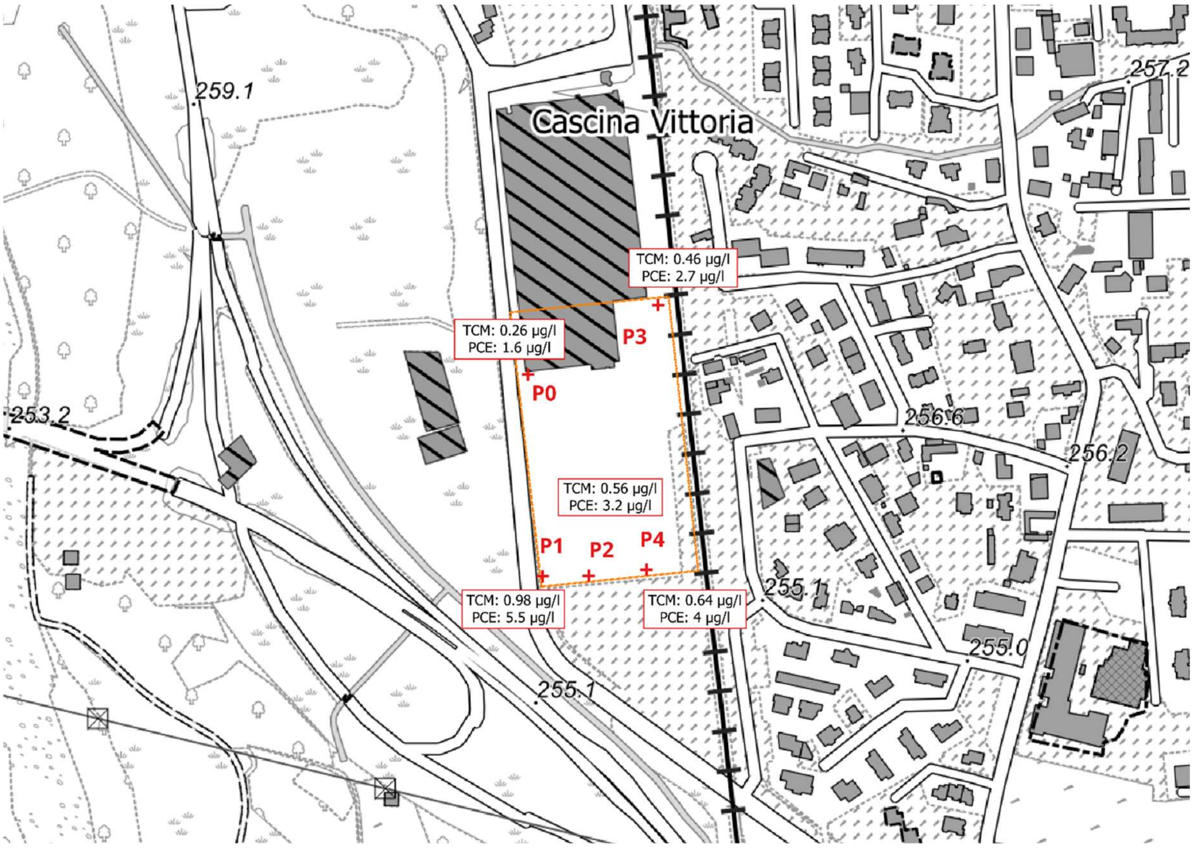


Figure 10. Exceedances of the threshold limits for TCM and PCE in historical piezometers.

2.3 2007 final remediation project

The original proposed remediation project, approved in October 2003, consisted in the partial demolition of the concrete slab covering the entire area, the removal of the contaminated soil to be replaced with "clean soil", and the reconstruction of the concrete pavement. However, nearly 4 years later, after the submission of further clarifications regarding aspects considered

insufficiently defined in the documentation provided and the changes in the environmental remediation regulatory framework, the intervention had still not been carried out.
Again, the contamination was confirmed to be limited to the superficial soil layers located beneath the concrete slab, at a depth of 15 to 20 cm; indeed, the samples taken at a depth of approximately 40 to 50 cm consistently showed no evidence of contamination. Consequently, the 50 cm depth was assumed as the design limit for the remediation intervention.
The total surface area of the contaminated soil was therefore quantified as 5 areas, mainly related to the zones of the past activities, of 100 square meters each, for a total of 500 square meters; Based on the assumed excavation depth, the total volume of soil to be removed was estimated at 250 cubic meters; analytical results classified the contaminated soil as suitable for disposal in a Category II, Type B controlled landfill.
In the meantime, however, the regulatory framework concerning environmental remediation had been modified following the entry into force of Legislative Decree No. 152 of April 3, 2006 (Part Four, Title V). This decree defined the objective of remediation as the reduction of contaminant concentrations to levels below either the Contamination Threshold Concentrations (CSC) or the Risk Threshold Concentrations (CSR), respectively defined as follows:

- contamination threshold concentrations (CSC): "levels of contamination in environmental media that represent values above which site characterization and site-specific risk analysis are required. If the potentially contaminated site is located in an area affected by anthropogenic or natural phenomena that have caused the exceedance of one or more contamination threshold concentrations, these are assumed to be equal to the existing background value for all the exceeded parameters." [8]

- risk threshold concentrations (CSR): "levels of contamination in environmental media to be determined on a case-by-case basis through the application of a site-specific risk assessment procedure, based on the results of the characterization plan. Exceeding these levels requires risk mitigation and remediation. These defined concentration levels represent the acceptability thresholds for the site." [8]

The target threshold concentration (CSO) – i.e. the value that must be achieved through remediation - was chosen as the higher value between the provided CSC and the calculated CSR.

The project was approved by Municipal Council Resolution No. 97 of the Municipality of Borgaro Torinese in July 2007. Remediation activities began in October 2007 and were completed by February 2008.

At the end of the remediation, a verification sampling of the intervention was executed: two representative samples of the soil left in place were collected for each intervention area, one average sample representing the soil at the perimeter of the excavation, and one sample from the bottom of the excavation in its central part. These samples were subjected to analysis of the parameters responsible for the original exceedance of contamination threshold in one or more contaminated areas: **lead**, **light hydrocarbons**, **total chromium**. The results confirmed compliance with the CSC values for industrial use.

The approved project also provided for groundwater monitoring, before, during and after the completion of the remediation activities. The contaminants analysed were: total hydrocarbons, chlorinated solvents, lead and total chromium.

The situation remained stable throughout the remediation period, in line with what had been observed during the monitoring campaigns in the design phase.

The groundwater was found to be affected by widespread contamination from **chlorinated solvents**, particularly tetrachloroethylene**,** with occasional and lower concentrations of trichloromethane and trichloroethylene. Higher contaminant levels were generally detected in the piezometers P0 and P3 than in P1, P2, and P4 in the area subjected to remediation. The only anomaly was the presence of chloromethane in piezometer P1.

Total hydrocarbon concentrations remained consistently low, in the range of a few tenths of μg/l, with no significant spatial or temporal variations.

Similarly, data for total chromium and lead showed no changes over time: concentrations remained below the instrumental detection limit throughout the monitoring period.

Given that the CSC values were met in all intervention areas, none of them required being subjected to Permanent Safety Measures and, respecting the previous conditions established by the plan, the site was deemed remediated.

2.4 2022 supplementary remediation project

Following the completion of the remediation works, a post-operam groundwater monitoring plan - consisting of annual analytical analysis for 5 years and further analytical determinations in the event of any exceedance of legal thresholds - was planned in order to better understand the contamination dynamics and to define any further necessary actions.

In 2011, the Plastic Components and Modules Holding Inc. (Ergom Holding Inc.'s new corporate name) started this monitoring activity, testing for the following parameters: Total Hydrocarbons, Lead, Hexavalent Chromium (Cr VI), Chlorinated Solvents.

Since from the initial survey, PCE showed values above the threshold limit, further monitoring activities were executed as prescribed in the plan.

After the first surveys characterized by concentrations of PCE at the upstream piezometers – P5, P6, P7 – higher than outlet concentrations at the downstream piezometers – P1, P2, P4 –, in the following years, from 2012 to 2018, after the realization of several surveys conducted by both private and ARPA Piemonte (Regional Environmental Protection Agency for the Piedmont Region) technicians, it was observed a not coherent behavior of contaminants concentration. This discrepancy primarily involved: Nickel, Cr VI, Chlorinated Aliphatic Hydrocarbons (CAHs), Trichloromethane and Manganese.

The trend showed in fact widespread concentration of Nickel evenly distributed across the site (both upstream and downstream), Cr Vi mainly in the upstream hydrogeological area, Chlorinated Aliphatic (PCE) only in the historical piezometers (P0–P4, except P2), located in the central portion of the site; while single exceedances for Trichloromethane and Manganese were registered in the central area of the site.

Then, after 2 boreholes were drilled in the southern area of the site, exceedances of Total Chromium, Nickel and Copper CSC were detected only in the soil sample collected at P14, which was attributed to the presence of a superficial layer composed of dark slag. In response, a supplementary document to the 2007 final remediation plan was drafted in July 2020, later updated, to reflect the operations carried out in the following years; the latest version dates back to 2022.

The 2020 intervention plan was structured into 2 main phases:

- Phase 1: Operational Project concerning the implementation of permanent safety measures for soil contamination detected in the area surrounding piezometer P14.
- Phase 2: groundwater quality assessment by updating the piezometric reconstruction, reviewing the groundwater contamination identified since 2011 near the boundary of the former "La Siderurgica" site, integrating new investigation points and simultaneously reducing the existing network.

In relation to the latter phase, while the piezometric reconstruction and the well dismission are discussed in the methodology of the present thesis (Subparagraphs 4.1 and 5.2), the analysis of the groundwater contamination noticed since 2011 and the related surveys – stratigraphic, piezometric, analytical – are reported up to the last update in 2023, and presented chronologically in the following subparagraphs, as already done for Paragraph 2.2.

2.4.1 Stratigraphic surveys

In parallel with the groundwater monitoring activities and with the aim of providing a more accurate hydrogeological characterization of the area, several additional piezometers were progressively installed over the years, as detailed below and showed in Figure 11. All the piezometers were drilled using core drilling which, unlike destructive drilling, allows the extraction of a continuous cylindrical sample (core) of the subsurface material, therefore enabling detailed reconstruction of the subsurface stratigraphy.

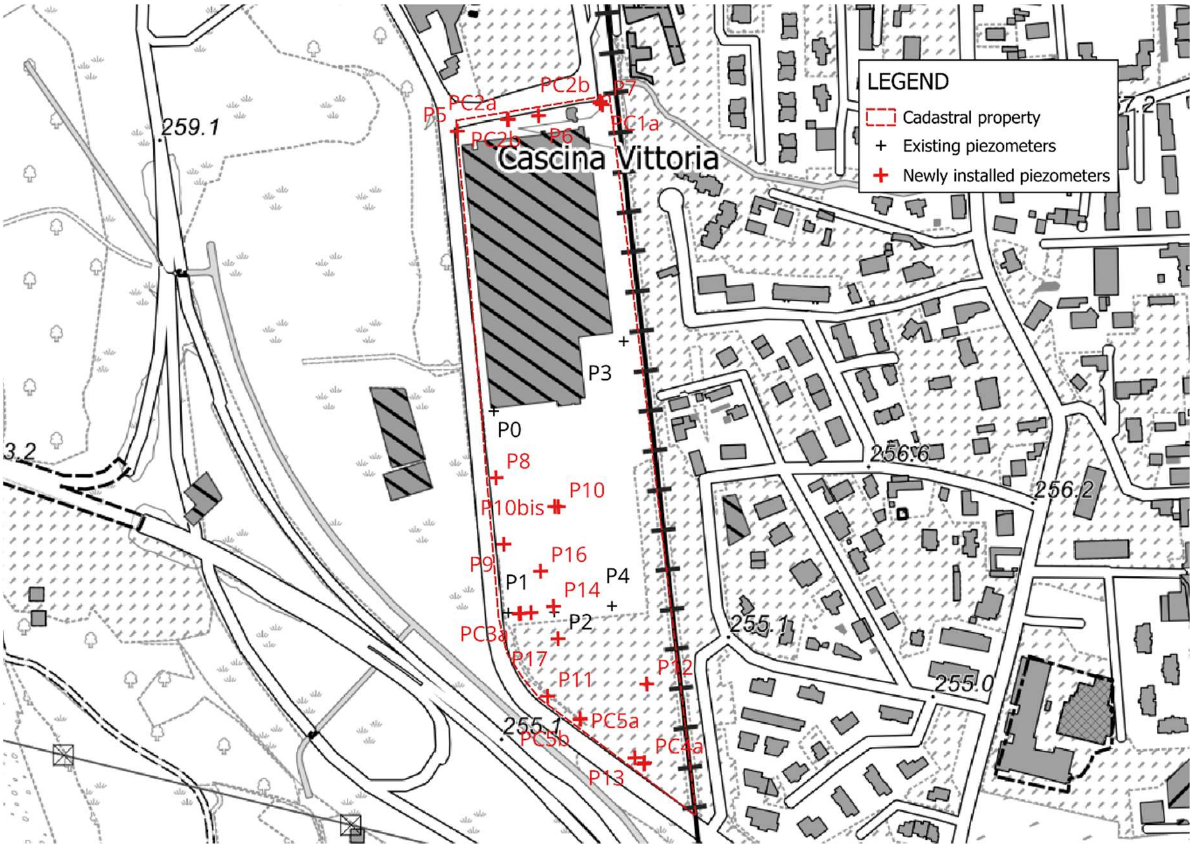


Figure 11. Overview of the total piezometers in 2023

First ones to be installed, in 2011, were P5, P6 and P7 in the northern part of the site. This was followed in 2013 by the installation of 7 new piezometers: first 2 along the western boundary of the site, labelled P8 and P9 and next 5 – P10, P10bis, P11, P12, P13 – respectively positioned, first 2 in the central part of the site and the other 3 beyond the southern boundary of the site, in a wooded area approximately 3–4 meters lower than the ground level of the site.

As for the wells completion: P10 was screened between approximately 11.00 and 16.50 meters below ground level with a total depth of 16.60 meters while the remaining upper part was sealed up to ground level, P10bis was screened from 3.0 to 10.0 meters, corresponding to the depth. Thus, the former was screened only within the lower aquifer portion while the latter within the shallow one.

In 2016, 4 other piezometers were installed: P14, P15, P16, P17.

First 2 were placed in the southern area near the historical wells P1 and P2, while the others were respectively located above and below the former two, to allow a complete lithological and stratigraphic interpretation of the area. Being intercepted during all the fore-mentioned perforations a silty clay layer at around 18 meters from the ground level, all the piezometers were realized at this depth.

After the discovery of the contaminated soil and the proposal of the supplementary 2020 plan, five monitoring clusters, screened piezometers completed in separate boreholes at different depths [1], were installed as part of the groundwater monitoring network expansion project. Each cluster consists of:

1. 3" diameter piezometer realized through core drilling to a maximum depth of 24 meters below ground level, with a screened section within the deep aquifer - generally found below 18 meters – and an unscreened section, crossing the shallow aquifer, properly sealed with a bentonite plug and cement grout to prevent vertical flow.
2. 3" diameter piezometer realized through destructive drilling, installed to a maximum depth of 17 meters and screened across the entire interval corresponding to the shallow aquifer.

Of the 5 clusters in total – PC1, PC2, PC3, PC4, PC5 - the first category, screened exclusively within the deep aquifer, was labeled with the suffix "**a**", while the latter, screened only within the shallow aquifer, with the suffix "**b**".

The first two - PC1 and PC2 - were installed upgradient of the site, cluster PC3 along the southwestern boundary, while clusters PC4 and PC5 were placed downgradient of the site.

The installation of the above-mentioned clusters, as well as the one of the previous piezometers, allowed the proposal of a more accurate **litho-stratigraphic configuration** at the site scale, described as follows in the 2022 updated report of the 2007 final remediation project, drafted by Marca Ltd company:

> Historical data suggest the presence of a sequence of partially independent but hydraulically interconnected shallow aquifer horizons at the site scale. The shallow stratigraphy is characterized by alternating sandy-gravelly aquifer layers with cobbles, embedded in a slightly silty matrix, interbedded with lower-permeability horizons. These lower-permeability layers show an increasing fine fraction with depth, […] configuration that suggests local hydraulic compartmentalization within the shallow aquifer system. At greater depths, approximately 16–17 meters below site grade, a low-permeability clayey to silty-clayey horizon was encountered. At the site scale, this horizon acts as a confining layer, effectively separating the shallow unconfined aquifer […] from a deep, confined aquifer located beneath it. The deep aquifer, under artesian pressure, is hosted within slightly sandy silt and silty clay deposits, and is typically encountered at depths greater than 17–18 meters below site grade. [9]

A summary of the available well completion data is reported below:

Table 7. Available 2011 – 2023 well completion data

Piezometer	Depth from ground level (m)	Well screens from ground level (m)
P10	16.60	11 – 16.50
P10 bis	10	3 - 10
PC1a	24	18 - 23
PC1b	17	5 - 16
PC(2-3)a	24	17 - 23
PC(2-3)b	16	4 - 15
PC(4-5)a	24	15-23
PC(4-5)b	14	3 - 13

2.4.2 Piezometric surveys

Following the expansion of the piezometric monitoring network, the depth to water table measurements taken from 2011 to 2018 all led to a general groundwater flow trend characterized by a water level at approximately 6 meters below ground level and a flow direction oriented from north-northwest toward south-southeast.

Data coming from the 2018 groundwater monitoring campaign, conducted on the total 19 available piezometers, confirmed the trend observed in previous years, with the trend showed in Figure 12 through the Contour Map produced with Surfer using the available historical data.

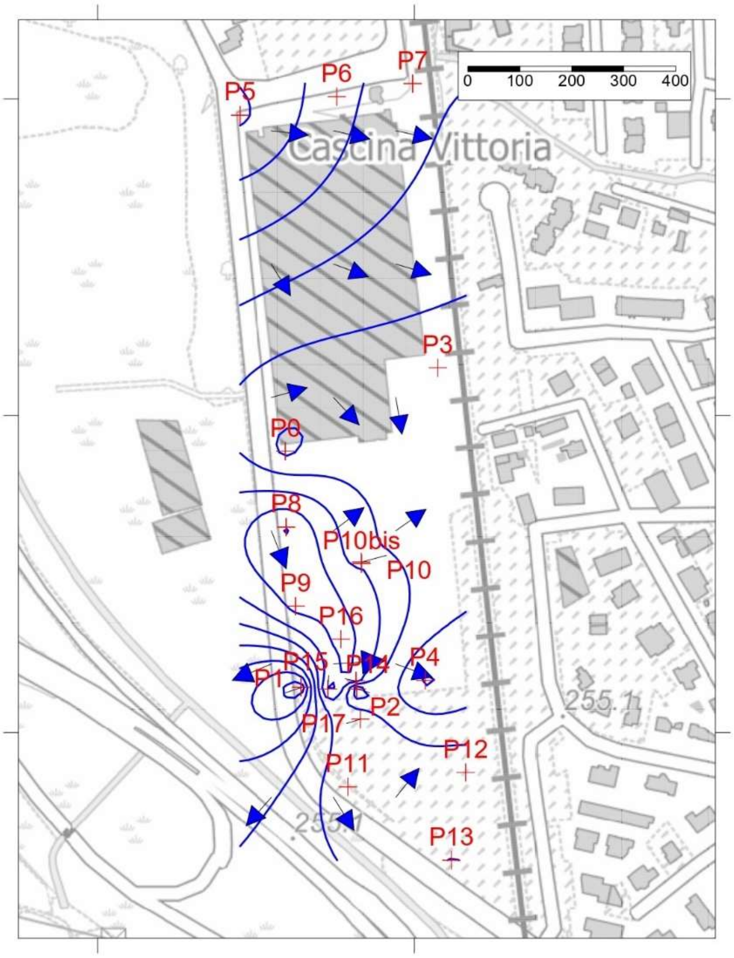


Figure 12. Piezometric Contour Map - 2018.

As observed in Figure 12, these measurements were characterized by anomalous hydrogeological conditions related to the historical piezometers, whose levels were generally lower than those observed in the new ones; suggesting that the historical wells could have been influenced by a different hydraulic input, for example by intercepting an aquifer horizon distinct from the shallow one. This hypothesis was confirmed as well by hydro-chemical characteristics not in line with the one recorded in the other wells.

The flow pattern resulting from these data, consistent with previous observations dating back to 2011, showed again a general flow direction from NNW to SSE, with piezometric head values ranging from approximately 253 meters in the northern area of the site to around 249.8 meters in the southern green area, showed in detail in Table 8.

Name	Piezometric level (m)
P5	253,36
P6	251,9
P7	251
P3	249,7
P0	249
P1	246,09
P2	248,3
P4	248,24
P8	252,49
P9	251,89
P10	250,09
P10bis	250,76
P11	250,6
P12	250,6
P13	249,98
P14	251,42
P15	252,04
P16	251,89
P17	250,75

Table 8. Piezometric levels – 2018

Based on these values, the piezometers P5, P6, and P7 were set as upgradient piezometers and P11, P12, and P13 as downgradient piezometers.

With the first update of the remediation project in 2020, these discrepancies led to the proposal of closure of the historical piezometers – P0, P1, P2, P3, P4 – as they were no longer considered reliable for an accurate piezometric reconstruction of the site; in addition, 5 other piezometers - P10, P10bis, P14, P16, and P17 – were also proposed for dismission at the request of the property owner, as they were located within the footprint of a planned new building. The proposal, accepted by both the Metropolitan City of Turin and ARPA in 2023, was executed in 2025 as described later in Paragraph 4.1.

the installation of the 5 new clusters; piezometers P6, P7, P10, P15 were excluded from the analysis due to inconsistent data.

As for the **deep aquifer**, the historical wells together with the 5 new clusters were taken into account; the reconstruction of its groundwater flow showed a N-S direction and a regular hydraulic gradient of approximately 0.5%.

The **shallow aquifer** instead, reconstructed using data from the remaining piezometers, displayed as well a constant gradient of approximately 0.8%, with the exception of the central area likely influenced by local presence of low-permeability layers**.**

2.4.3 Soil and groundwater analysis

Since 2011 until 2016, the analytical surveys focused exclusively on groundwater monitoring.

The first analysis, conducted in 2011, showed concentrations of PCE in the order of hundreds of μg/l at the upstream piezometers – P5, P6, P7 – higher than outlet concentrations at the downstream piezometers – P1, P2, P4. Additionally, both Trichloroethylene and Cr VI exceeded only in upstream piezometers.

However, regarding the chlorinated solvents, since 2012, the following surveys performed by both private and ARPA technicians, displayed a reversal in this trend. Specifically, it was observed a concentration of tetrachloroethylene (PCE) at the inlet and in the central area - P5, P6, P7 and P0, P3 - of the former "La Siderurgica" site - order of tens of μg/l - that was significantly lower than that at the outlet on the order of hundreds of μg/l in P1, P2, P4; in contrast, in all other more recently installed piezometers – P8, P9, P10, P10bis – it was in the order of some μg/l and below the limits in the ones located south of the site in the wooded area, and placed downstream of the entire property

As for the metals, since 2015, Nickel started to be detected with widespread exceedances in the all the piezometers, except for the historical ones, with a minimum in the order of tens of μg/l in both the upstream – P5, P6, P7 – and downstream wells - P11, P12, P13, P17 - and a maximum of approximately 80 μg/l in P8 and P9, compared to the CSC value set at 20 μg/l; while, regarding Cr VI, concentrations remained constant on the order of 10 μg/l, exclusively in the upgradient piezometers – P5, P6, P7.

The exceedances - coherent with the above discussed trend - resulting from the sampling campaign conducted in October 2018, are reported in the following Table 9.

Table 9. CSC exceedances in 2018

Name	Mn (μg/l)	Ni (μg/l)	Cr VI (μg/l)	TCE (μg/l)	PCE (μg/l)	Σ Organohalogen compounds (μg/l)
P0	-	-	-	-	12	12
P1	-	-	-	0.16	130	130
P3	-	-	-	-	5.5	-
P4	66	-	-	-	17	18
P5	-	54	6.1	-	-	-
P6	-	43	6.1	-	-	-
P7	-	35	6.8	-	-	-
P8	-	86	8.5	-	-	-
P9	-	86	-	-	-	-
P10		66	-			
P10 bis	-	72	-	-	-	-
P11	-	45	-	-	-	-
P12	-	43	5.1	-	-	-
P13	-	36	-	-	-	-
P14	-	71	-	-	-	-
P15	-	42	-	-	-	-
P16	-	57	-	-	-	-
P17	-	61	-	-	-	-
CSC	**50**	**20**	**5**	**0.15**	**1.1**	**10**

In addition to the previous analysed parameters, Manganese showed a single exceedance in P4.
Regarding soil contamination, identified during the drilling operations for piezometer P14, a project modification was proposed in 2020. This modification included two phases: one related to permanent security measures for the soil and the other to the expansion of the piezometric network. The soil remediation intervention, executed at the end of May 2025, consisted in the restoration of the concrete paving achieved through the construction of a 5 cm thick lean concrete base layer, overlaid by a 20 cm thick reinforced concrete slab equipped with electrowelded steel mesh.
Subsequently, in 2023, after the implementation of the new piezometer clusters, a new sampling campaign was conducted and a general contamination by PCE, Chloroform, Cr VI, Nickel and Manganese was confirmed in both the shallow and deep aquifer.
The results are presented in Table 10 and Table 11, where piezometers are listed according to their position relative to the vertical development of the site.

Table 10. Shallow groundwater CSC exceedances in 2023. [9]

Name	PCE (μg/l)	Trichloromethane (μg/l)	Cr VI (μg/l)	Nickel (μg/l)	Manganese (μg/l)
Upstream					
PC1b	–	0.24	9.7	>20	–
PC2b	2,8	–	6.6	>20	–
P5	<2.0	0.23	5.9	>20	–
P6	–	–	6.6	>20	–
P7	–	–	8.3	>20	–
Intermediate					
PC3b	4.8	–	–	>20	–
P8	–	–	–	74	–
Downstream					
PC4b	<2.0	–	–	>20	–
PC5b	<2.0	–	–	>20	86
P11	<2.0	–	–	>20	–
P13	<2.0	–	–	>20	–
CSC	**1.1**	**0.15**	**5**	**20**	**50**

Table 11. Deep groundwater CSC exceedances in 2023. [9]

Name	PCE (μg/l)	Trichloromethane (μg/l)	Cr VI (μg/l)	Nickel (μg/l)	Manganese (μg/l)
Upstream					
PC1a	5.2	0.17	7.5	28	–
PC2a	110	0.28	5.1	>20	–
Intermediate					
P1	–	0.22	–	>20	–
P4	–	–	–	>20	160
PC3a	210	0.28	–	>20	–
Downstream					
PC4a	110	–	–	>20	–
PC5a	110	–	–	>20	96
CSC	**1.1**	**0.15**	**5**	**20**	**50**

Regarding the **shallow groundwater,** as also represented in Figure 13, PCE showed exceedances of the CSC (1.1 μg/L) both upstream and in the southern- intermediate area of the site, with the highest concentration of 4.8 μg/L in PC3b; Trichloromethane (Chloroform) and Hexavalent Chromium, both exceeded their respective CSC - 15 μg/l and 5 μg/L - only at the upstream piezometers; Nickel showed widespread exceedances of the CSC (20 μg/L) in both upstream and downstream piezometers ranging in the tens of μg/L, with the highest value of 74 μg/l in P8; Manganese exceeded only at the downstream piezometer PC5b.

Figure 13. Shallow aquifer exceedances in 2023.

As for the **deep aquifer**, PCE was detected with concentrations of the order of hundreds of μg/L both upstream and downstream, while the highest concentration was found at PC3a (210 μg/L); Trichloromethane (Chloroform) exceeded upstream and in the central portion of the site; Cr VI and Nickel maintained a pattern consistent with previous campaigns, being respectively detected only upstream the former and both upstream and downstream the latter; Manganese exceeded only in P4 and PC5a. The aforementioned data are also showed in Figure 14.

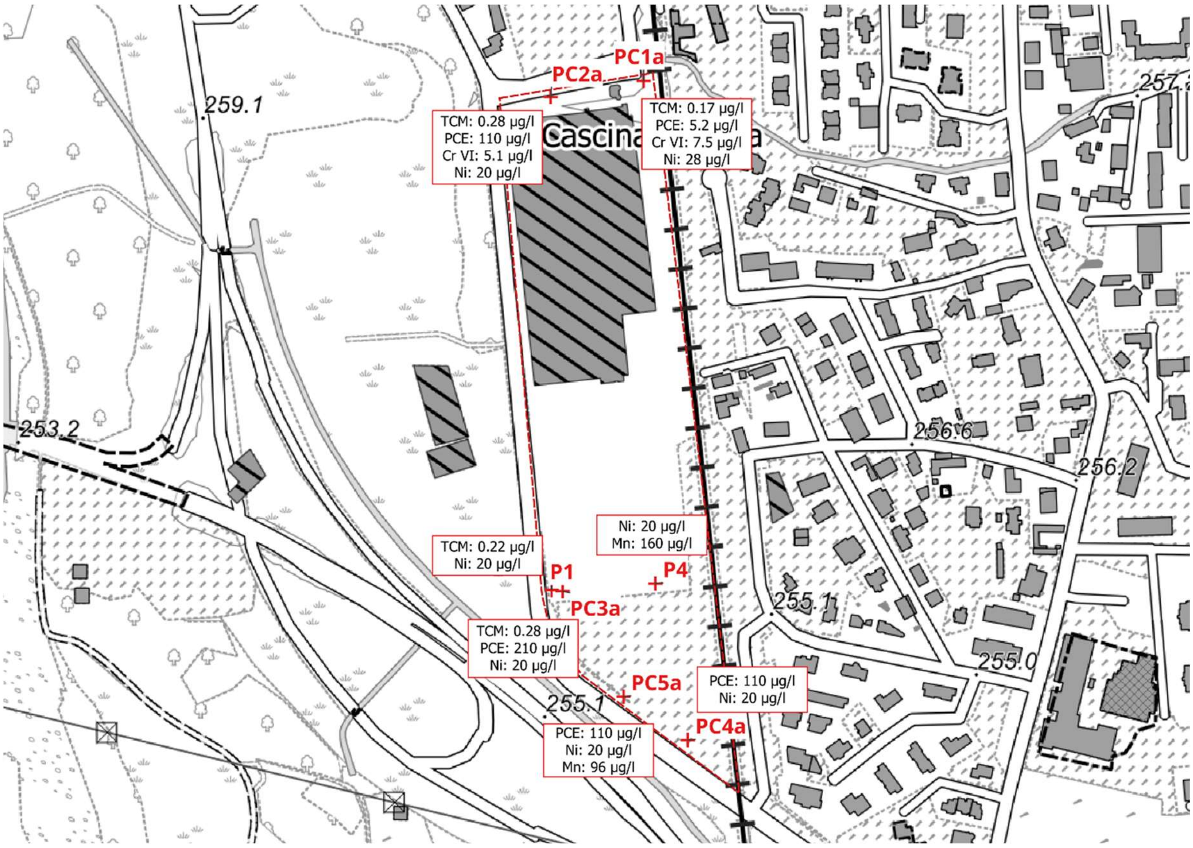


Figure 14. Deep aquifer exceedances in 2023.

3 Regulatory and technical framework

As already mentioned, this thesis work was developed to support the realization of a Human Health Risk Analysis as part of the second phase of a broader remediation plan focused on the assessment of groundwater quality.
Human Health Risk Assessment is defined, in Groundwater Engineering, as:

> the scientifically and technically most advanced approach for the evaluation of the degree of contamination of a site and for the definition of intervention priorities at the site itself [1].

The main goal of the HHRA is to analyze the effects on human health or environment coming from contaminated sources whose emissions exceed the target values set by the legislation; to achieve this, HHRA is structured around the analysis of 3 main factors – sources, pathways, receptors – and on the relationship between them. It develops in several stages, from site characterization, fulcrum of this analysis, to the definition of a conceptual model, determination of contaminant concentrations at the receptors and, at last, to the final risk calculation and assessment [1]. The first 2 stages, which constitutes the so-called Characterization Plan, aim to collect all the available data in order to be able to assess and characterize in the best way possible the site of interest by defining the sources, migration pathways and receptors; then, knowing the possible migration pathways, it is possible to proceed to the third phase whose result is a quantitative analysis of the concentration at the point of exposure, determined through the application of dilution and attenuation factors; at the end, after the actual risk assessment, follows also the evaluation of uncertainties, the goal contaminant concentration we want to obtain and the actual remediation intervention.
In Italy, since 2006, the management and remediation of contaminated site have been governed by a risk-based approach, structurally aligned with international best practices. This approach is framed by the Legislative Decree No. 152, also known as the Environmental Code. In particular, topics related to contaminated site remediation are addressed in Part IV, Title V of the aforementioned Code.
Prior to the adoption of the Environmental, Italian legislation lacked a unified regulatory framework which included all the necessary acknowledgements and information to assess the

several environmental pressures affecting soil, air and water matrices, and the consequent possible mitigation strategies.
In this specific study case, the adoption of a risk-based assessment approach was primarily driven by the presence of contamination across multiple environmental matrices – soil, groundwater – identified at the conclusion of the industrial activities previously conducted on site. Then, the subsequent transfer of ownership of the area represented an additional factor that contributed to the need for a structured risk assessmentand, aimed at protecting the interest of the new owner; in particular, this transfer occurred on 2 separate occasions in 2000 and 2018, respectively with the passage from La Siderurgica to Ergom Inc. and again to Marca Ltd.
Being the remediation plan started for the first time in 1999, it fell under multiple legislative frameworks that evolved over time, particularly concerning groundwater contamination assessment and the definition of applicable threshold values.
Specifically, for the sampling and analysis activities carried out between 2000 and 2003, the applicable contaminant threshold limits were those established by Legislative Decree No. 152/99 and Ministerial Decree No. 471/99; the former served as a legislative reference for water pollution control while the latter provided the regulatory framework in the field of contaminated site remediation. Moreover, with regard to sampling methodologies, in those years there wasn't a unique regulation, however some procedural guidelines were outlined in Annex 2 of Legislative Decree No.22/97, which offered partial but relevant indications for conducting environmental analysis activities.
The *Manual for Environmental Investigations at Contaminated Sites*, developed in 2006 by APAT - former Italian Agency for Environmental Protection and Technical Services, now part of ISPRA (Italian Institute for Environmental Protection and Research) – serves as a widely adopted technical-operational reference for the implementation of the regulatory framework established by the Environmental Code, playing a key role in guiding environmental investigations, particularly in relation to site characterization and risk assessment procedures. The manual is frequently updated and supplemented by regional authorities or ARPA agencies which adopt their own operational protocols, mainly based on the structure outlined in the ISPRA manual, but adapted to the specific local environmental context.
Chapter 2 of the present thesis has been developed following the structure of a Characterization Plan, as outlined in the manual; for this reason the following Paragraph 3.1 and subparagraphs are dedicated to the key topics that have to be addressed as part of such a plan.

Then, as part of the site characterization process itself, delving deeper into the information provided in the introduction regarding Borgaro Torinese area, Paragraph 3.2 aims to lay the foundation for a more effective interpretation of the thesis results. To this end, a detailed description is provided of the aquifer complexes interesting Turin area, based on the Managerial Decree concerning the reconstruction of the Shallow Aquifer Base (BAS), with a particular focus on Borgaro area features.

3.1 General criteria of a Characterization Plan

In order to provide a comprehensive overview of the topic, both the Manual for Environmental Investigations at Contaminated Sites and Legislative Decree 152/06 through the Article 242 - *operational and administrative procedures* – and the Annex 2 to Part IV, Title V were taken into account on the following reconstruction of operations.

Indeed, all remediation plans and operative projects realized up to 2023 and reported in the second chapter of the thesis, were developed in accordance to Article 242 and the relative Art. 242-bis - *simplified procedure for remediation operations* – and Article 242-ter - *interventions and works on sites undergoing remediation*.

The Characterization Plan aims to provide a detailed and structured description of the site, taking into account both current and historical activities carried out within it, and to establish clear links between such activities and the potential contamination in terms of type, location, and spatial extent. Additionally, it outlines the environmental features of the site itself as well as those of the surrounding area potentially impacted. Finally, the plan defines the necessary conditions to ensure adequate environmental protection and safeguarding public health. [5]

To achieve these objectives, the main sections which constitute the plan are: collection and organization of existing data, site characterization and preliminary investigation plan. These 3 components are briefly discussed in the following subparagraphs.

3.1.1 Collection of existing data

The first section, after analysing the site's geographical framework of the site, the area classification - industrial in the case under study - is dedicated to the organization and systematization of existing bibliographic and historical data; effort aimed at the reconstruction of the chronological evolution and development of the study area. In order to provide a clearer and

more comprehensive understanding of the site evolution, all the previous data and information have to be supported by planimetries and pictures, both current and historical.
Subsequently, a detailed description of the productive processes and activities conducted - both historical and ongoing – should be provided, including information on input raw materials and output secondary or final products of the processes, on the specific location within the site where each activity was carried out; together, a list of all the temporary and permanent storage areas, as well as the methods and practices adopted for waste management should be provided.
In the end, a clear description of all the previous environmental surveys conducted on the site – e.g., perforations, piezometer installation, sampling and analytical campaigns - must be reported as well.

3.1.2 Site characterization

The second section is the core of the plan. First, the geologic and hydrogeologic framework of the site, as well as of the area in which it is collocated, is discussed in detail. This initial part includes: a detailed description of the local stratigraphy, with particular attention to grain size distribution (granulometry), depth and features of the single layers with related available stratigraphic log attachments; the groundwater surface setup, describing the various aquifer involved, their respective thickness, the characterizing subsidence and groundwater flow direction. The latter analysis is essential for understanding, at a later date, the potential movement and distribution of contaminants within the subsurface environment.
In the end, the final objective is the identification of the potentially contaminated areas within the site and of any possible preliminary mitigation or containment actions that could be implemented to limit the spread of the contamination. This analysis leads to the development of a preliminary conceptual site model in which, potential contamination sources, pathways and receptors are defined.

3.1.3 Preliminary investigation plan

The last section is the most practical one among the total 3, aiming at deepening the understanding of the site through the execution of direct investigation activities of the area. It constitutes the experimental part of the present thesis, represented by the Methodologies chapter, concerning the topographic, stratigraphic and piezometric surveys carried out at the site.

With the scope of this thesis, these activities may include: inspections of existing wells and piezometers - as done through the video inspection during the 7 July survey (ref. Paragraph 4.4) – to better assess well construction details such as total depth and screens; analysis on interstitial gases, used as a preliminary screening tool to identify potentially contaminated zones – whether in the soil, subsoil, groundwater - that need to be submitted to direct investigation themselves; survey and new piezometers installations where necessary.

Legislative Decree 152/06 does not specify a fixed number of boreholes to be carried out within a contaminated site or, in the same way, piezometers to be installed, as Annex 2 of Ministerial Decree 471/99 did by recommending a minimum number of boreholes based on the surface area of the site under investigation. In fact, both the number and the depth to be reached depends on the specific case; for example, in case of limited knowledge of the geology, it may be useful to extend some of the surveys to depths greater than those planned, in order to obtain a clearer picture of the geological and hydrogeological structure of the site.

With regard to piezometers, it is prescribed the installation of at least one piezometer for each aquifer under study: immediately upstream of the site, from a hydrogeological point of view, serving as a reference point for the assessment of the groundwater quality entering the area under investigation and immediately downstream, in the same way, to evaluate the characteristics of the groundwater as it exits the site boundaries.

Topographic survey - essential for the assessment of groundwater flow direction - and sampling campaigns with the relative analytical campaigns are the last and most important steps that lead to the formulation of a final conceptual model, which essentially represents the key to the implementation of the HHRA.

Being the following Chapter 4 focused on the practical application of the preliminary investigation plan concepts to the case study of Borgaro Torinese site, before introducing it and its results, in the next paragraph follows a brief description of the geological and hydrogeological framework of the plain area of the Province of Turin, including a definition of its aquifer systems – as reported in DD 63/A1600A of 7/03/2022.

3.2 Aquifer complexes

The previously mentioned Managerial Decree, corresponding to the update of the Cartography of the Base of the Superficial Aquifer (BAS), divides the Province of Turin in 2 distinct sectors: plain and alpine.

The former, where the investigated site of Borgaro Torinese is located, as previously described in Chapter 1, is mainly characterized by fluvial deposits with variable permeability; in contrast with the alpine sector which is instead composed of essentially impermeable rock formation, which can limit groundwater movement. [10]

As for the plan sector, or Turin lowlands, two main sedimentary deposits are present: alluvial deposits, mainly made of gravels, constitute the superficial aquifer and continental and marine deposits, prevalently silty-clayey, thus characterized by low permeability. Nonetheless, the presence of interbedded gravel and sand layers within these finer deposits enables localized groundwater flow.

From a geological perspective, Turin lowlands are structured into 5 main complexes – Superficial, Villafranchian, Pliocene, Marin Deposits, Christalline Substrate – which contribute, according to their own composition, to the region's hydrogeological structure.

The Superficial Complex is composed of continental deposits - fluvial and fluvioglacial sediments - primarily made up of gravels and sands with occasional silty-clayey interbeds with a relatively high permeability and constituting the Superficial Aquifer. This description aligns well with the geological setting of Borgaro Torinese study area.

The Villafranchian Complex consists of an alternance of fluvial sediment layers - generally coarse-grained and permeable (gravels and sands) - and lacustrine or palustrine deposits, which are usually fine-grained and impermeable (silty clays and clays); the presence of the latter impermeable layer can act as an effective barrier to groundwater flow, creating in this way favourable conditions that lead to the presence of confined aquifers.

Then, Pliocene Complex is mainly characterized by sands and clay. Due to its specific lithological features and the typical permeability, it is usually characterized by a high availability of water, mainly hosting confined aquifers.

Marine Deposits Complex, being composed of silty sediments with interbedded coarse detrital layers is essentially an impermeable complex; thus, even though the presence of coarse material has the potential to generate localized permeable layers, the overall structure has as a main feature the limitation of groundwater flow.

Lastly, Crystalline Substrate - not so far from the previous marine deposits in terms of behaviour – is mainly made of metamorphic and intrusive rocks, such as granites, gneiss, limestone; although locally characterized by permeable layers, it usually behaves as an impermeable complex.

Going back to the regulatory framework, the Managerial Decree also reports a definition of phreatic and confined aquifers, as established in the article 2 of Regional Law 22/1996, titled

'Research, Use and Protection of Groundwater'. This law also includes an important provision aimed at the protection of groundwater quality which see the prohibition of the construction of structures that allow communication between phreatic and confined aquifers located at different depths. [11]

The phreatic aquifer is the one directly related with the hydrographic network and fed by surface waters; it is found directly below the soil surface.

Beneath the phreatic aquifer lie the deep aquifer, which may be confined or semi-confined depending respectively on the presence of one or 2 impermeable formations (aquiclude) below and above the aforementioned aquifer. Main characteristics of deep groundwater are low flow and turnover rate and usually a higher quality compared to shallow aquifers.

Focusing on the specific case of Piedmont Region, thanks to the definition of the Base of the Superficial Aquifer, it was possible to actually collocate these 2 aquifer types in the subsoil space; the BAS basically reflects the end of the phreatic aquifer, that is where the impermeable layer placed at the top of the confined aquifer starts.

The latest available reconstruction dates back to the year 2022 and in this specific case the document of April 4, 2022 - was taken into account. It provides an updated mapping of the superficial aquifer base for Torino municipality, also covering a limited area of the nearby towns, among which Borgaro Torinese one.

The new dataset produced, consisting of BAS isolines, was obtained by collecting stratigraphic data from a total of 20 surveys characterized by a depth higher than 25 meters and located in the nearby areas of the investigated site. Then, the point data obtained from this analysis were integrated with the pre-existing BAS surface dataset – the 2016 one – through an automatic interpolation process. To this end, a specific function of Arcgis software – named *Topo to Raster* – was performed allowing in this way the interpolation of surface data with point data.

The new resulting isoline, generated as the output of the software, were then improved through a manual refinement to enhance the consistency with the local geological and hydrogeological conditions and the overall accuracy of the interpolation. [11]

The final results of the process, later provided in shapefile format on the Piedmont Geoportal, are showed in the figure below.

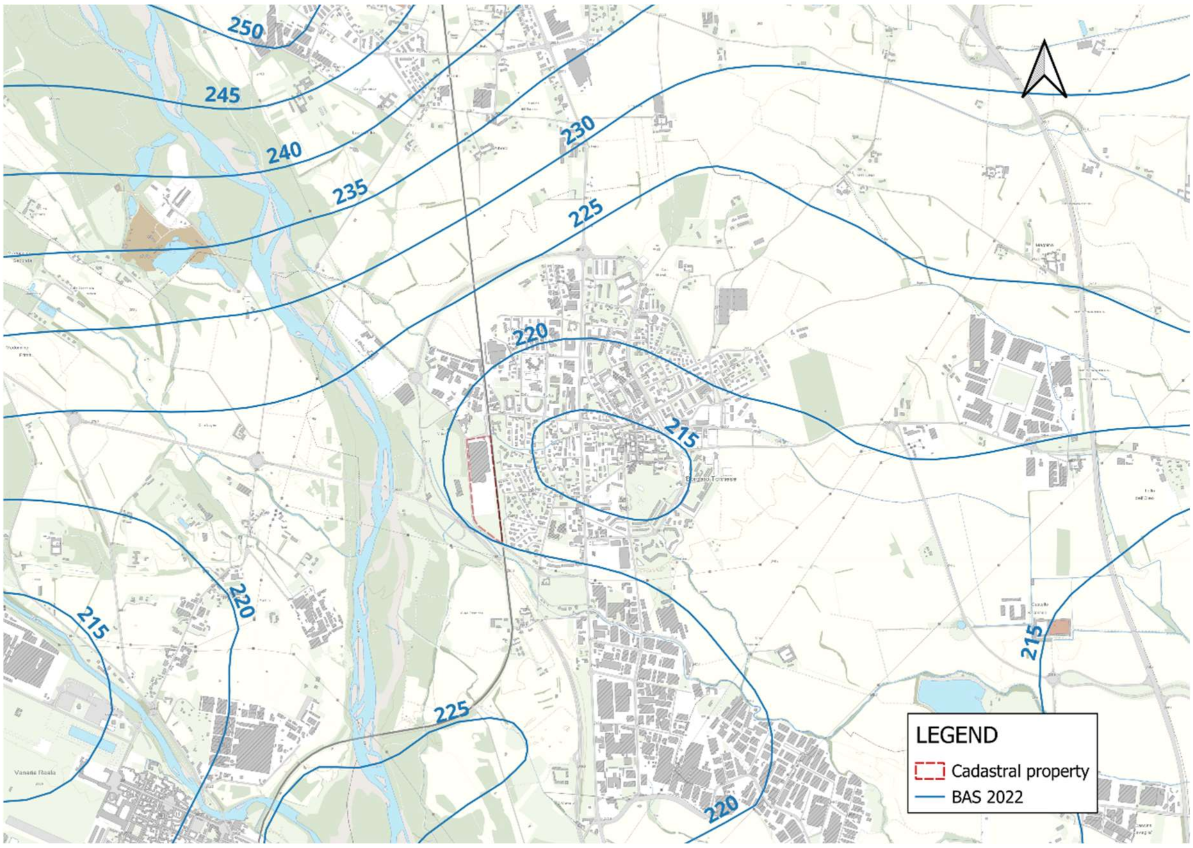


Figure 15. Base of the Shallow Aquifer Map [2]

The blue contour lines, shown on the map, represent how the aquifer base elevation varies throughout the subsoil space; a specific depth level is assigned to each line and, as illustrated in Figure 15Figure 15. Base of the Shallow Aquifer Map [2], these levels decrease starting from northeast and going toward southeast.

As for Borgaro Torinese area, and more specifically for the investigated site, it is clearly visible a change of the flow direction trend, which is more oriented toward the east, and of the hydraulic gradient which appears to be lower compared to the surrounding areas.

Additionally, the presence of the closed loop at the 215 meters elevation line, located near the central area of the municipality, suggests a local depression in the aquifer base.

This variation in both orientation and gradient, could be caused by the presence of a localized stratigraphic structure different from the adjacent subsurface areas.

A more detailed description of this stratigraphy is analyzed later in Paragraph 5.1.

In fact, knowing that the base elevation of the shallow aquifer is placed at a value of 220 meters below the ground level in the vicinity of the site - thanks to the updated map – and knowing both the value of the piezometric surface and topographic elevation of the well at which the measurements were taken, it was possible to reach a clearer understanding of the structure of the shallow aquifer and its thickness. Specifically, by subtracting the aquifer base elevation to ground level quota and to the piezometric level, it was possible to obtain respectively the total and the saturated thickness of the shallow aquifer.

4 Methodologies

This chapter outlines the various phases that have contributed to the development of this thesis project.
First, the procedures adopted for the decommissioning of the 10 wells, in accordance with the prescriptions set out in Phase 2 of the remediation plan, are provided; this activity included the removal of both historical wells - deemed obsolete and no longer reliable - and the well that needed to be dismantled because located within the footprint of a planned new industrial shed.
Subsequently, a topographic survey was conducted using an Emlid GNSS receiver to acquire the planimetric and altimetric coordinates of the remaining 19 wells. The resulting plano – altimetric map is provided in the Appendix to the thesis.
Once the GPS data had been collected, they were integrated with information from the Geotechnical and Geophysical Database of the Piedmont Geoportal, allowing for a comprehensive overview of all the surveys carried out both within and around the project site. Based on this dataset, two stratigraphic correlation sections were developed — one oriented West-East and the other North-South. These sections aim to reconstruct a realistic stratigraphy framework of the Borgaro Torinese area, with a particular focus on the site under investigation. The stratigraphic configuration details are then discussed in Chapter 5.
The chapter continues with the description of two piezometric surveys, conducted on April 7 and July 9, 2025, respectively. The results coming from the second survey, which involved nearly the entire network, are considered more reliable than the one from the first survey which was limited to a smaller subset of 13 wells, due to the temporary inaccessibility of the others.
As part of the hydrogeological characterization, a video inspection was also carried out during the second campaign. This inspection confirmed and, in some cases, integrated the the available well screen data derived from previous site remediation plans.
Finally, last chapter provides an overview of the main functionalities of the Surfer software, along with a step-by-step description of the development of the groundwater flow model. As with the stratigraphic analysis, the outcomes of this modelling activity are presented and discussed in the following Chapter 5.

4.1 Wells dismission

As already highlighted in Subparagraph 2.4.2, the first update of the remediation project in 2020 saw the proposal of closure of the historical piezometers – P0, P1, P2, P3, P4 - as they were no longer considered reliable for an accurate piezometric reconstruction of the site, due to several discrepancies related both to piezometric and analytical data; together with the above mentioned wells, 5 other piezometers - P10, P10bis, P14, P16, and P17 – were also proposed for dismission at the request of the property owner, as they were located within the footprint of a planned new building.

This dismission, proposed in 2020 as part of the Phase 2 of the remediation plan, was approved only between July and August 2023 by both the Metropolitan City of Turin and ARPA and was carried out 2 years later, during the summer of 2025.

As notified by the Metropolitan City, the "Guidelines for the closure and reconditioning of wells" - a technical protocol recognized at the national level, specifically by Determination no. 539 dated 03/12/2015 by the Piedmont Region – had to be followed. In particular, for the closure of old wells used for monitoring purposes in environmentally sensitive areas, it was prescribed the application of the method labeled with the lowercase letter "b", which, as discussed later, is associated to a specific filling material – either concrete or cementitious grout - of the borehole during its closure process.

Among the three well types analyzed by the guidelines – shallow wells (A), non-mixing deep wells (B), mixing deep wells (C) – each associated to a different dismission method, all the 10 wells fell within the shallow aquifer category, thus they were all dismissed following **methodology 1A_b**.

According to the requirements [12], the method consists of 2 main executive phases: well column filling (b) and realization of a concrete cap.

For the former, the well must be filled through concrete up to 0.25 m below ground level (b.g.l.), using a volume of the filling material at least equal to the total volume of the well column. Furthermore, the filling should occur through the use of a pipe, brought in a continuous motion from the bottom to the upper part of the borehole and not by gravity.

The second phase was divided in 3 further steps, represented in Figure 16:

1. excavation around the well until reaching, where possible, a diameter which is twice that of the well casing;
2. removal of at least 0,25 m of the original casing, starting from ground level;
3. filling of the excavated volume (ref. point 1) with concrete.

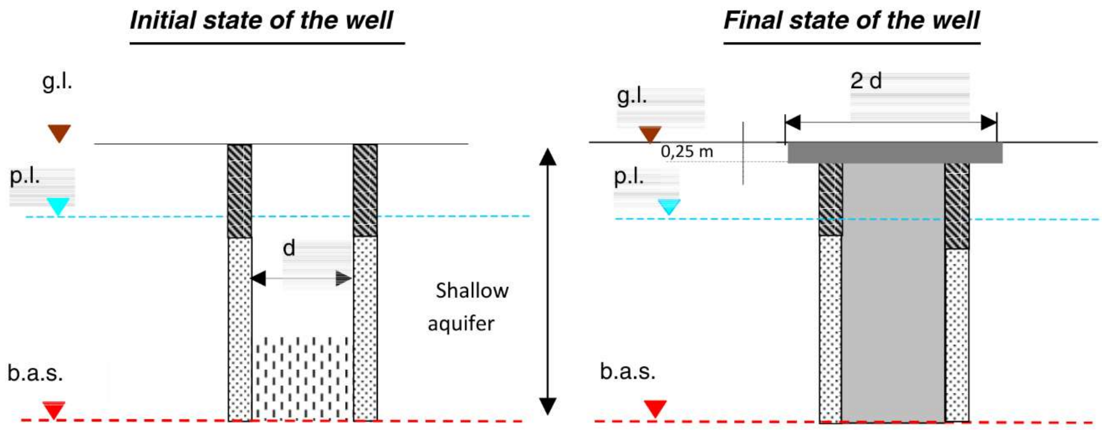


Figure 16. Decommissioning methodology 1A_b for shallow wells in environmentally sensitive areas. [12]

In the following Figure 17, the closure of piezometers P2 and P14 is shown representatively. In particular, the image on the left illustrates the first two stages described before - excavation and partial removal of the piping - while the image on the right shows the closure performed after concrete filling the excavated volume.


Figure 17. Closure of P2 – above – and P14 – below - piezometers

4.2 Topographic survey

Regarding the georeferencing of the wells, all the measurements were carried out using a RTK GNSS receiver - Emlid Reach RS3 - equipped with a 1.534 meters high antenna.

This setup ensured centimeter-accurate output and allowed for the performance of tilt compensation and geoid correction, both, in different ways, ensuring more accurate elevation values. The former allowing GNSS receiver to correct for pole tilt, without requiring bubble leveling, while the geoid correction converts raw GNSS ellipsoidal heights Z – height above the reference ellipsoid, WGS 84 geodetic datum - into orthometric height z – height above mean sea level, based on the geoid - taking into account the local geoid undulation N.

Being both provided, the ellipsoidal eight and the elevation, the geoid undulation N was calculated as $N = Z - z$, which, in this case, for the northern part of Italy, stood at around 50 meters.

Figure 18. GPS survey on July 9, 2025.

As showed in Table 12, both the ground level and the wellhead height were measured, in order to obtain the height of the well above the ground.

Table 12. Wellhead and ground level quota

Name	Wellhead z_t (m)	Ground level z_s (m)	Height above ground (m)
P13	252.627	252.397	0.23
PC4a	252.645	252.225	0.42
PC4b	252.572	252.232	0.34
P12	253.701	253.391	0.31
PC5a	254.047	253.627	0.42
PC5b	254.057	253.677	0.38
P11	254.026	253.756	0.27
P6	258.82	258.56	0.26
PC2a	258.615	258.615	-
PC2b	258.657	258.657	-
P5	258.81	258.51	0.3
PC1a	258.779	258.779	-
PC1b	258.768	258.768	-
P7	259.152	258.872	0.28
PC3a	256.159	256.159	-
PC3b	256.158	256.158	-
P9	256.837	256.567	0.27
P8	256.93	256.82	0.11
P10	257.337	257.017	0.32
P10bis	257.237	257.007	0.23

As for the coordinates, they were both provided in cartographic coordinates, Easting and Northing expressed in meters and used later as input data for both QGIS and Surfer and geographic coordinates, Longitude and Latitude, reported in Table 13.

Table 13. Cartographic (E, N) and geographic (Long., Lat.) coordinates

Well	Easting (m)	Northing (m)	Longitude (°)	Latitude (°)
P13	393823.364	5000119.377	7.64939407	45.14656516
PC4a	393830.571	5000115.594	7.64948653	45.14653221
PC4b	393830.234	5000114.748	7.64948242	45.14652454
P12	393832.347	5000174.745	7.64949654	45.14706479
PC5a	393782.379	5000148.2	7.64886675	45.14681839
PC5b	393782.279	5000148.814	7.64886535	45.14682389
P11	393757.898	5000165.628	7.64855172	45.14697154
P6	393751.063	5000601.317	7.64837212	45.15089136
PC2a	393727.648	5000598.597	7.64807491	45.15086335
PC2b	393728.431	5000598.615	7.64808487	45.15086363
P5	393690.008	5000589.698	7.64759811	45.1507776
PC1a	393797.397	5000610.856	7.64895935	45.15098417
PC1b	393797.510	5000612.123	7.64896052	45.15099559
P7	393798.898	5000609.656	7.64897870	45.1509736
PC3a	393736.552	5000227.518	7.64826710	45.14752529
PC3b	393737.612	5000227.840	7.64828051	45.14752835
P9	393724.988	5000279.740	7.64810892	45.1479935
P8	393719.056	5000329.651	7.64802287	45.14844176

4.3 Stratigraphy

Given the availability of the site borehole stratigraphic logs perforated through core drilling, collected over a span of 10 years, a stratigraphic correlation was developed by comparing them with those from boreholes located in the surrounding area, allowing for a broader scale interpretation. The latter external data were obtained from the Geotechnical and Geophysical Database of the Geoportal of Piedmont, subsystem of SIGeo (the Geological Information System of Piedmont), managed by ARPA Piemonte. [2]

The figure below, generated using QGIS, shows all the boreholes and wells located in the vicinity of the site of interest, together with the Base Map of Piedmont Region. Different symbols identify different boreholes, specifically: red and green squares represent, respectively, surveys and boreholes retrieved from the Geoportal, while the blue Xs indicate the wells constructed within the site as part of the remediation activities.

The 2 stratigraphic correlations proposed later in Chapter 5, are based on cross-sections of non-aligned boreholes, which, as showed in Figure 19, follows the 2 black dash-dot lines.

The choice of the 2 section lines oriented along 2 main directions - North - South and West – East - was based on the idea to include the largest possible number of wells located outside the site boundaries. This approach aimed to provide a broader understanding of the stratigraphic trends at a larger spatial scale.

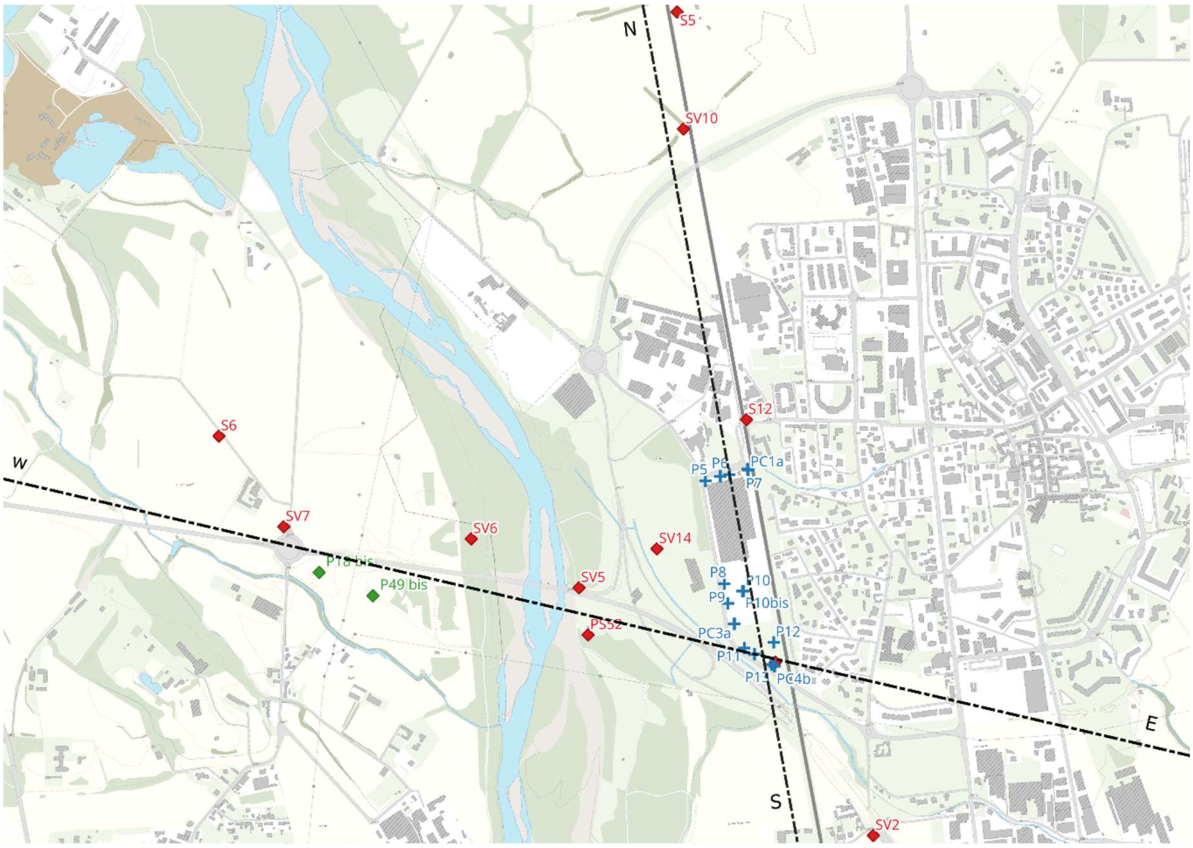


Figure 19. N-S and W-E stratigraphic cross-section.

Based on the available stratigraphic logs, only some of the totality of the surveys and wells were taken into account along the N – S direction – S5, SV10, S12, PC1, P10, PC5, SV3, PC4 – and along the W – E direction – SV7, P18 bis, P49 bis, SV6, SV5, PS52, PC5, SV3, PC4 – allowing to obtain a complete framework of the sub-soil composition. The results and the proposed correlation are discussed later in Chapter 5.

4.4 Piezometric survey

As previously mentioned, a core section of a Characterization plan is represented by the reconstruction of the groundwater surface configuration, which is typically carried out through piezometric level measurements. This process allows to the definition of groundwater flow direction, hydraulic gradient and the aquifer thickness as well. In the context of a contaminated site, such analysis is essential for a better understanding of the contaminants distribution within the subsoil and is therefore a key element for the development of a targeted intervention and mitigation strategy.

To this end, two piezometric surveys were conducted on April 7 and July 9. The depth to water table measurements obtained during these surveys were used to calculate the piezometric level, defined as the water level reached inside a piezometer, which is a small-diameter well used for groundwater monitoring, opened at the top and equipped with short screened sections at lower end to allow water to enter from the aquifer of interest. By calculating this level in different points, it is possible to obtain a potentiometric surface – surface representing the piezometric level – which, in the case of unconfined aquifer, as in this study, coincides with the water table. [1].

In this analysis, the hydraulic head was determined by measuring the depth to water table within the available site piezometers.

Specifically, a water level meter, showed in Figure 20, was used to carry out the water level measurements; it essentially consists of a meter which emits an acoustic signal upon reaching the water surface.

Figure 20. Depth to water level measurements using a water level meter (left) and well video-inspection (right).

As can be seen in the figure above, each subsidence measurement was taken with respect to the wellhead elevation; then, according to this method, coherent with the past years campaigns - see Eq. () - the hydraulic head was calculated as the difference between the elevation of the measuring point at the wellhead z_t (Table 12Table 12) and the depth to water table h_w measured in the piezometers.

The results are reported in Table 14 and Table 15.

Table 14. April 7 survey.

Name	Depth to water table h_w (m)	Piezometric level *h* (m)
PC4a	5.94	246.705
PC4b	3.92	248.652
PC5a	6.8	247.247
PC5b	4.96	249.097
P11	4.65	249.376
P12	4.75	248.951
P7	8.85	250.302
P6	8.4	250.42
PC2b	6.1	252.557
P9	6.05	250.787
P8	6.34	250.59
PC1a	10.22	248.559
PC1b	6.48	252.288

Table 15. July 9 survey.

Name	Depth to water table h_p (m)	Piezometric level *h* (m)
P13	4.72	247.907
PC4a	5.68	246.965
PC4b	3.75	248.822
P12	4.51	249.191
PC5a	5.43	248.617
PC5b	4.71	249.347
P11	4.41	251,216
P6	8.14	250.68
PC2a	9.78	248.835
PC2b	6.1	252.557
P5	6.21	252.6
PC1a	9.38	249.399
PC1b	6.27	250.498
P7	8.41	250.742
PC3a	8.62	247.539
PC3b	5.63	250.528
P9	5.7	251.137
P8	6.03	250.9

Together with the depth to water table measurements, as showed in Figure 20 on the right, a video inspection of the wells was carried out as direct investigative method that enabled real-time visual evaluation of the well's condition through the use of a camera and, in some cases assessment of the well screens depth – as for the value reported in Table 16 - of their preservation state and the casing pipes one. [12]

Table 16. Well screens data.

Name	Well screens (m)
PC1a	18.8 - 23.9
PC1b	5.1 - 16.9
PC2b	6.0 - 15.6
P6	9.05 - 18
P7	9.1 - 19.9
P8	9.1 - 16.72
P9	8.97 - 18.6
P11	3.3 - 13.5
P12	3.1 - 12.8
PC4a	18.3 - 23.6
PC4b	3.3 – 13.2
PC5a	18.9 - 23
PC5b	3.2 - 13

4.5 Surfer

In this thesis, Surfer was employed as a tool for numerical modeling and spatial data processing, enabling the reconstruction of the piezometric surface of the site.
Surfer is in fact a specialized software used for the visualization and analysis of geospatial data, widely adopted in geotechnical, geological, and environmental applications to support numerical modeling processes. These processes involve the mathematical and computational representation of physical phenomena, using measured data and interpolation algorithms to simulate and predict the spatial and temporal behavior of environmental variables and subsurface properties.
The software enables the creation of continuous surfaces and three-dimensional models from discrete datasets, employing advanced spatial interpolation techniques such as Kriging, Inverse Distance Weighting (IDW), and Minimum Curvature. In this study, Kriging method was used. These numerical models are crucial for analyzing and predicting the distribution of stratigraphic, hydrogeological, and geotechnical features, including permeability, soil stratification, piezometric levels, and other physical characteristics.
Surfer allows for the generation of contour maps and 3D surfaces that visually represent the spatial variability of the investigated properties, facilitating the interpretation of complex subsurface phenomena. Furthermore, it supports the calibration of advanced numerical models by providing accurate input parameters and graphical outputs that can be used in more complex simulations, such as groundwater flow modeling, slope stability analysis, and contaminant transport. [13]
In the following subchapters, the main steps that led to the reconstruction of the groundwater flow model are briefly described following this sequence: Post Map, Gridding Data, Contour Map and Vector Layer.

4.5.1 Post Map

Prior to the import of a Post Map, the georeferenced BDTRE 2025 – topographic reference map in Italy, containing detailed geographic and territorial data – obtained from the Piedmont Geoportal, was set as a Base Map.
Then, through the cartographic coordinates, it was possible to create the Post Map, which allowed the visualization of the spatial distribution of the point data, previously measured as discussed in Paragraph 4.3. As for the reference coordinate system, the selected one was **WGS 84 UTM zone 32N**, a projected coordinate system based on the WGS 84 geodetic datum, using

the Universal Transverse Mercator (UTM) projection for zone 32 in the northern hemisphere. This system is commonly used for mapping and GPS data in northern Italy, its coordinates are expressed in meters (E, N) and it is marked by EPSG (European Petroleum Survey Group) code number 32632

The complete dataset of piezometers used during this analysis is showed in the following Figure 21.

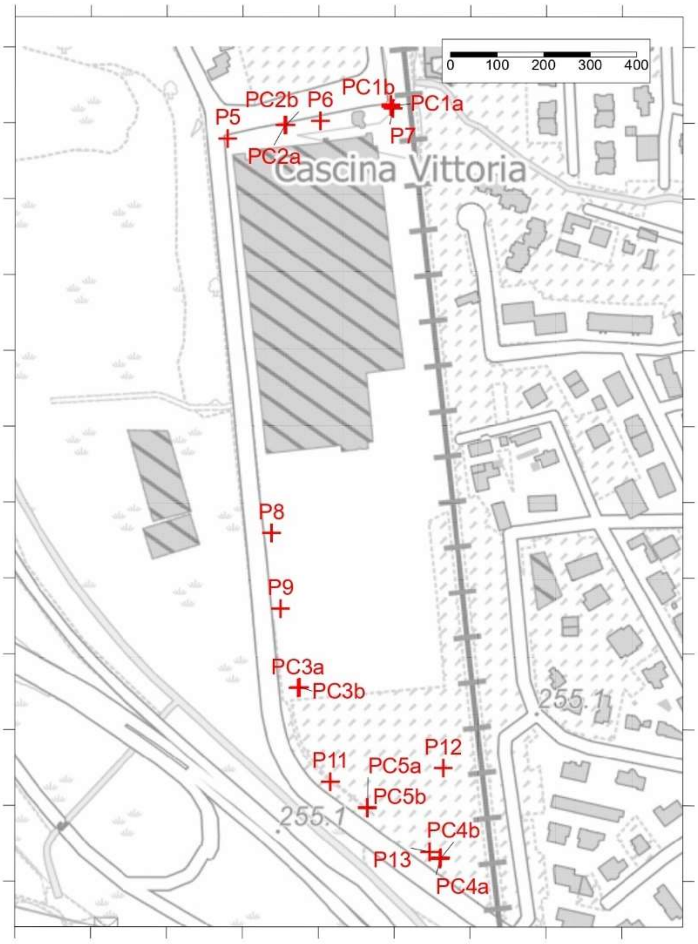


Figure 21. 9 July survey – Surfer.

4.5.2 Gridding Data

To create a piezometric surface, the piezometric levels, registered in correspondence with the 2 measuring campaigns, were associated to the previous point data.

Grid command was used for reconstructing the piezometric surface, and so the spatial distribution of the groundwater hydraulic head or water table elevation across the study area. This operation is carried out through the interpolation of discrete point data to generate continuous surfaces and enabling comprehensive spatial analysis and visualization of groundwater conditions; the choice of interpolation method depends on the spatial distribution of data points and the desired accuracy or smoothness of the resulting surface.

In this case, **Kriging method** was used; it is based on the trends of the uploaded data, from which it extrapolates information for the areas of no data, sometimes resulting in minimum and maximum Z values in the grid which are not actually present in the original data file.

Prior to the visualization of the map, in addition to the gridding methods, another important setting is represented by the adjustment of the spacing between the lines of the grid - related to the grid cell size - which, as a consequence, can be considered responsible for the total smoothness and accuracy level of the Grid Map. Specifically, it is possible to vary 2 parameters which are directly linked to each other: Spacing and # of Nodes.

The former corresponds to the size of the grid cells, that is the spacing between the grid lines – in both X and Y directions - while the latter is the number of grid lines, made of points (nodes) where the interpolated values are calculated. In this way, the smaller the Spacing, the higher the # of Nodes and, as a consequence, the higher the resolution of the resulting map. However, higher resolutions also mean longer processing times and larger file sizes, so it's important to find the right balance between having enough detail and keeping the processing time manageable.

In this specific case, a number of 100 nodes in the Y direction was used, resulting is a grid file - representing the interpolated piezometric surface as a matrix of regularly spaced cells, each containing a calculated Z-value, in this specific case the piezometric level - characterized by the following parameters:

- Grid Size: 100 rows x 24 columns
- Total Nodes:2400
- X Spacing: 4.93
- Y Spacing: 5.02

The gridded piezometric surface, realized to identify groundwater flow directions (from high to low piezometric values) and evaluate temporal changes in the aquifer system by comparing datasets from different times, was then used to visualize a contour map.

4.5.3 Contour Map

The Contour Map is the graphical representation of the spatial interpolated data in the previous grid, where lines, known as contour lines, connects all the points of equal values across the surface, allowing for an intuitive interpretation of spatial trends, creating, in this case, what is also called potentiometric map. This last one also provides information on the direction of groundwater flow through fictitious lines which represent the water particles flow within an aquifer. [1]

As for the direction of groundwater flow, it can be directly related to the hydraulic gradient, which, as defined in (2) is the variation of hydraulic head per unit of horizontal distance.

In fact, groundwater flowing from point at higher hydraulic head to point at lower one, moves in a direction perpendicular to the contours of the piezometric surface. Therefore, by analyzing the slope of the potentiometric surface, it is possible to infer both the direction and the relative magnitude of groundwater flow.

As for the different spacing between the equipotential lines, the lines characterized by a close spacing have a higher hydraulic gradient than the one characterized by a wider one, being set, by convention, a constant hydraulic head contour interval. [1]

In the end, a Vector Layer was created to display the direction of the groundwater flow.

5 Results

To overcome the uncertainty relative to the subsoil compositions and distribution of shallow and deep aquifer, several stratigraphic logs, located both within the site and in the surrounding area – within approximately 1 km – were analysed and compared.

Correlation lines were drawn to connect layers of equal composition, in order to establish a clearer and more realistic stratigraphic framework., thus reducing the degree of uncertainty in the conceptual site model.

The second part of the analysis focuses on the development of the groundwater flow model, produced with Surfer software and based on the data collected during two piezometric monitoring campaigns, conducted in April and July. Comparison of the two campaigns allowed the identification of a potential seasonal trend, while the analysis of each individual campaign provided a detailed representation of the hydraulic head distribution and flow directions across the site.

5.1 Stratigraphic framework

As already discussed in Paragraph 3.2, Borgaro Torinese geological setting falls within the Superficial Complex, composed of fluvial and fluvioglacial sediments.

Initially, the stratigraphic log data, extracted from the Geotechnical database of Arpa Geoportal and obtained from surveys conducted in different years (ref. Appendix), were standardized in terms of composition. The subsurface materials are essentially composed of: scattered boulders, gravels, sands, and silty – clay matrix, resulting in high permeability framework interbedded with layers of relatively lower permeability.

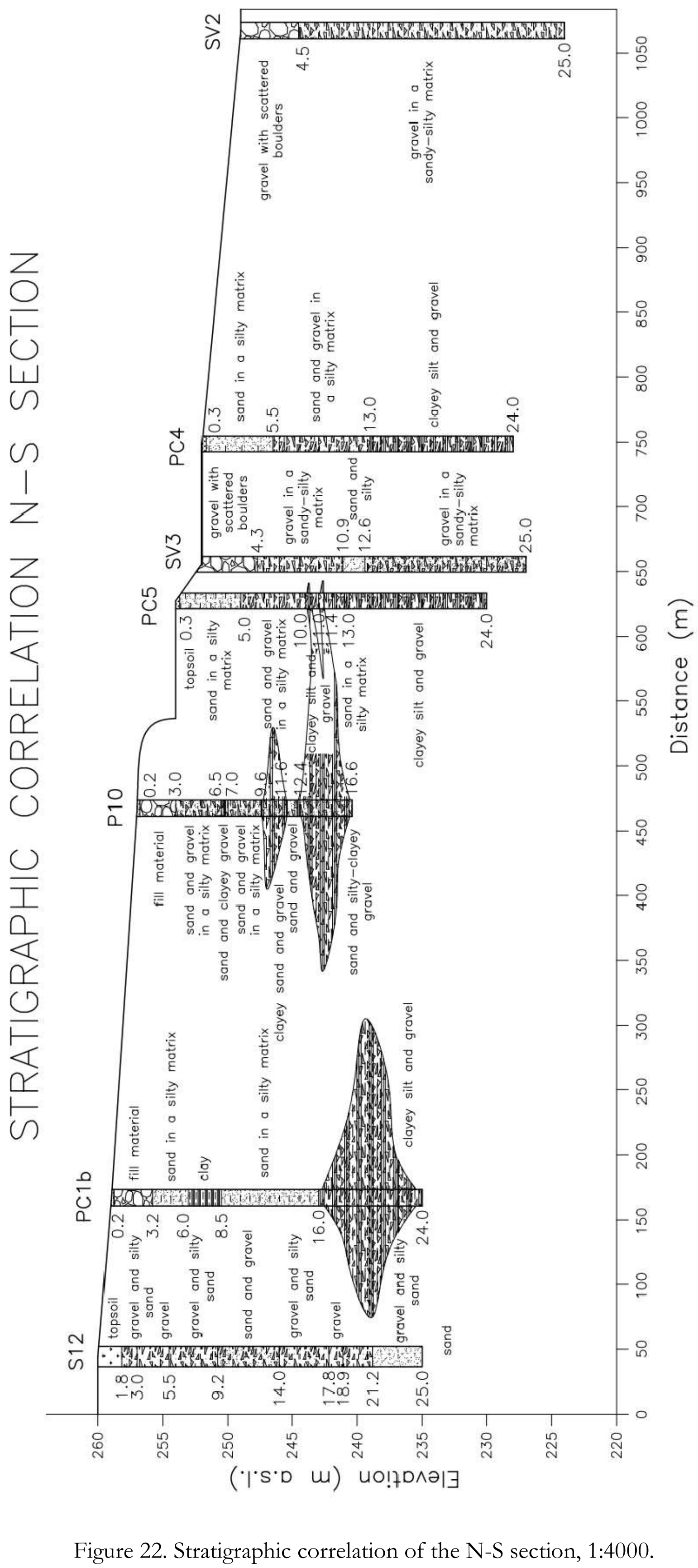
Specifically, 2 cross-sections were realized, as showed in Figure 19, proposing a correlation between 7 logs in the N – S direction – S12, PC1, P10, PC5b, SV3, PC4b, SV2 – and 9 logs along the W – E direction – SV7, P18 bis, P49 bis, SV6, SV5, PS52, PC5, SV3, PC4.

To support this analysis, the base elevation of the superficial aquifer and the ground surface elevation were considered, respectively from the managerial Decree DD 63/A1600A of 2022 - updating the Cartography of the Base of the Superficial Aquifer (BAS) - and from the topographic survey conducted in April. By comparing the BAS to the site stratigraphic sections, a more reliable subsoil configuration was proposed.

As for the 2 sections, while the N-S one primarily concerns the on-site piezometers installed over a period of 25 years, as part of the remediation plan, the W-E provides a broader-scale view of the subsoil, including data from external surveys and only 2 of the piezometers realized during the remediation plan – i.e. PC5 and PC4.
As specified in the following figures, almost all the boreholes taken into account are not aligned along the section axis; thus, the 2 correlations are to be considered both qualitative and interpretative.
In the following paragraphs, the 2 section are described separately.

5.1.1 N-S section

For the N-S section, 2 different horizontal and vertical scales were chosen to allow a clearer representation of the stratigraphic logs of the wells: the horizontal scale corresponds to the real scale, while a vertical exaggeration of 10:1 was applied.
This section covers the entire vertical extent of the site, as well as small northern and southern portion beyond its boundaries. For representation purposes, SV2 was slightly shifted northward from its original position, resulting in a total section length of slightly more than 1 km.
The general stratigraphic trend is based on the presence of gravel mixed with sand with a predominantly silty matrix. Then, at around 16 meters below the ground level of the central area of the site (259-257 m a.s.l.), corresponding to around 13 meters from the lowered southern wooded area (254-252 m a.s.l.), a clayey horizon was identified from the on-site piezometers, interbedded with silt and gravel, generally between 230-240 m a.s.l.
In previous analyses conducted within the framework of the remediation plan, this horizon was interpreted as the separation between the shallow and deep aquifers. However, comparison with the base of the superficial aquifer and external stratigraphic log data, suggests that this interpretation may not be entirely reliable.
Indeed, the aforementioned clayey layers do not appear continuous, neither in the nearby SV3 survey nor in the more distant SV2, whose composition instead better corresponds to the general gravel-sand-silty matrix of the site.
Further supporting to this observation, the base of the shallow aquifer showed in Figure 15, where the contour lines represent the topographic elevation of the shallow aquifer base – or, in other words, the top of the underlying impermeable formation that contains the deep aquifer - indicates that. in the area surrounding the site, the aquifer base corresponds to approximately 220 m a.s.l. or lower, which is 15–20 meters below the depth of the analysed piezometers.



N.B. The stratigraphic section is based on boreholes that are not aligned along the section axis; stratigraphic correlations are therefore qualitative and interpretative.

Figure 22. Stratigraphic correlation of the N-S section, 1:4000.

5.1.2 W-E section

The W-E section includes, as already mentioned, only 2 on-site piezometers, while the remaining data were obtained from external surveys and wells. As a consequence, while the previous section was more related to the small-scale stratigraphic composition of the site, the W-E section provides a larger-scale view, offering a clearer understanding of the subsoil in the surrounding areas, particularly near the Stura di Lanzo stream.

This section covers a greater spatial extent than the N–S section - approximately 1.3 km - and includes deeper stratigraphic logs, with a maximum investigated depth of 85 meters in the P49 bis well – although characterized by a total depth of 307 meters, for the purposes of this analysis it was unnecessary to consider elevations below approximately 200 m a.s.l.. Consequently, the representation scales were adjusted: the horizontal scale was maintained, as before, at 1:1, while the vertical scale was represented with a 4:1 exaggeration.

Consistent with observations from the N–S section the stratigraphy is dominated by gravel within a sandy-silty matrix with thin clay layers, mainly between 240 and 230 meters above sea level. Moreover, thanks to the deeper surveys P18bis and P49bis and well PS52, it was possible to confirm the correspondence of the base of the shallow aquifer with a continuous and consistent layer of clay. This layer can thus be considered the bottom of the shallow aquifer. Since it lies approximately 10 to 15 meters below the maximum depth of the piezometers installed on site – as showed at the extreme right of the section – it can be assumed that the current piezometers, with a maximum depth of 25 meters below ground level, do not provide hydraulic communication between the phreatic and the confined aquifer.

This W-E section, together with a detail view of the southern area of the site are represented in the following Figure 23 and Figure 24.

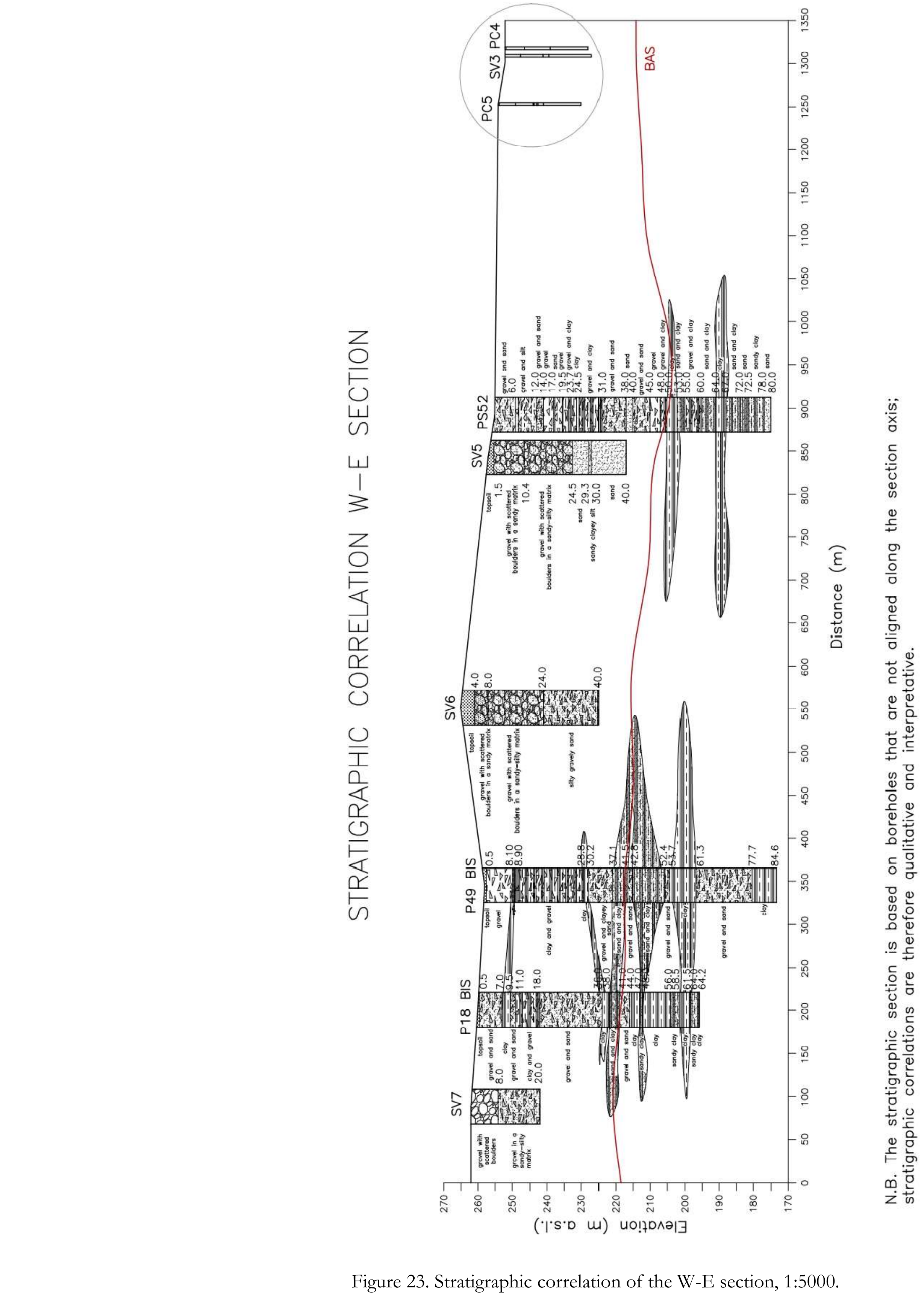


Figure 23. Stratigraphic correlation of the W-E section, 1:5000.

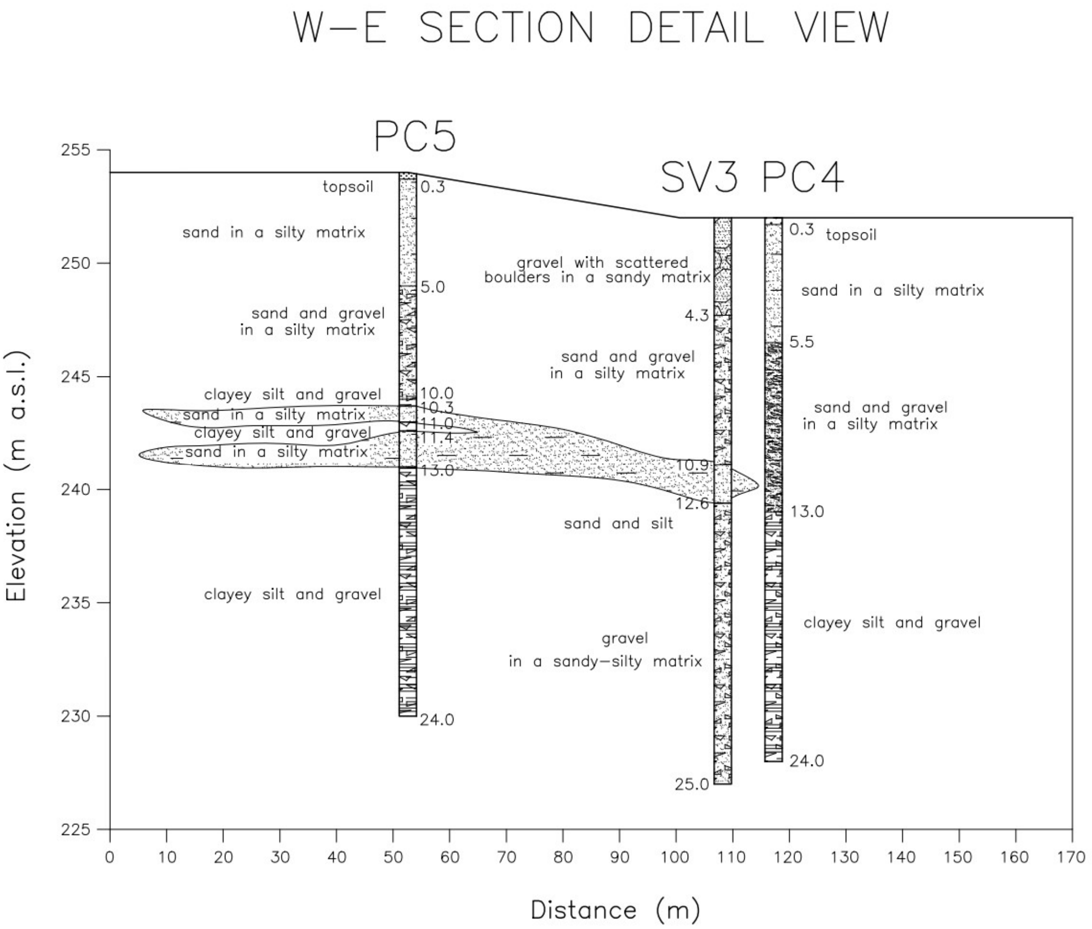


Figure 24. Detail view of the W-E section

As showed in Figure 19, in the southern area of the site and near the wells represented in the section above, piezometers P11, P12, P13 are located. Although detailed stratigraphic data for these piezometers are not available and thus, they were not represented in the section, previous documents suggested a sandy gravel horizon in a silty matrix at around 245 m a.s.l. and some sandy-clayey layers with lower permeability between 230-240 meters a.s.l, interbedded with gravel, configuration coherent with the well logs in Figure 24.

In light of these observations, the final interpretation is that, consistent with the characteristics of the Superficial Complex in the Borgaro Torinese area, the subsoil, within the depth range investigated by the site piezometers, is predominantly composed of gravels and sands with occasional silty-clayey interbeds, resulting in generally high permeability with some localized lower-permeability layers. Consequently, potential hydraulic interference between the shallow and deep aquifers may be reasonably excluded.

5.2 Groundwater Flow Model

In line with the authorities' requests to clarify the site's conceptual model, particularly following the closure of historical piezometers, a groundwater flow model was developed. Following the framework established by previous piezometric monitoring campaigns, two distinct groundwater flow models were developed: one concerning the piezometers associated with the deep aquifer, which are the 5 cluster piezometers screened between 15 and 24 meters – PC(1-5)a - and another concerning those related to the shallow aquifer, corresponding to clusters screened at shallower depths, up to a maximum of 15 meters.

Moreover, since two measurement campaigns were conducted, an analysis of the temporal differences, in terms of hydraulic head and flow pattern, between April and July was also carried out, showed respectively in Figure 25 and Figure 26.

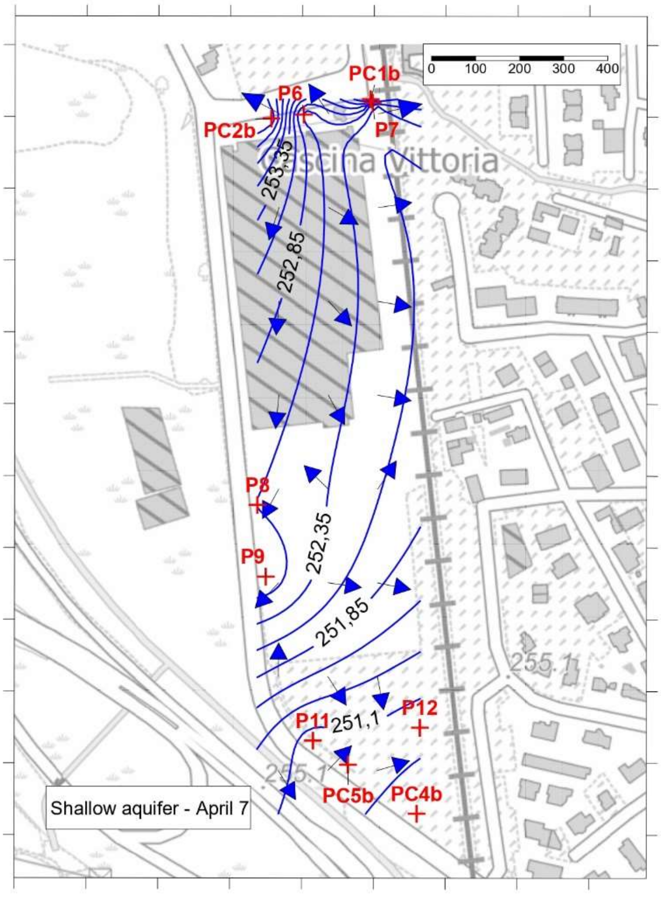


Figure 25. Groundwater flow model of the shallow aquifer – April 7 campaign.

As for the first measuring campaign conducted on April 7, the set of piezometers used to generate the groundwater flow model was made of the total 10 piezometers accessible at that date; this set included only 4 of the new cluster – PC1b, PC2b, PC4b, PC5b - screened between 3 and 15 meters, and 6 other piezometers realized during the years 2011-2013 – P6, P7, P8, P9, P11, P12. For this first dataset, the contour lines revealed a gradual decrease in piezometric head from the north-western part of the site - with a maximum value near PC2b - toward the south-eastern sector - with a minimum value around 249 meters a.s.l. at PC4b - delineating the main flow path. The overall hydraulic gradient ranges approximately from 254 to 250 meters above sea level.

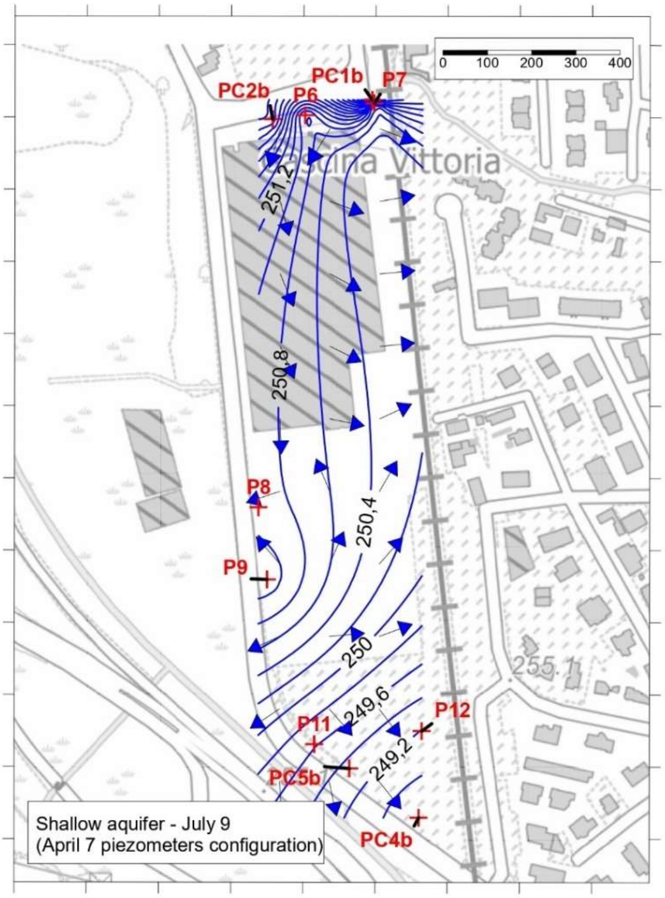


Figure 26. Groundwater flow model of the shallow aquifer – July 9, based on the piezometer's configuration of April 7 campaign.

For the purposes of enabling a direct comparison between the April and July piezometric maps, the piezometric surface reconstruction resulting from the July 9 campaign, was carried out using only the same set of piezometers that had been accessible during the July 7 campaign. The hydraulic heads recorded during this second campaign ranged from approximately 253 meters a.s.l. to 248 meters a.s.l.

From this comparison, the previously identified general NW – SE flow orientation was confirmed and a potential seasonal trend could also be inferred. Specifically, a slight overall decrease in groundwater levels from April to July was observed.

This variation is most likely linked to seasonal hydroclimatic factors, such as reduced precipitation, increased temperatures, higher evapotranspiration rates. Each of these terms contribute to limit aquifer recharge and enhance groundwater discharge.

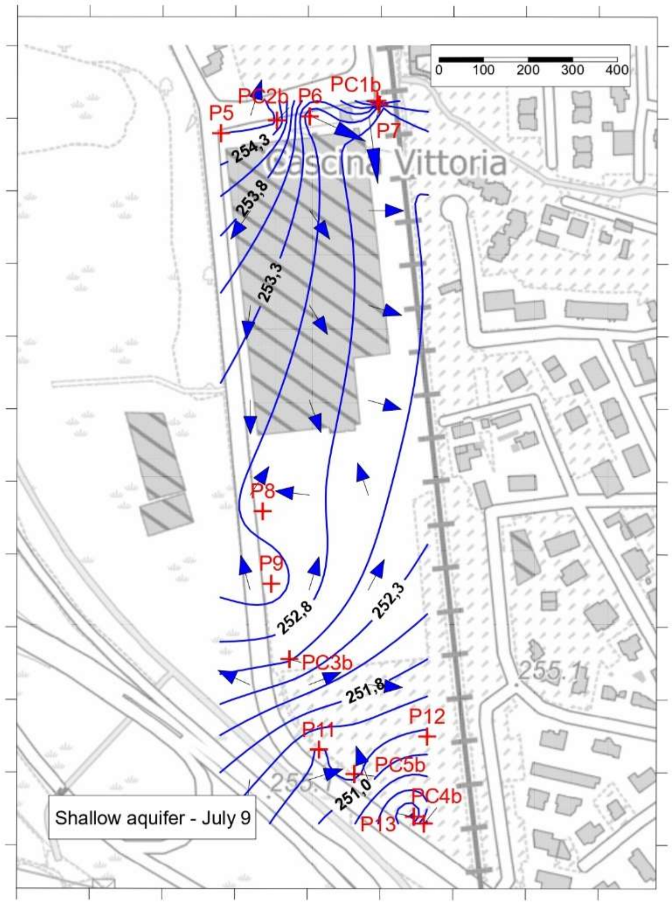


Figure 27. Groundwater flow model of the shallow aquifer – July 9 campaign.

The most complete configuration was achieved during the campaign of July 9, showed in Figure 27, when piezometric measurements were taken from the 13 available piezometers – PC(1-5)b, P5, P6, P7, P8, P9, P11, P12, P13. Again, the reconstructed flow model confirmed the general NW–SE orientation observed in the previous survey, with hydraulic heads ranging from approximately 254 to 249 meters. The highest heads were recorded at piezometers PC1b (254.5 m) and PC2b (252.6 m) in the northern part of the site, and at P8 (251 m) and P9 (251.1 m) in the western area, while the lower one in correspondence of PC4b and P13 in the southern part of the site, with values around 248-247 meters. The superficial aquifer, on the whole, appears to be characterized by a fairly uniform gradient of 0.8%. A deviation from this trend was detected in the central area of the site, likely attributable to the lack of sufficient data points in that zone. Moreover, the resulting trend suggests identifying the piezometers located to the north and west as hydrogeological upstream piezometers, while those to the south can be considered as downstream monitoring points. In this context, the absence of piezometers in the eastern area of the site, towards which the groundwater flow appears to be directed, does not allow for a complete assessment of the groundwater system, thus leaving the hydrogeological trend in the central area of the site unclear.

In this context, Figure 28, already discussed in Subparagraph 2.4.3, showing all the threshold exceedances of the contaminants identified on site, is reported below to allow an easier understanding of the hydrogeological position of the piezometers, which is essential for evaluating both inflow and outflow areas.

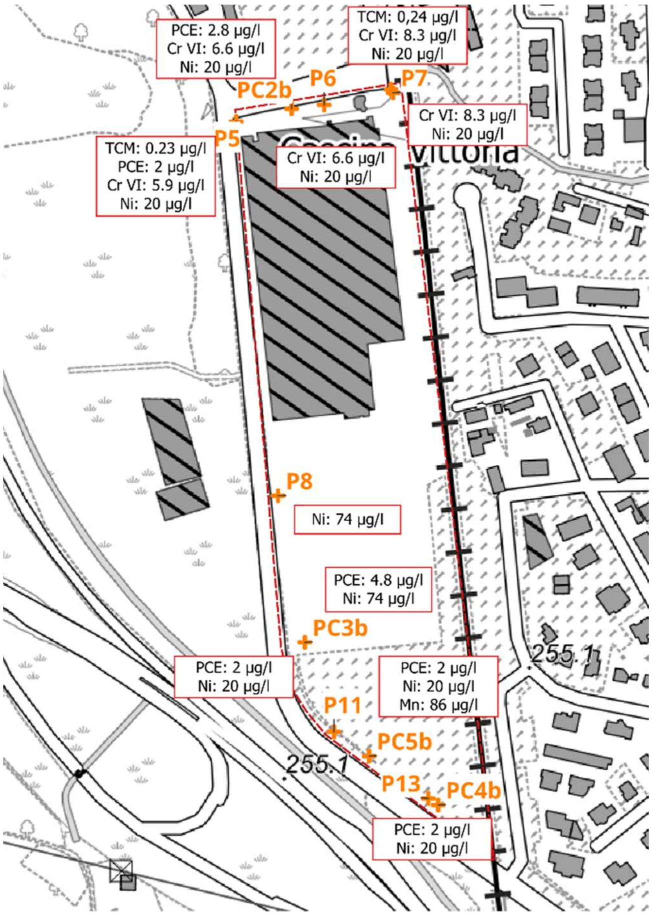


Figure 28. Reference to Figure 13. Shallow aquifer exceedances in 2023.

In fact, the interpretation of PC3b as an upstream piezometer is further supported by the fact that the highest concentrations of PCE and Ni were recorded at this point, followed by PC2b and P8; the latter only related to Nickel contamination. On the basis of these observations, the northwestern corner (PC2b) and probably the entire western boundary of the site can be considered as the hydrogeological inflow, with the flow directed eastwards in the upper and central sectors of the site, while assuming a more southward orientation in its lower sector.

Then, in order to confirm the effectiveness of the well decommissioning, the flow trend reconstructed in 2018, showed in Figure 29, which also relied on the historical piezometers, was used as a basis for comparison.

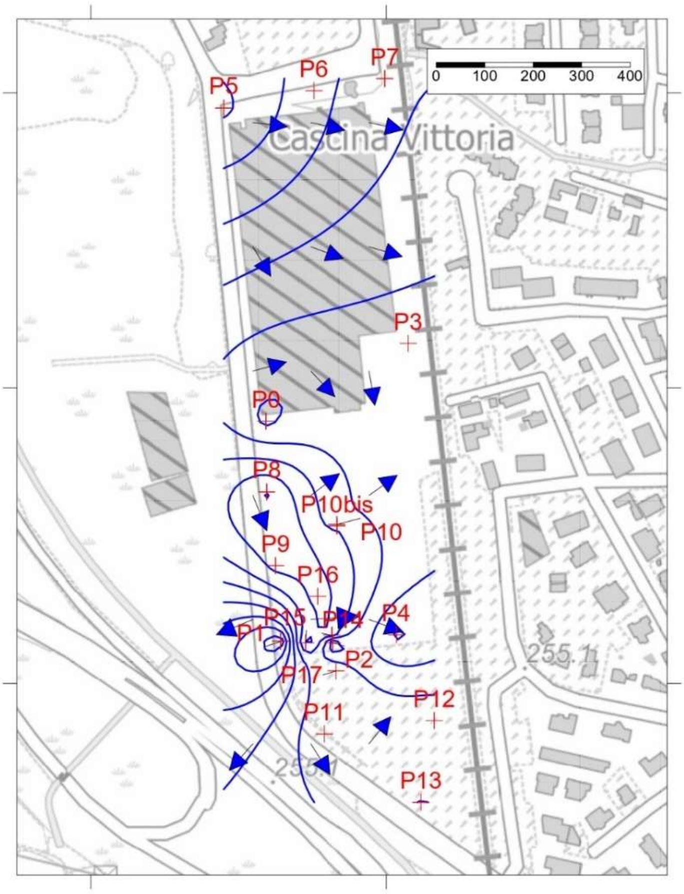


Figure 29. Reference to Figure 12. Piezometric Contour Map - 2018.

The previous trend was in fact characterized by punctual hydrogeological anomalies in the central area, possibly attributed to a drawdown effects of the shallow aquifer towards the underlying deep aquifer by the histroical piezometers, whose levels were generally lower than those observed in the new ones.

As for the clusters reaching greater depths, ranging between 15 and 24 meters, the following groundwater flow reconstructions were developed on the basis of the two monitoring campaigns. The first analysis conducted on April 7, in Figure 30, showed a groundwater flow directed from northwest to east-southeast, coherent with the previous ones, but characterized by hydraulic heads lower than in the previous cases, ranging between 250 and 248 meters a.s.l., with a uniform hydraulic gradient of approximately 0.4%.

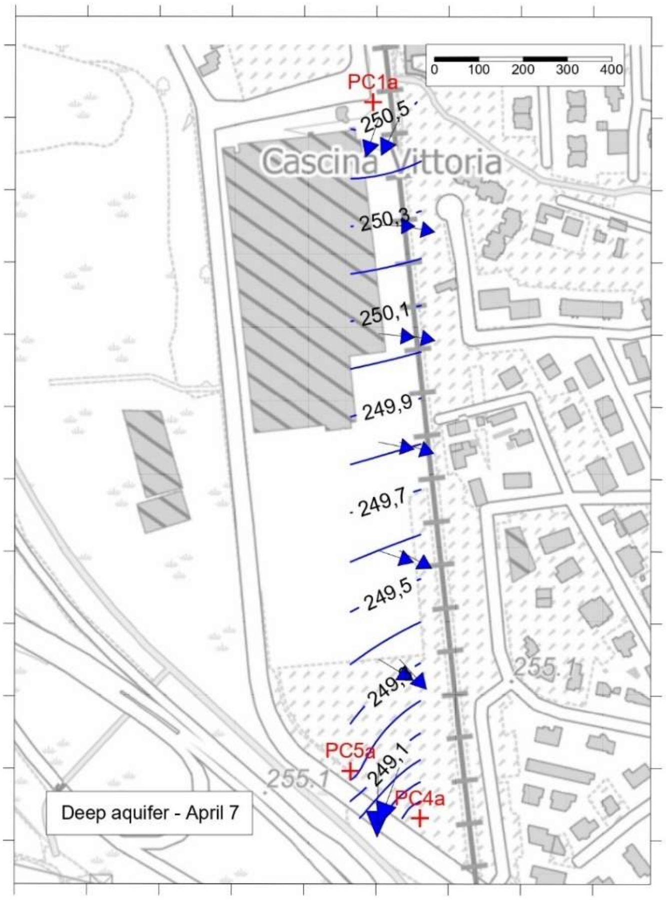


Figure 30. Groundwater flow model for the deep aquifer – April 7 campaign.

A clearer configuration is obtained from the survey of July 9 - Figure 31 - characterized as well by nearly uniform gradient of 0.4%. In this case, the flow in the northern part of the site presents a slight deviation towards west, and then continues southwards towards the wooded area of the site; in the southern area, higher hydraulic head values were recorded at piezometer PC5a (around 249 meters) which in turn drives the flow lines towards areas of lower head, such as at PC4 and PC3 (around 247 meters).

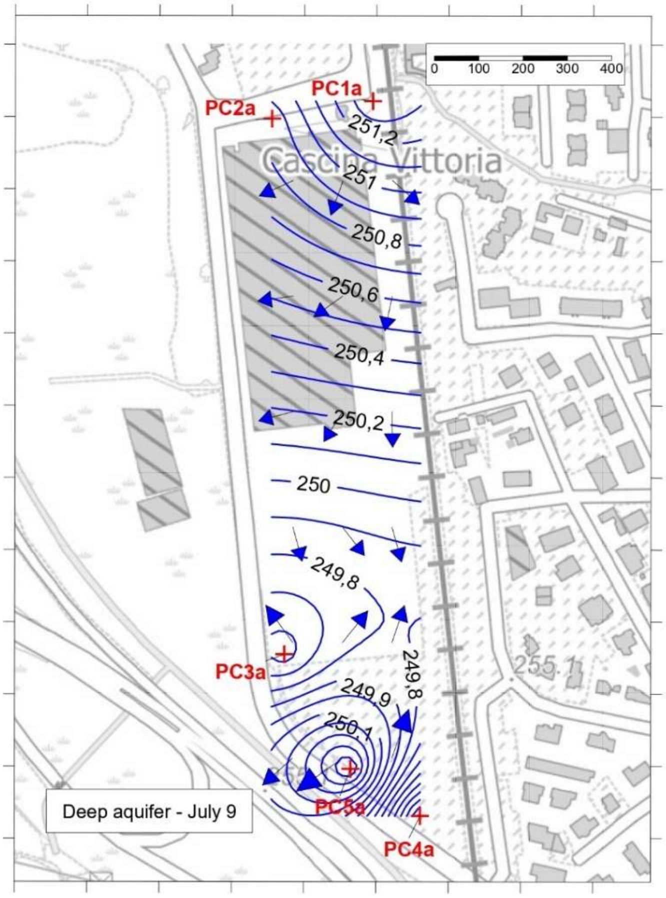


Figure 31. Groundwater flow model for the deep aquifer – July 9.

In the end, as done for the shallow aquifer, a comparison with the exeedances reported in the 2018 sampling campaign is presented in Figure 32. Reference to Figure 14. Deep aquifer exceedances in 2023.Figure 32.

Maximum value – order of hundreds μg/l - of PCE are found near PC2a and PC3a; while Cr VI and Nickel were respectively detected only upstream the former and both upstream and downstream the latter.

In both cases, the 2023 sampling data support the hydrogeological setting in which groundwater inflow into the site occurs not only from the southern side (PC2) – as previously hypothesized - but also from the eastern side (P8, P9, PC3).

With regard to PCE in particular - chlorinated solvent - which behaves as a DNAPL (Dense Non-Aqueous Phase Liquid) - it is hypothesized that the presence of low-permeability layers in correspondence with the cluster piezometers screened between 15 and 25 meters may have led to the formation of contaminant pools, which can act as long-term sources of dissolved contaminants in the groundwater.

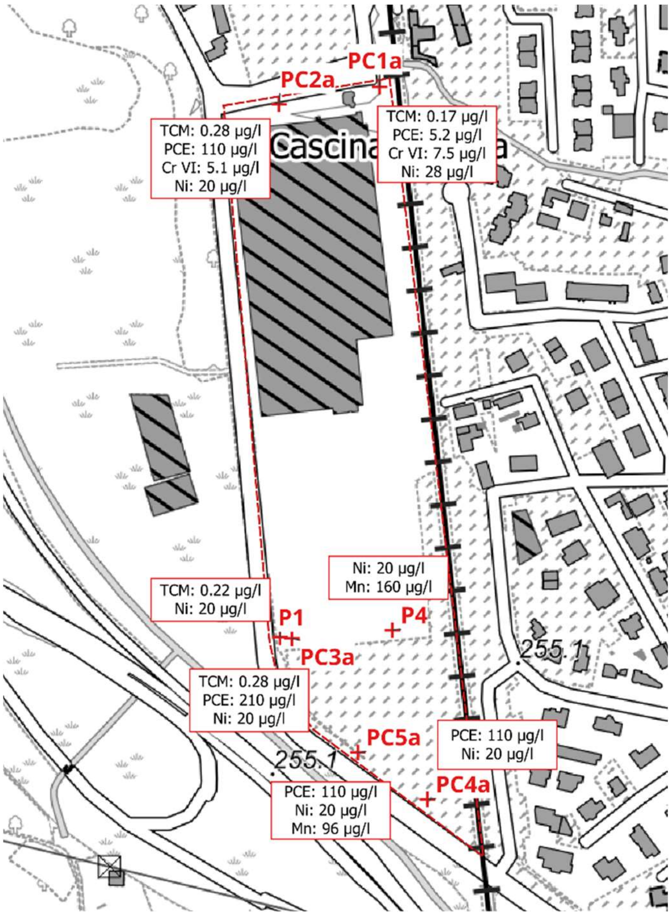


Figure 32. Reference to Figure 14. Deep aquifer exceedances in 2023.

6 Conclusion

The main goal of this study was to assess the reliability of the current piezometric monitoring network in representing the site's hydrogeological conditions, specifically evaluating the influence of stratigraphic heterogeneity.

From the comparison between site-specific stratigraphic data and regional geological information, including the location of the base of the superficial aquifer, it was possible to confirm a subsurface configuration characterized by a predominance of high-permeability materials, such as gravel and sand, with localized horizons of lower-permeability materials (clay) - responsible for local flow patterns - around 230 – 235 meters a.s.l.

Thanks to the 2 monitoring campaigns, a general orientation of groundwater flow from north to east – southeast was observed, with an overall hydraulic gradient of 0.8% at the superficial aquifer; at depths between 15 and 25 meters below ground level, not necessarily belonging to the deep aquifer, the flow showed a slight deviation towards the west, before turning southwards in correspondence with the wooded area of the site, with a gradient of 0.4%.

Limitations to the analysis can be identified in the lack of data in the central area of the site following the closure of the piezometers; this constraint prevents a detailed and reliable characterization of the hydrogeological conditions of the site.

As a consequence, for the purposes of the ongoing remediation project, future investigations could include the installation of new piezometers in the central area and along the eastern boundary of the site, opposite to the positions of piezometers P8 and P9, including potential clusters reaching depths greater than 25 meters, to better define local flow variations and refine the hydrogeological model.

In conclusion, the updated stratigraphic framework and the groundwater flow model developed in this thesis will provide an essential basis for guiding the upcoming sampling campaign, supporting the realization of the Human Health Risk Assessment and the design of the subsequent remediation plan for the groundwater system.

Appendix 1

PLAN – ALTIMETRIC SURVEY MAP

Figure 33. Plan-altimetric survey Map.

Appendix 2

WELL COMPLETION DATA

Table 17. Off-site surveys

Name	Drilling method	Perforation type	Ground level elevation (m a.s.l.)	Depth from ground level (m)
SV14	core drilling	survey	254.00	20.00
SV3	core drilling	survey	252.00	25.00
S12	-	survey	260.00	21.75
SV2	continuous core drilling	survey	249.00	25.00
SV7	continuous core drilling	survey	262.00	20.00
P18bis	-	well	260.00	64.2
P49bis	-	well	258.00	307.00
SV6	continuous core drilling	survey	265.00	40.00
SV5	continuous core drilling	survey	257.00	40.00
PS52	-	survey	255.00	80.00

Table 18. On-site piezometers

Piezometer	Drilling year	Drilling method	Ground level elevation (m)	Depth from ground level (m)	Well screens from ground level (m)
P5	2011	-	258.51	-	-
P6	2011	-	258.56	-	-
P7	2011	-	258.87	-	-
P0	1999	destructive drilling	258.98	18	6 - 18
P1	2000	destructive drilling	258.13	15	9-15
P2	2000	destructive drilling	258.08	15	9-15
P3	2000	destructive drilling	259.86	15	9-15
P4	2000	destructive drilling	258.44	18	6-18
P8	2013	core drilling	256.82	17	9 - 17
P9	2013	core drilling	256.567	17	9 - 17
P10	2013	core drilling	257.02	16.60	11 – 16.50
P10bis		core drilling	257.01	10.00	3 – 10.00
P14	2016	core drilling	258.05	-	-
P15	2016	core drilling	258.06	-	-
P16	2016	core drilling	258.30	-	-
P17	2016	core drilling	255.90	-	-

P11	2013	core drilling	253.76	15	3 - 13
P12	2013	core drilling	253.39	15	3 – 13
P13	2013	core drilling	252.39	14	3 - 13
PC1a	2023	core drilling	258.78	24	18 - 23
PC1b	2023	destructive drilling	258.77	17	5 - 16
PC2a	2023	core drilling	258.62	24	17 - 23
PC2b	2023	destructive drilling	258.66	16	4 - 15
PC3a	2023	core drilling	256.16	24	17 - 23
PC3b	2023	destructive drilling	256.16	16	4 - 15
PC4a	2023	core drilling	252.23	24	15-23
PC4b	2023	destructive drilling	252,23	14	3 - 13
PC5a	2023	core drilling	253.63	24	15-23
PC5b	2023	destructive drilling	253.68	14	3 - 13

List of Figures

List of Tables

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