D1c E-USE(aq)

Technical performance

& monitoring report

Italian pilot

Europe-wide Use of
Sustainable Energy from Aquifers

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1. Introduction

1.1 Barriers to overcome and issues to address

1.1.1 Poor characterization of the site

Poor and unreliable information was available about the aquifer of Martignone station which did not allow a thorough design of the ATES plant. In particular, it was known that one aquifer was present at approximatively 30 m below surface level (bsl), while details on water quality and water conductivity were unknown. A second aquifer was supposed to be placed at a larger depth, approximatively 80 m bsl.

University of Bologna (UniBo), in collaboration with Climate-KIC project partners, supported Terna SpA (pilot plant site owner) in the design and realization of several tests and analysis to increase the insight in the aquifer characteristics and to allow a more robust and effective design of the pilot plant. These tests included:

- Soil and aquifer characterization;
- Chemical-physical analysis of groundwater;
- Pumping tests;
- Tracer tests.

Furthermore, an energy audit of the existing building was carried out by UniBo to map the currently installed plants for heating and cooling, and an estimation of energy demand was completed through a combination of simulations and direct measurements.

The final results resulted in a better insight in i) the heating and cooling demand of the buildings, ii) the aquifer and groundwater characteristics (water extraction capacity, groundwater flow velocity and direction) and iii) potential concerns due to physical-chemical characteristics of the groundwater (i.e. clogging risk). All the information was used to upgrade and refine the original plant preliminarily drafted by Terna SpA.

1.1.2 Authorization/permit process

On 2nd November, 2015 Terna SpA made a first request to the regional authority (Technical Service of the Reno river basin) for the extraction of groundwater for energy purpose. The original project integrated in the same hydraulic circuit the fire-fighting system, and did not include the re-injection of the extracted water in the aquifer. The maximum water flowrate was estimated to be 27 m^3/h (7.5 l/s). The project included the installation of four heat pumps, each one of about 75 kW th, two for continuous working (one per building) and two as back-up units (one per building). The heat pumps were sized only for heating purpose. Heat exchange with groundwater was provided through plate exchangers. Nevertheless, the technical assumptions on which the project was based were not supported by experimental data (i.e. pumping test), and no impact study on the aquifer was included in the project (i.e. thermal plume analysis). So, the regional authority responded on 17th November 2015 asking to renew the authorization request including the water re-injection after thermal use. The regional authority also asked to separate the fire-fighting system water circuit from the one used for energetic purpose.

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The request made by the regional authority had two effects: the first was that Terna SpA decided to separate the fire-fighting system project from the one regarding the extraction of water for energy purpose. The second effect was that Terna SpA had to investigate the characteristics of the aquifer, since no relevant data were available, in particular by a chemical-physical soil characterization with determination of aquifer depth and a pumping test. Starting from March 2016, UniBo got in touch with Terna SpA and supported Terna SpA both with the necessary redesign of the plant using the knowledge developed in the E-USE(aq) consortium, as well as with the communication with the regional authority.

From the beginning of 2016 informal communications started between the regional authority and both Terna's geologist and UniBo with the final aim of drafting an authorization request that can be accepted by the authority without further delays. An unexpected change in the normative framework occurred starting from May 2016, since the regional authority in charge of the authorization release was not anymore the Technical Service of the Reno river basin, which was "eliminated" by the Emilia-Romagna region. Permits for groundwater water extraction were attributed to the regional environmental agency (ARPAE). This passage of skills has created a stalled situation in the communication with the regional authority that lasted for several months. The situation became clearer after the summer of 2016, when a new regulatory counterpart was identified. The exchange of information restarted, and the following conditions were agreed in order to proceed with the authorization request resubmission:

- the realization of chemical-physical analysis on water samples;
- the realization of a pumping test, to verify if critical conditions can be reached during water pumping;
- the realization of a monitoring system to verify the impact of the plant on the groundwater system (suggested by UniBo and partially financed in 2016 by the E-USE(aq) project);
- the study of thermal plume impact.

Preliminary pumping test was realized by the end of 2016, after monitoring well realization. The results were fundamental for the redesign of the plant. At the same time, a water sample was analyzed, but a high benzene concentration was measured. This fact was not positive, since the regional authority asked to repeat the test after some months to verify if benzene is still present.

Meanwhile, the redesign of the plant went on accordingly to the results of the preliminary pumping test. In particular, the original project (that foresaw one extraction and one injection well) was enlarged to three extraction and three injection wells (plus three monitoring wells). The size of the system was also changed, according to the energy audit carried on by UniBo. Furthermore, cooling was included, while the original project foresaw only heating.

On 14th March 2016 Terna SpA submitted an updated version of the authorization request for groundwater extraction. The procedure is so defined: the regional official requests two technical advices, one from ARPAE technical office and one from the Province. Based on these answers, ARPAE must respond within 60 days. Once groundwater extraction is allowed, Terna SpA has six months to complete the wells realization, and then send back to ARPAE the as-built project of the wells. Then, after a further 30 days, the final authorization for water extraction can be released by ARPAE.

After 60 days ARPAE communicated that the authorization demand should be modified, taking into account that:

- the planned tank storage of groundwater is perceived as a potential source of risk for groundwater contamination, and so it was advised to avoid it when possible;
- the thermal plume study should be integrated with a cross section analysis of the plume shape.

The project was then modified through the elimination of the groundwater storage tank, and the thermal plume study was updated. Then, a new authorization demand was submitted on 7th June 2017. Finally, on 28th June 2017 ARPAE communicated to Terna SpA that the authorization demand was accepted (Annex 01). ARPAE asked for the realization of an additional monitoring well to be placed within the thermal plume cone, as drafted in the authorization request. On 11th December 2017 Terna SpA communicated to ARPAE the as built project of the wells (three extraction wells, three injection wells, four monitoring wells).

Nevertheless, another authorization was requested: the authorization to re-inject the groundwater into the aquifer. A separate request for water injection had to be done to Bologna Province. Another relevant obstacle was then identified: starting from April 2014 the Provinces were formally abolished in Italy, but no substantially. As a result, the skills that were in charge of the Provinces were in part taken by the Region, while other skills are still under the responsibility of the Provinces, but without a clear normative framework. In Emilia-Romagna the authorization for water injection in groundwater was a competence of the Provinces, but has been recently moved to the regional environmental agency (ARPAE). Terna SpA submitted the injection authorization request at the beginning of November 2017 to ARPAE. On 11th December 2017 Terna SpA communicated to ARPAE the as built project of the wells. The final authorization was released on 24th January 2018 with some minor recommendations (Annex 02) and the limit of 5°C of temperature difference with respect to the natural groundwater temperature. The overall regulatory process starting from the involvement of Terna plant as pilot site in the E-USE(aq) project has been almost 48 months: March 2016, first request issued, January 2018, last authorization released.

1.1.3 Different knowledge and specific competences for pilot plant design and realization

UniBo and other project partners integrated the local team of experts that has been built by Terna SpA, including geologist, thermo-hydraulic designer, electric and electronic expert. Several meetings were organized on site to evaluate the best solutions to overcome the technological barriers that were identified step by step. The result of this collaboration was the complete redesign of the plant, including the drafting of a new executive project. The main modifications included in the project were:

- groundwater reinjection;
- installation of reversible heat pumps to supply both heating and cooling energy;
- sophisticated monitoring system and automatized control station.

Furthermore, UniBo supported Terna SpA in the identification of potential candidates for the participation to the tender for the realization of the plant.

1.2 Partners involved

A local consortium has been formed, including:

- Terna SpA (site and plant owner);
- Subsoil Srl (geologist, design and realization of wells, thermal plume simulation);

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- Omega Associati (design studio for both thermo-hydraulic and electric/electronic);
- Medielettra SaS (company in charge of the realization of the plant).

Several project partners participated in the re-design phase of the pilot plant. In particular:

- Deltares: support in the characterization of manganese and identification of clogging potential;
- WUR: techno-economic analysis of potential site for pilot installation;
- Arcadis: monitoring system development;
- TUDelft: ATES system design.

Finally, ASTER collaborated with UniBo and Terna SpA in the realization of communication materials and tools.

1.3 Organizational history

E-USE(aq) project proposal included the city of Modena as pilot site for the Italian case study, where an Aquifer Thermal Energy Storage (ATES) heat pump would have been integrated in a district heating project under development. In the first months of 2015, after a deeper techno-economic analysis carried out by the plant owner in collaboration with UniBo, the project was stopped due to current unreliable conditions for district heating development in that area (Annex 03). So, UniBo and ASTER started a survey in Emilia-Romagna to find a new possible site for the ATES heat pump application.

After a preliminary screening, in July 2015 two new potential sites were identified (Annex 03): the first one (Forlì) for a developing project, the second one (Bologna) for the revamping of an existing plant. Both new pilot applications foresaw the integration of the ATES heat pump in a district heating system. Moreover, for both cases there was also the opportunity to integrate an aquifer remediation activity within the project. After a preliminary techno-economic analysis, the final conclusion was that no one of the potential sites identified would be realistically achievable due to economic concerns and/or potential authorization delays.

A new possible solution was identified by the end of 2015, which differs from the one analyzed in the past since it did not include a district heating/cooling network (Annex 04). The new application foresees the realization of the ATES heat pump in a composting plant for the separate collection of municipal solid waste. The composting plant, placed in S.Agata Bolognese (very near Bologna) was under upgrade to an anaerobic digestion plant. The revamping was supposed to be concluded within 2016. The anaerobic digester needed heat to sustain the microbial activity at relatively low temperature (around 40-50°C), which is very good for an ATES heat pump application. Moreover, there was also a cooling demand, since the biogas needs to be cooled down during treatment and upgrading to biomethane. Additionally, being the composting plant near an exhausted landfill, it was likely that the aquifer could be contaminated and therefore the site could give the opportunity to test aquifer remediation through the open loop heat pump. This seemed a very interesting opportunity for plant owner, to be replicated also in other sites. Calculations were made also by project partner WUR on the heat and cold balance for the aimed combination of anaerobic digestion and the heating and cooling for the buildings at the site in Bologna (Annex 05). This analysis was finalized with a report in May 2016. The conclusions of this deliverable show that the combination of ATES with anaerobic digestion in the configuration as present in Bologna does not lead to an attractive combination. The main reason for this conclusion lies in the fact that the demand for cold at this site in this combination is too low. As there is a continuous demand for heat in the anaerobic digestion and there is no additional demand for cooling, the combination of anaerobic digestion

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with ATES is not feasible. Moreover, during the analysis of heat and cold demand for the combination of ATES and anaerobic digestion it became clear that the site was not contaminated with chlorinated solvents, as was reported and thought of before. At the end of spring 2016 it became clear that the selected case in Bologna was not fit for the combination of ATES and enhanced natural attenuation of chlorinated solvents. Furthermore, meanwhile the composting plant owner communicated to UniBo that some delays on the realization of the revamping activities should be taken into consideration due to high investment required and uncertainty on the authorization route. Therefore, the overall conclusion for this site was that a new Italian site will be searched for.

Since the evaluation of several potential sites that did not come to finalization, UniBo and ASTER started a survey in Emilia-Romagna to find new possible sites by getting directly in touch with Emilia-Romagna region officers in charge of authorizing the realization of open loop heat pump plants (i.e. Servizio Tecnico di Bacino). A list of under authorization plants was released by these officers, and among others UniBo identified a plant under authorization in Anzola dell'Emilia (near Bologna) as the most interesting one, due to the size of the plant (i.e. not residential). The area of the installation is within the electric station of Martignone, near Bologna, owned by Terna SpA.

2. Pilot description

2.1 Site depiction and pilot design

2.1.1 Existing framework description

The Italian pilot plant site is situated in the electric station of Martignone, owned by Terna, which is the Italian power grid operator. The electric station of Martignone is a transformation station for 380 kV/132 kV. Moreover, the station includes two buildings, one (letter A in Figure 1) hosting the emergency teams that cover the ordinary and extraordinary maintenance of 2,800 km of electric lines and the other one (letter B in Figure 1) hosting offices and a remote control station.

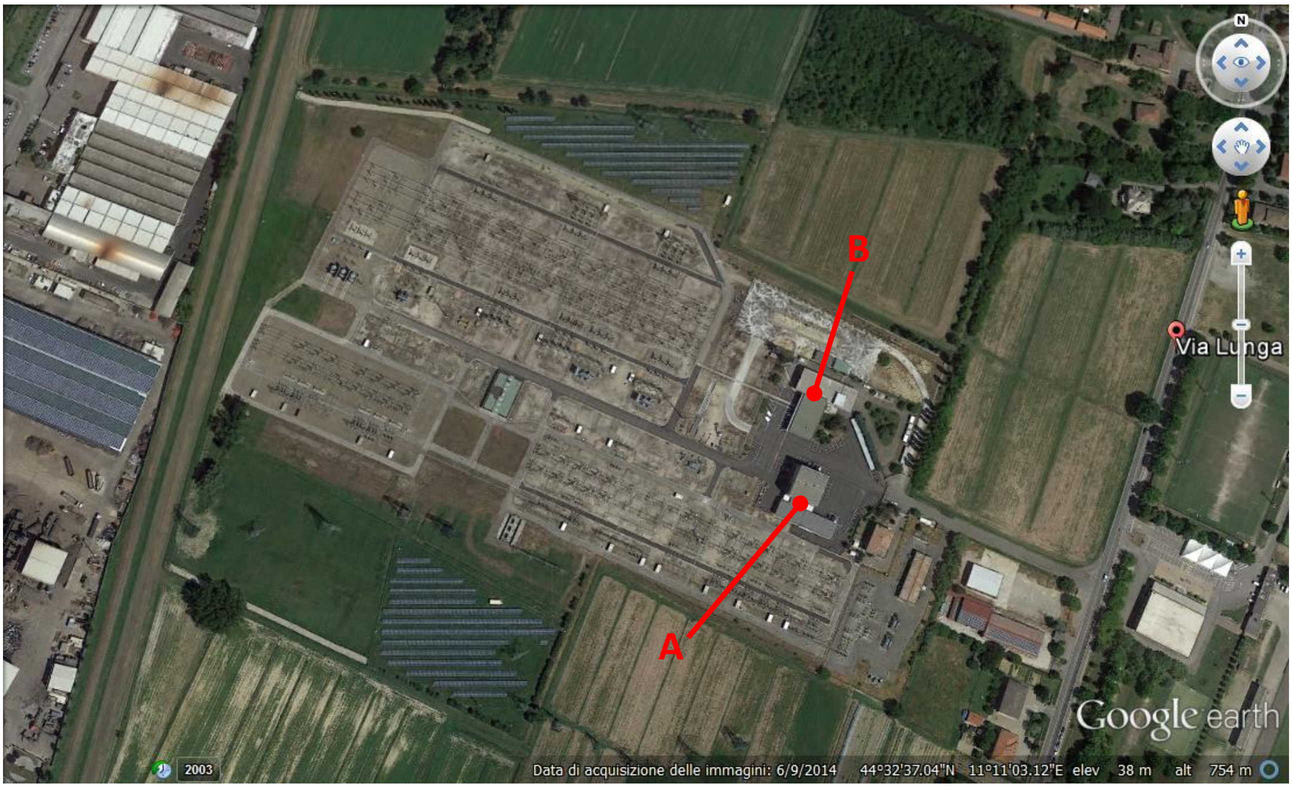

Figure 1. Aerial picture of Terna's Martignone station.

The A building (Figure 2), which is named "changing room building", is a single floor building which includes a kitchen, two changing rooms, two shower rooms, three bathrooms and one tooling shed. The conditioned rooms have a volume of about 1,600 m^3 and are currently heated and cooled by a complex series of plants. Figure 3 is a summary of the existing plants, which includes:

- n°1 103.5 kW th methane boiler;
- n°2 10 kW th and 9 kW fr heat pumps;
- n°3 iron cast radiators;
- n°4 radiant ceiling panels;
- n°4 electric splits for air cooling;
- n°6 100 lt electric boilers for the production of domestic hot water.

The plant would be integrated with a 57 W th electric boiler, which will be used as back-up unit.

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Figure 2. Entrance of the changing rooms building.

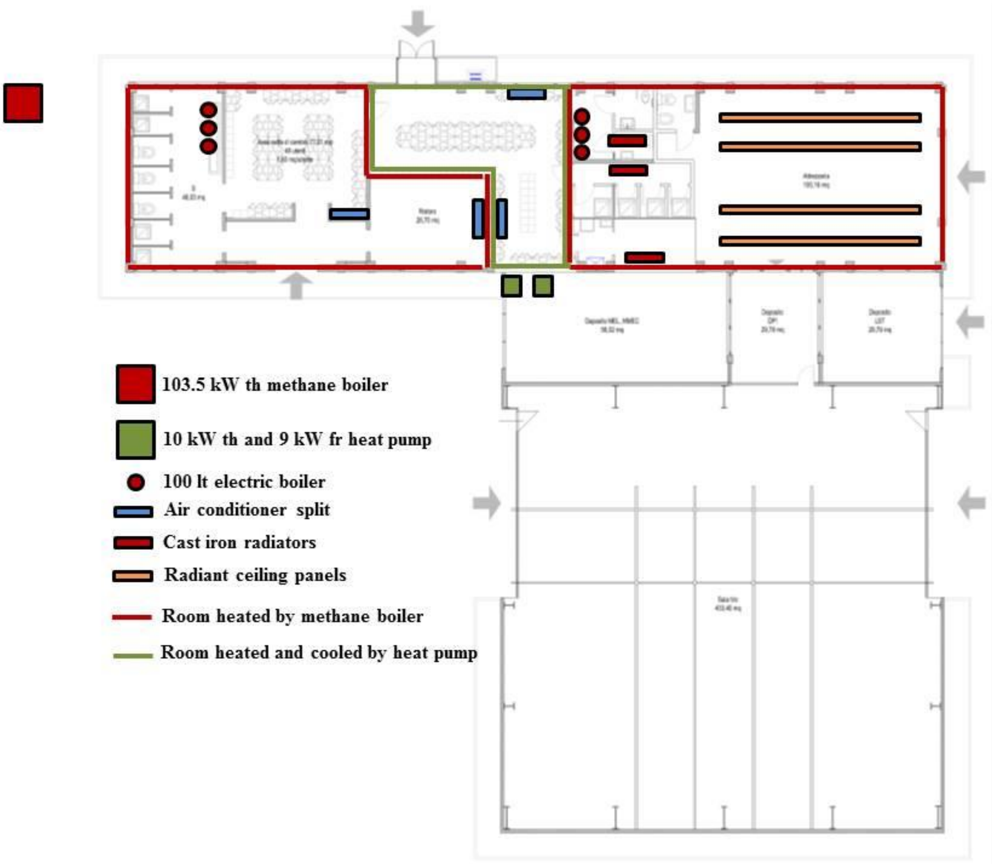

Figure 3. Changing room building thermal and cooling plants.

The B building (Figure 4), which is named “office building”, is a two floors building which includes several offices, four bathrooms, three data centers, one battery room, one remote control station. The conditioned rooms have a volume of about 3,800 m^3 and are currently heated and cooled by the following plants, schematized in Figures 5 and 6:

- n°1 109.7 kW th methane boiler;
- n°1 162 kW fr liquid-air chiller;
- n°4 50 lt electric boilers for the production of domestic hot water.

All conditioned rooms are equipped with fan coils and are fed by a methane boiler and liquid-air chiller, with the exception of data center rooms, which are only cooled. Recently, the plant has been integrated with a 57 kW th electric boiler, which is used as back-up unit.

Figure 4. Office building.

Figure 5. Ground floor of the office building thermal and cooling plants.

Figure 6. First floor of the office building thermal and cooling plants.

The plants of buildings A and B are not connected.

2.1.2 Pilot plant description

Aquifer Thermal Energy Storage (ATES) systems help reduce energy use by providing seasonal storage and recovery of heat, which allows sustainable space heating and cooling for buildings. Where aquifers of sufficient capacity exist, the seasonal heat and cooling discrepancy can be overcome by seasonal thermal energy storage and recovery in the subsurface. An ATES system works as follows (see Figure 7): in winter a building is heated by means of a heat pump that extracts heat from warm groundwater that was stored in the previous summer. While delivering its heat to the building, the heat pump simultaneously cools this groundwater, which is re-injected into the subsurface with a second well, the “cold” well. During the summer, the flow is reversed, and then cold water is extracted and used to cool the building (directly or through a chiller). While cooling the building, the groundwater is warmed up and immediately injected into the other well, the “warm” well. So, an ATES system balances out seasonal discrepancies in the supply and demand of heating and cooling. The warm and cold ATES wells can be separated horizontally; each pair thus formed is then called a “*doublet*” (Figure 7). The well screens can also be installed vertically in a single borehole, forming a pair called a “*monowell*” (Figure 7). In aquifers with a high ambient groundwater flow velocity (> 25 m/year), losses of thermal energy caused by groundwater advection can be limited by choosing a shorter screen length. However, in many cases this strategy is neither possible nor desirable, because short screens limit the capacity of the wells and increase their thermal radius, which precludes optimal use of available aquifer space. In practice, under high

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ambient groundwater flow conditions the so-called "*recirculation system*" (see Figure 7) is often applied.

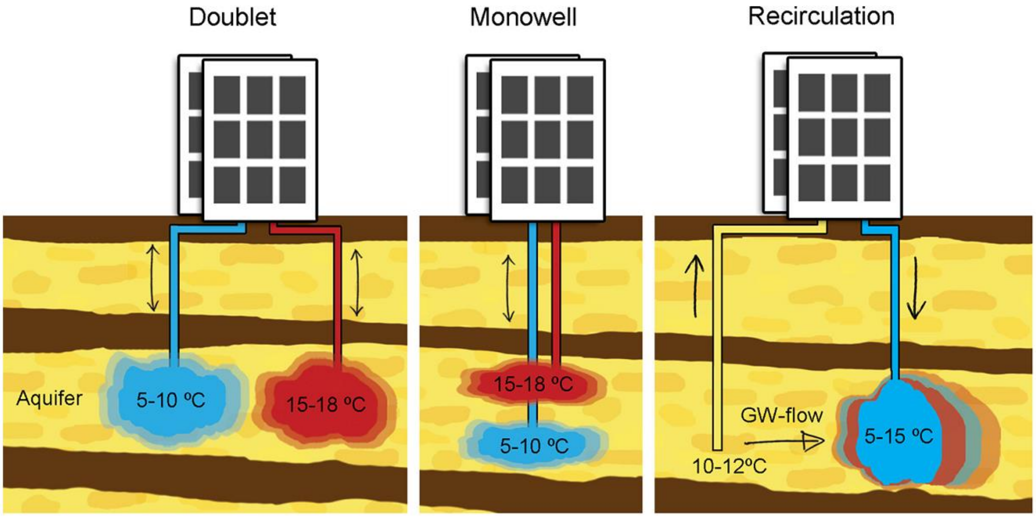
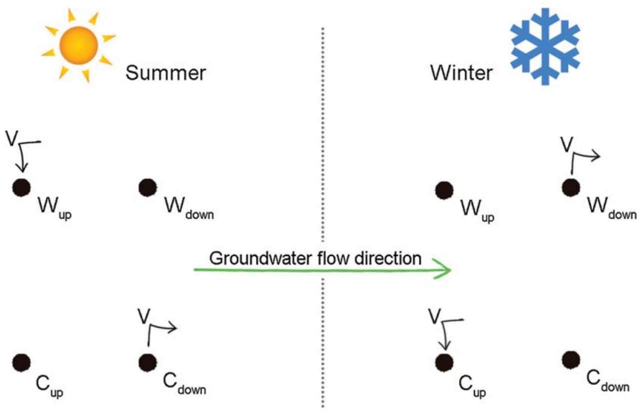


Figure 7. Schematic representation[1] of ATES doublet, monowell and recirculation systems.

Recirculation systems always use the same wells for extraction and infiltration; water is extracted from the upstream well and injected into the downstream well (the arrow in Figure 7 represents the ambient groundwater flow direction). Compared to the normal ATES systems, these systems have a smaller temperature difference between the warm and cold well, a lower efficiency and a large downstream thermal plume, which may affect other ATES systems or groundwater uses.

Based on the results of the on field tests carried out on the pilot site, the pilot plant at Terna site was designed as a recirculation ATES system. In particular, three extraction and three injection wells have been designed, while four monitoring wells have been installed to verify the impact on the plant during operation and evaluate further arrangements to improve ATES efficiency. In fact, novel studies show that an alternative ATES design strategy can be implemented in aquifers with high ambient groundwater velocity[1]: thermal losses due to groundwater displacement can be prevented by installing multiple doublets, where at least two wells of the same type (warm-cold) are aligned in the direction of the ambient groundwater flow. By injecting the yearly storage volume (V) in the upstream well and extracting it from the downstream well in the next season, the ambient groundwater flow is counteracted, resulting in higher recovery efficiency (Figure 8).



[1] Source: ATES systems in aquifers with high ambient groundwater flow velocity, *Geothermics*, 2018.

Figure 8. Schematic representation[1] of warm and cold wells lay out and basic pumping scheme for counteracting the ambient groundwater flow.

Moreover, the pilot plant is designed to completely replace the methane boilers, while electric boilers and air-liquid chiller remain as back-up and integration units. The pilot plant includes three reversible heat pumps and one chiller fed by groundwater.
Terna pilot plant main figures are summarized in Table 1, while the wells positioning and the Piping and Instrumentations Diagram (P&ID) of the pilot plant are schematized, respectively, in Figure 9 and Figure 10. The peculiarity of the pilot plant is that there are some rooms in building B that need cooling all year long. This gives the opportunity to test at a small scale the concept of cold district heating (CDH)[2].

Table 1. Pilot plants main characteristics. (*) extraction and injection wells.

Parameter	**Bologna**
N° of production wells (*)	3 + 3
N° of monitoring wells	4
Wells' depth (m bgl)	30
Max groundwater flowrate (m^3/h)	19.4
Max cooling power (kW)	140
Max heating power (kW)	160
Annual cooling demand (MWh)	49
Annual heating demand (MWh)	170

[2] Cold District Heating (CDH) network can be defined as a system for distributing cold water in a temperature range between 10 °C and 25 °C to end-users' substations where it is used to produce, also simultaneously, hot and cold water at different temperatures and for different purposes (space heating, cooling, domestic hot water production) via heat pumps and chillers (https://www.mdpi.com/1996-1073/11/1/236).

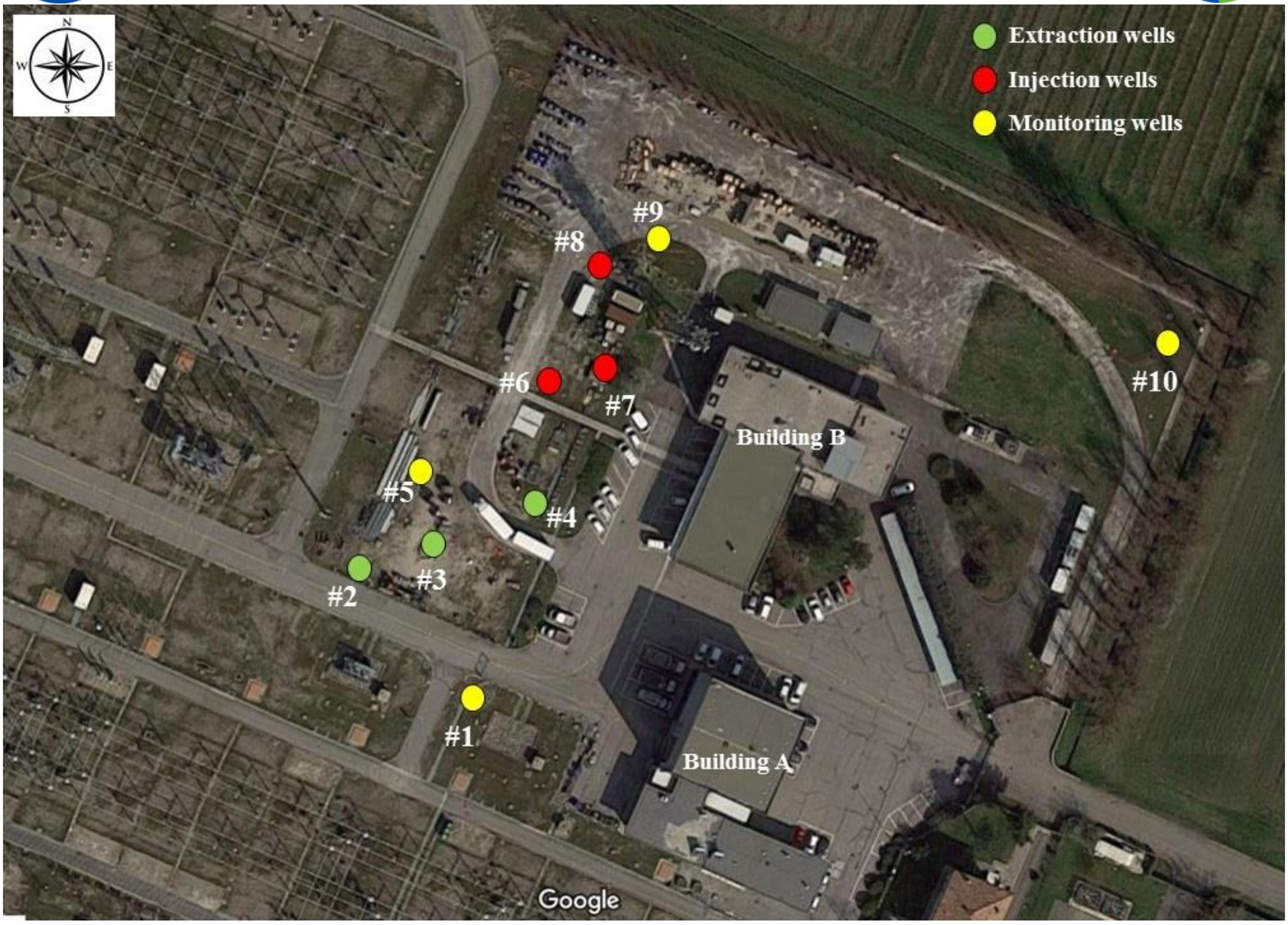


Figure 9. Wells positioning in the Italian pilot plant.

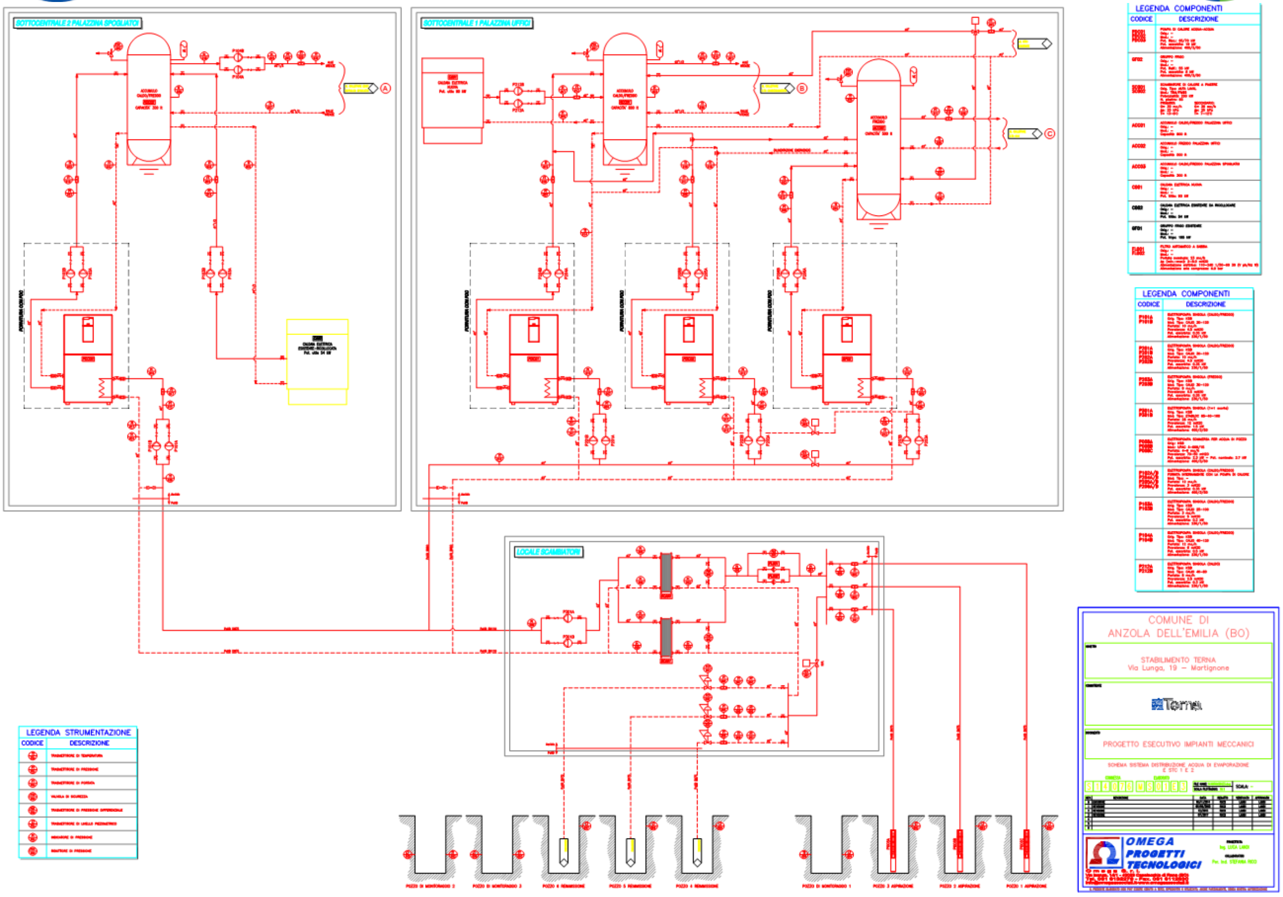


Figure 10. P&ID of the pilot plant (extracted from the executive project).

Groundwater cannot be used directly to feed the reversible heat pumps and the chiller since it is characterized by very high hardness and high concentration on manganese. In particular, manganese is a potential cause of clogging. So, a secondary circuit has been designed to exchange energy with the groundwater and carry it to the heat pumps/chillers. As a result, in wintertime the heat that is extracted from the rooms to be cooled is transferred via the secondary circuit to the rooms that need to be heated, thus reducing the seasonal unbalance - produced by the difference in space heating and cooling demand - between warm and cold water injection in the aquifer.

The monitoring system of the plant includes two different monitoring applications. The first one concerns the monitoring of the aquifer, the second one the performance of the heat pump/chiller system. The monitoring wells are 4 in total: two monitoring wells located near extraction and injection areas (one per area) and further two monitoring wells placed far away from both areas, to evaluate long term influence of the plant on the aquifer. Aquifer monitoring system includes:

i) extracted water temperature and flowrate, groundwater level (measured in the extraction wells),
ii) injection water temperature and flowrate, groundwater level (measured in the injection wells),
iii) aquifer temperature and level (measured at four different points by the three monitoring wells).

Moreover, every 18 months one sample of water will be analyzed to evaluate (if any) the impact of the pilot plant operation on water chemical-physical characteristics. The monitoring of the groundwater will also allow to verify the thermal plume of the plant and compare it with the predicted thermal plume development as a result from the modeling requested in the authorization phase. Heat pumps and chillers performances will be monitored through:

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i) heat pumps/chillers electricity consumption,
ii) flowrate and temperatures of the hot/cold water produced by and fed to the heat pumps/chillers,
iii) electricity consumption of back-up units (electric boilers, heat pumps, chillers).

Furthermore, in order to assess pilot plant efficiency and effectiveness in energy production and to compare the pilot plant performance with a standard air-to-water heat pump/chiller, a local meteorological station is installed, which measures local solar irradiation, air temperature and humidity. All monitoring data are collected via an automated monitoring system and stored in a database which can also be accessed remotely. A control system software will be developed to automatically manage the plant. In particular, groundwater flowrate will be controlled on the basis of users' energy demand, but keeping groundwater temperature variation within 5°C.

2.2 System installation

A borehole has been realized starting from 27th of July 2016 (Figure 11). The borehole was realized at a depth of 50 m bsl, taking soil samples of each meter (Figure 12). The soil consisted mainly of silts and clays, except for the aquifer layer, that was identified at a depth of 20-28 meters, where sand and stones are also present. The same borehole was then dug up to 100 meters, but without storing up samples. No further aquifers were found, and the soil was characterized again by the high presence of silts and clays. So, the only available aquifer was identified at a depth of about 25 meters.

The borehole is used as an extraction well in the pilot plant configuration (well n°3 in Figure 9). Then, two further wells were realized at 35 bsl for the realization of the preliminary pumping test. Wells realization was completed by 12th August 2016. These wells are monitoring wells in the pilot plant configuration (wells n°1 and n°10 in Figure 9).

Figure 11. Picture of the equipment used to realize the wells.

Figure 12. Picture of samples taken from 26 meters' depth up to 30 meters' depth in the first borehole.

On 13th September 2017 the realization of all remaining wells started (i.e. after authorization was released by ARPAE), plus the fourth monitoring well requested by ARPAE (well n°9 in Figure 9). All the wells were realized at 35 meters' depth and completed by 27th October 2017.

Figure 13. Pictures of the first well realized.

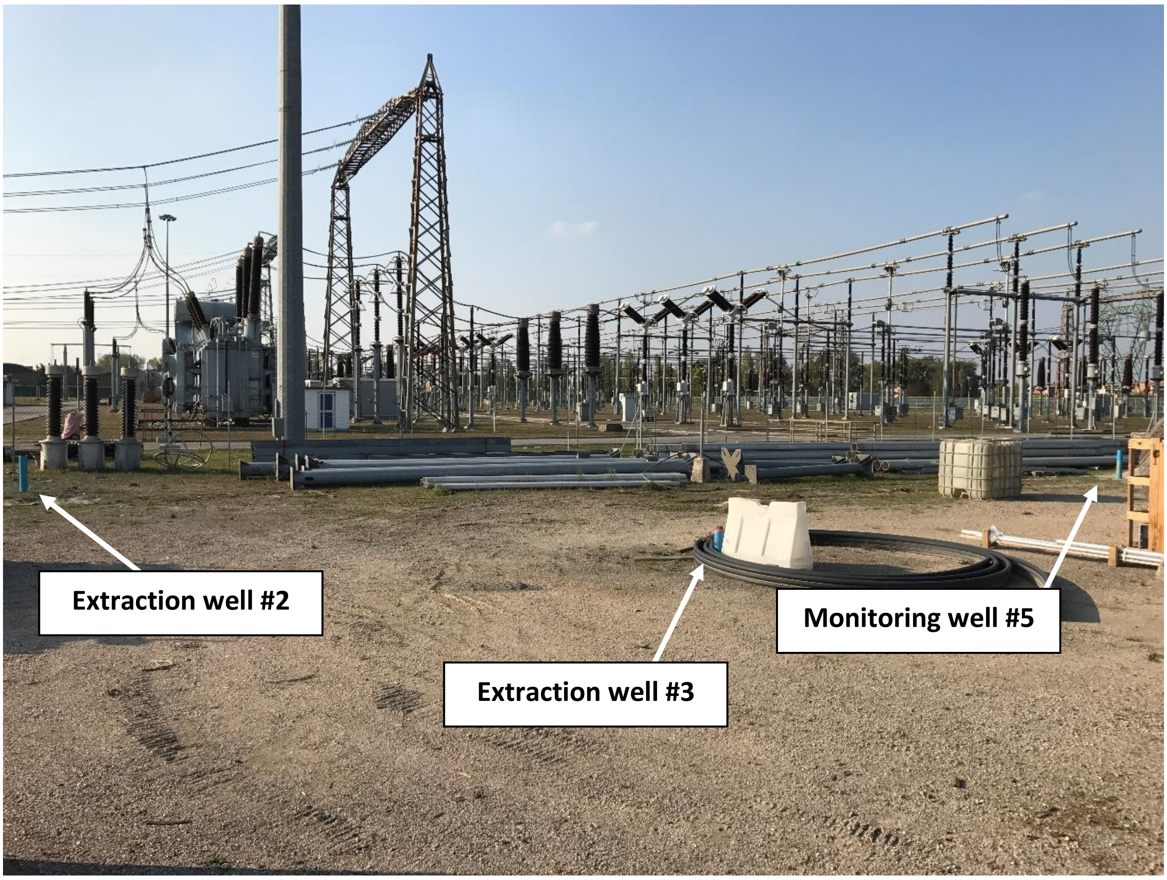

Figure 14. Picture of two extractions and one monitoring wells (reference in Figure 9).

On March 2018 the tender for the realization of the pilot plant was open: 8 companies were invited to submit their proposal. On May 2018 some companies' visits were organized at Martignone station. On July 2018 the tender was closed: Terna SpA received only 2 offers for pilot plant realization. Both companies proposed some modifications, so it was necessary to evaluate them from a techno-economic point of view. Terna SpA officially entrusted the company Medielettra for the realization of the pilot plant. On September 10th with the civil works and the hydraulic connections between the wells and the technical rooms (Figure 15 and following).

Figure 15. Realization of the technical vane for hydraulic connection of the pilot plant with building A.

Figure 16. Realization of the technical vane for heat exchange between primary (groundwater) and secondary circuits of the pilot plant.

Figure 17. Example of well realization (well n°5, reference in Figure 9).

2.3 System operation

2.3.1 Preliminary pumping test

Preliminary pumping test started on 19th September 2016 and was completed on 31st October 2016. The aim of the preliminary pumping test was to identify the maximum groundwater flowrate that can be extracted from one well. This information is relevant for the design of the extraction-injection system, since the aquifer level should be kept in equilibrium while the pilot plant is in operation. The preliminary test was performed in the well n°3 (see Figure 9) through i) a submersible centrifugal pump with vertical axis (Figure 18), ii) a water volumetric flowrate meter (Figure 18), and iii) a phreatimeter, used to measure water level variation.

Figure 18. Picture i) of the water pump and ii) of the water volumetric flowrate meter.

The preliminary pumping test was realized accordingly to ISO 22282-4. A variable rate test was firstly performed: the starting flowrate was fixed at 0.3 l/s. This type of test involves pumping the test well increasing the pumping rate step-wise up to the maximum capacity of the pump. The variable rate test is fundamental to determine the optimal discharge rate for the realization of the constant rate test, which requires a long duration (up to 72 h) and includes also the monitoring of other wells. Moreover, a variable rate test is important to monitor drawdown and recovery of water levels in the well test as a function of time, and to verify how water discharge rates vary during the test as a function of time.

2.3.2 Thermal plume modelling

The regional authority asked Terna SpA to include a thermal plume analysis in the authorization request for groundwater extraction. The thermal plume estimation has been carried out on the basis of literature data and information available from the first preliminary pumping test (i.e. number of extraction/injection wells and groundwater flowrate).

Pilot site municipality of Anzola dell'Emilia (Bologna) is part of the hydrographic water reservoir of the Reno river. The investigated area is characterized by the presence of one superficial and of one deeper and coarser groundwater layer. The superficial groundwater layer consists of, predominantly fine, lime and clay deposits, up to its base, which is about 20 to 28 meters from ground level. There are no significant coarse bodies. Underneath the superficial aquifer there are coarse deposits, gravel, sandy gravel and sand, belonging to the deeper aquifer system with a thicknesses of about 8-10 meters. Figure 19 shows well n°3 design in comparison with the soil stratigraphy.

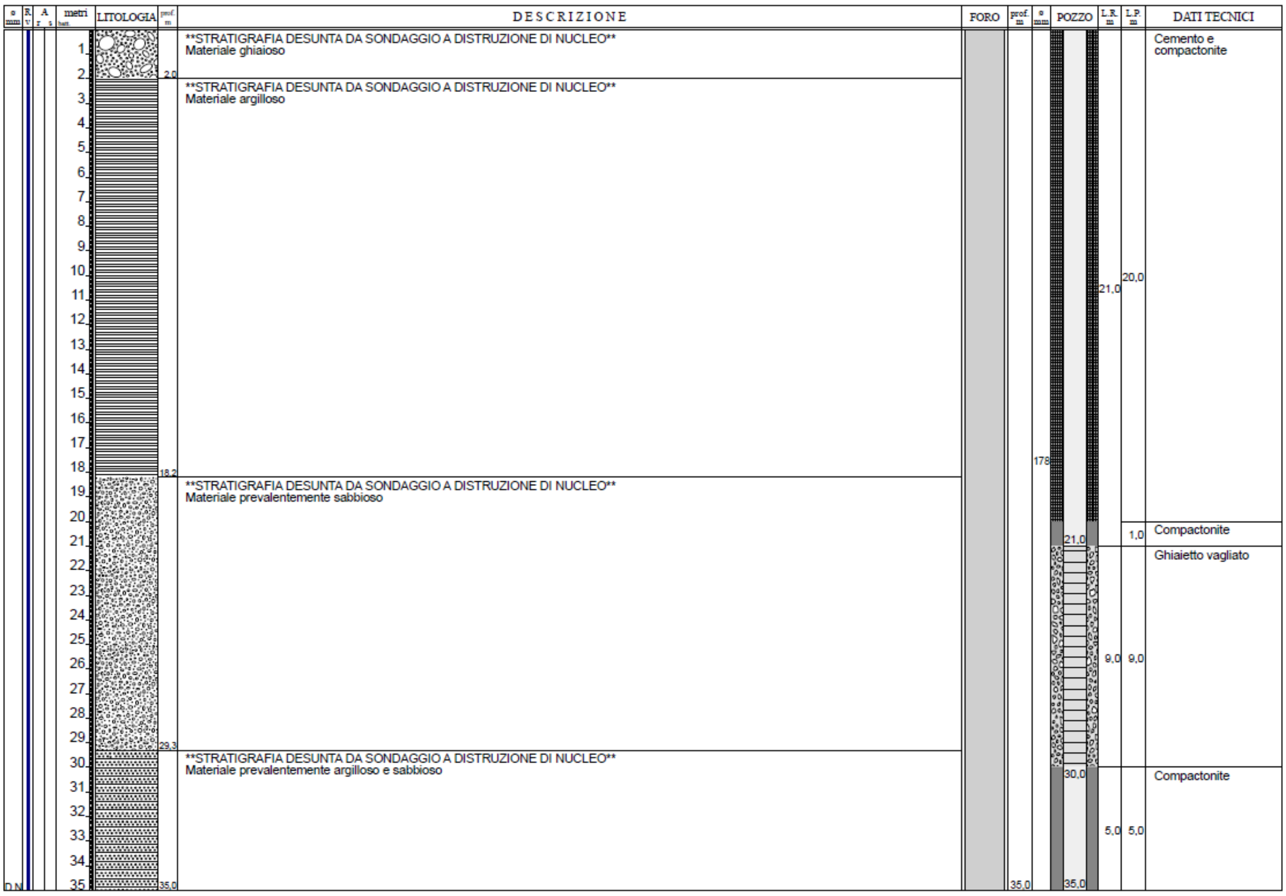

Figure 19. Stratigraphy of the soil and well n°3 design.

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The prevailing groundwater direction in the deeper groundwater is supposed to be S/SO-N/NE. According to existing regional mapping of groundwater vulnerability (potential for penetration and diffusion of groundwater pollutants), which depends on the surface characteristics and hydrogeological conditions, the degree of vulnerability to the pollution of the pilot plant area is classified as "low". Literature analysis also confirms that in the area there are no particular issues with subsidence induced phenomena, but mainly related to the natural dynamics of the Padano basin.

Jacob's equation and Theis' equation were used to estimate the piezometric lowering induced near one well using the maximum water flowrate of 5.6 l/s for groundwater extraction, starting from the undisturbed piezometric portion of 35 m b.g.l. and by applying the following parameters:

- Estimated mean hydraulic conductivity $K = 6*10^{-4}$ m/s;
- Maximum extracted water flowrate Q = 5.6 l/s;
- Saturated thickness of the aquifer b = 3 m;
- Diameter of the well ø = 0,125 m;
- use time of the well t = 14 hours.

The maximum piezometric lowering has been computed to be 4,5 meters (see Figure 20, which shows the Excel sheet used to compute the piezometric lowering through Jacob's equation and Theis' equation). This estimation was conservative since in the real application three extraction wells will be realized instead of one well.

PARAMETRI IDRAULICI					
γ	peso specifico dell'acqua			1.0E-03	Kg/cmc
β	Coeff. di compressibilità acqua			4.50E-05	cmc/Kg
α	coeff. Compressibilità fase solida			1.0.E-03	cmc/Kg
pe	porosità efficace			0.25	
I=e	spessore acquifero			3.0	m
K	coeff. Permeabilità (cond. Idraulica)			6.00E-04	m/s
Q	portata massima pozzo di progetto	5.6	l/s	0.0056	mc/s
H_1	altezza piezometrica indisturbata			35.00	m
H_2	altezza piezometrica dinamica			29.74	m
X	distanza			0.06	m
t	tempo di utilizzo del pozzo	14.0	h	50400	s
Φ	diametro pozzo di progetto			0.13	m
T	Trasmissività (K*I)	$T = K * I$		0.0018	mq/s
Δs	Abbassamento in un ciclo logaritmico	$s = \frac{0.183 * Q}{T}$		0.5693	m
S	Coefficiente di immagazzinamento	$S = \gamma * p_e * e * \left[\beta + \left(\frac{\alpha}{p_e}\right)\right]$		3.03E-05	-
Δh	Depressione piezometrica (Equazione di Jacob)	$\Delta h_p = \frac{0.183 * Q}{T} * \log \frac{2.25 * T * t}{r'^2 * S}$		**5.26**	m
u	u = Equazione di Theis	$u = \frac{r^2 * S}{4 * T * t}$		5.23E-09	
s	Abbassamento piezometrico medio Equazione di Theis	$s = \frac{Q}{4\pi T} W(u)$		3.88	m

Figure 20. Excel sheet used to compute the piezometric lowering (in Italian). In red the input data.

A simulation has been carried out after preliminary pumping test with the configuration of Figure 21, which shows the location of the wells called "P1_E", "P2_E" and "P3_E" (extraction wells) and "P1_I", "P2_I" and "P3_I" (injection wells). The distance between the wells is approximately 90 meters. The configuration is different from the real one (compare with Figure 9), since the simulation has been completed before the re-design of the executive project of the pilot plant.

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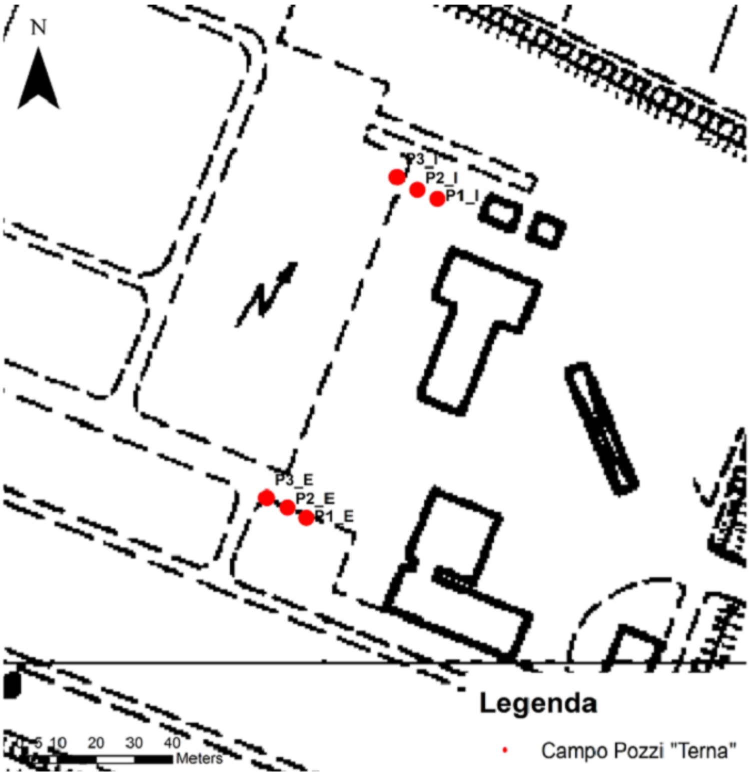

Figure 21. Extraction and injection wells position in the thermal plume simulation.

2.3.3 Final pumping test

Further pumping tests were carried out i) to characterize groundwater extraction impact on aquifer equilibrium and ii) to estimate ambient groundwater flow velocity and direction in operation. The first information is crucial to properly design the extraction-injection system (number of wells and position, pumps size), while the second information is fundamental to evaluate the thermal plume generated by the plant operation and to effectively realize an ATES system.

Once the three extraction and three injection wells were completed, new pumping tests started on 30th October 2017. A first set of tests has been realized with a constant flowrate pumping from one of the extraction wells, while the other ones were monitored with depth meters during the test (Figure 22 and following). The water was reinjected into one of the injection wells. Data were acquired for three working days. Then, each extraction well has been tested with a variable pumping test, to verify if differences can be found from one well to another and to confirm the previous test results from 2016.

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Figure 22. One of the monitoring wells during a constant flowrate pumping test.

Figure 23. The acquisition data device.

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Figure 24. The extraction well with the pump and measuring/regulating devices installed.

2.3.4 Tracer test

The use of tracers is a technically valid and cost-effective method for characterizing contaminant fluxes and hydraulic properties in complex hydrogeologic systems. In the Italian pilot, this method is applied to acquire relevant information about water flow direction within the groundwater during pumping tests at variable flowrate and with the maximum flowrate allowed. The test has been performed with simultaneous groundwater extraction from the three extraction wells and water re-injection in the three injection wells. The evaluation of water flow direction allows to better evaluate the thermal short-circuit risk.

No international standards are available to determine how the test should be carried out: this is a relevant barrier to groundwater characteristics identification. The test has been designed as follows, using electrical conductivity of groundwater as a proxy:

1. Approximately 6 m^3 of groundwater have been mixed in a tank (see Figure 25) with salt tablets for water softener (EN 973) until an electrical conductivity of 9.53 mΩ/cm was measured. Natural groundwater electrical conductivity is about 900 mΩ/cm.

2. The groundwater mixed with salt tracer was then pumped into the well n°6 (see Figure 9), while groundwater was extracted from the well n°5 (see Figure 9) at a constant water flow of 1.5 l/s. The mixed groundwater and the groundwater extracted from the well were alternatively pumped into the injection well, as can be seen from Figure 26.

Figure 25. The tank wherein groundwater and salt tables were mixed together.

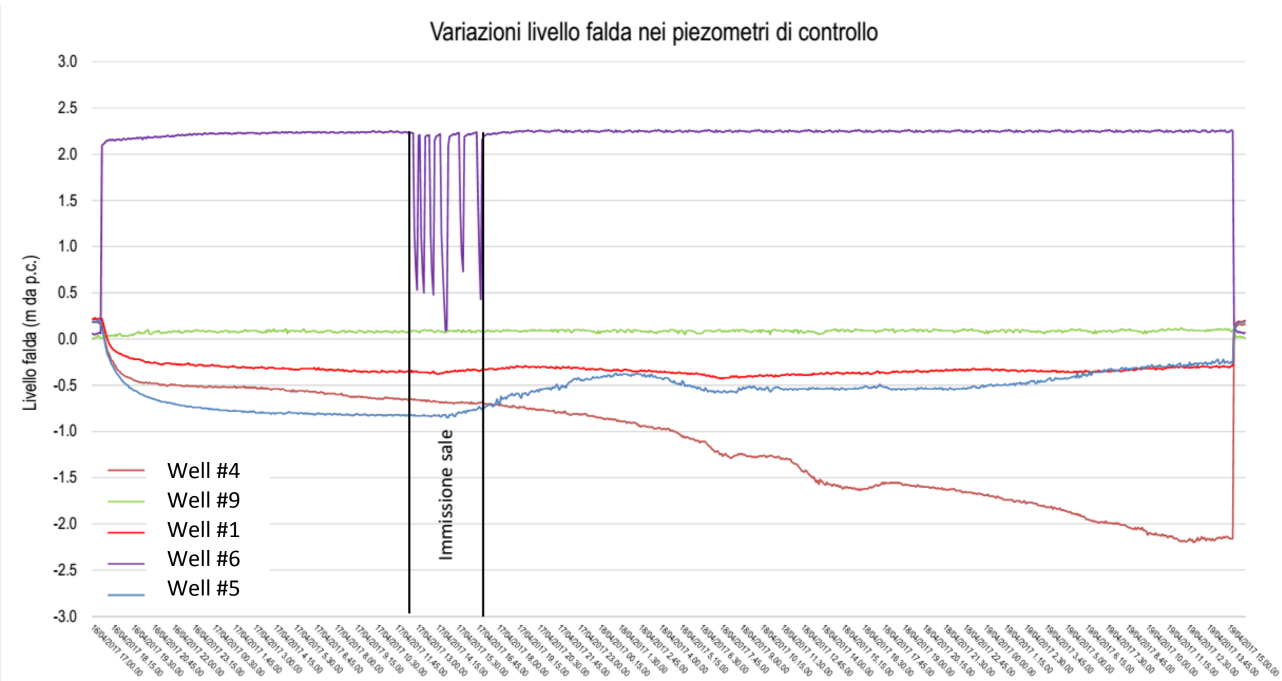

Figure 26. Level variation in the monitored wells during the tracer test. See Figure 9 for wells numbering.

3. During the test, the groundwater was also extracted from the well n°3 (see Figure 9) at a constant flowrate of 2.0 l/s and then re-injected into the well n°7 (see Figure 9 for reference).

4. After the injection of the mixed groundwater was completed, the electrical conductivity was continuously monitored in the well n°5 (see Figure 9). The instrument used for electric conductivity measurement was a Mettler Toledo M200.

5. The phreatic level variation was monitored in several wells (Figure 26), while electric conductivity was monitored in the extraction well.

2.4 Monitoring activities

2.4.1 Groundwater samples chemical-physical characterization

UniBo suggested analyzing chemical-physical characteristics of the water to verify if the aquifer contains some pollutants and to evaluate the risks of wells clogging. A first water sample was taken on 13th July 2016 from an existing well used by Terna SpA for irrigation purposes and sent to a laboratory for analysis. This first sample was characterized by a high manganese concentration.

Once the monitoring wells were realized on October 2016, it was possible to withdraw a water sample directly from one well of the pilot plant (on 9th November 2016). The results showed a high manganese and benzene concentration. Further investigations were needed to analyze:

- manganese characteristics;
- benzene presence.

In particular, the presence of benzene[3] in the aquifer could become a critical issue in the authorization process. In agreement with the regional authority, it was decided to wait about 6 months to repeat water sample analysis from different wells and to verify whether or not benzene is still present. Regarding manganese, the geohydrologist Johan Valstar from Deltares was involved in the analysis of data results. He suggested to realize further tests to verify i) redox potential and ii) manganese form (colloidal or not). The analysis aims to better evaluate the clogging risk. So, further tests were arranged in May 2017.

2.4.2 Energy audit

The purpose of the energy audit was to determine where, when, why and how energy is used in the Martignone station buildings, and to identify opportunities to improve efficiency through ATES system application. The audit typically began with a review of historical and current utility data and benchmarking of building's energy use against similar buildings, including several onsite inspection of the buildings and of the existing space heating and cooling plants. Simulation software have been used to estimate space heating and cooling demand of the buildings, and the estimated figures have been compared with energy bill, if available.

3. Results

3.1 System operation

3.1.1 Preliminary pumping test

[3] The presence of benzene, if confirmed in future samples analysis, can be an interesting case study to apply the bioremediation process also to the Italian pilot. Bioremediation is already under testing in Utrecht and in Denmark, where the biodegradation of contaminants is studied for its accelerated conversion in the warm well. The cases in Utrecht and Denmark deal with chlorinated compounds, however in principle also biodegradation of non-chlorinated compounds might be stimulated under optimal biodegradation conditions. WUR will eventually collaborate on this issue.

Figure 27 shows the results of the preliminary pumping test. The maximum water flowrate that can be extracted from each well has been set at 1.8 l/s (6,5 m^3/h). During the constant rate test at 1,8 l/s carried out in the same well, the other two wells completed at that time (well n°1 and well n°10, see Figure 9) have been used as monitoring wells: monitoring wells (well n°1 in particular) showed a lowering of the aquifer depth that was in the order of centimeters. It was also noted that the aquifer has a very quick recharging, since, after the pump was stopped, in less than two minutes the level turns into the starting value. This is a very interesting characteristic of the aquifer, taking into consideration that the pumping test has been realized in summer and after several weeks of drought.

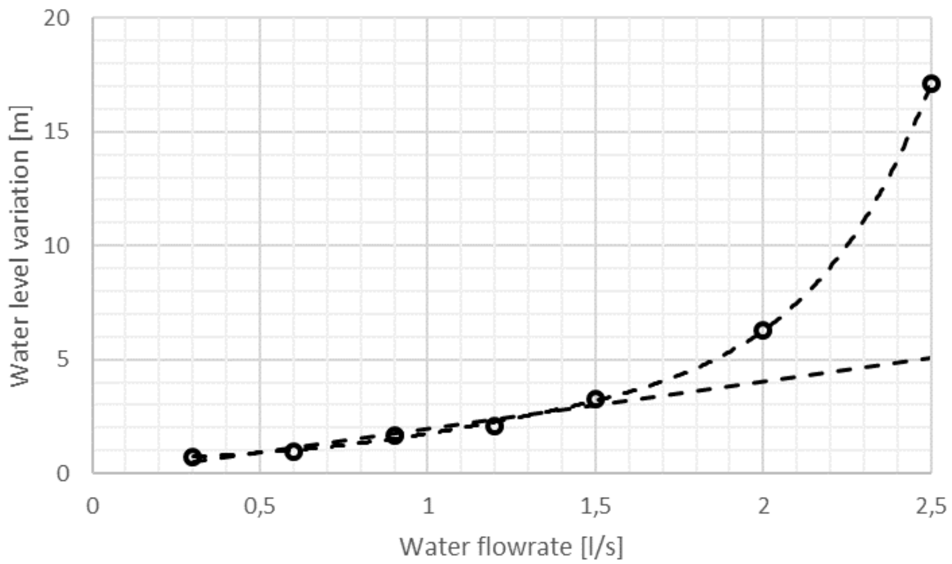

Figure 27. Preliminary pumping test results.

Therefore, on the basis of the preliminary pumping test, the following wells configuration was identified to meet space heating and cooling demand: three extraction wells plus three injection wells.

3.1.2 Thermal plume modelling

The thermal plume was computed with the following data:

- Mean hydraulic conductivity[4] $K = 4.4 \cdot 10^{-3}$ m/s;
- Mean extracted water flowrate Q = 2.5 l/s (0.0025 m^3/s);
- Saturated thickness of the aquifer b = 3 m;
- Diameter of the well ø = 0.125 m;
- Estimated[5] hydraulic gradient i = 0.002;
- Simulation time: 150 days.

The analytical approach is mainly based on literature data and parameters that can be related to the physical properties of the groundwater system under evaluation. In this model, the phenomenon of thermal dispersion and of thermal emission are not considered. So, it will need some kind of validation once the pilot plant will be running. By considering an estimated porosity of 0.3, the ambient groundwater flow velocity can be evaluated in about 900 m/year. So, groundwater ambient

[4] Value computed starting from preliminary pumping test results.
[5] Based on literature data.

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flowrate velocity is really high, and justifies the wells design and positioning (recirculation ATES system). Since injection wells in the thermal plume simulation are quite close (about 15-20 meters), the shape of the thermal plume has been modeled considering the three injection wells as one well. Todd's model has been applied to define the thermal plume shape. The injection influence zone has an elongated shape in the S/SO-N/NE direction due to the estimated maximum slope of the hydraulic gradient which coincides with the direction of the flow lines under undisturbed operation. The maximum length of the cone of influence results as about 290 meters after 150 days (Figure 28), while the length increases up to 1,400 meters with a simulation time of 3 years.

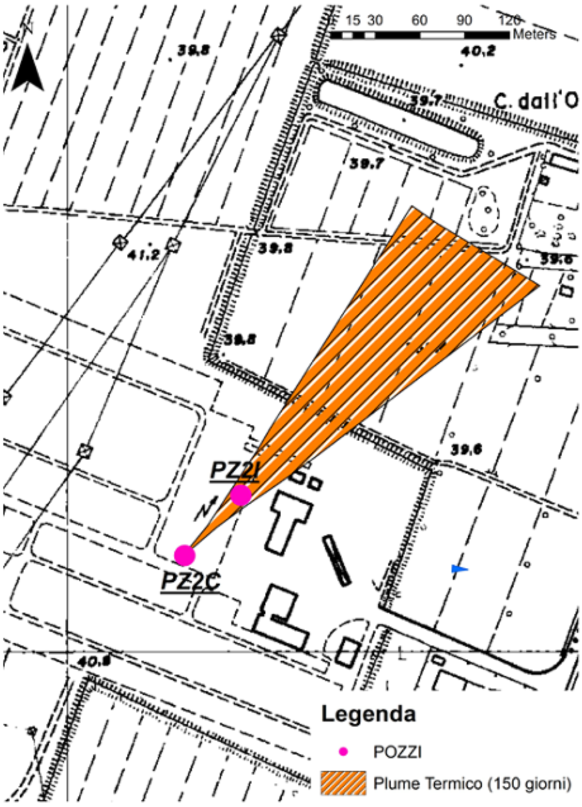

Figure 28. Thermal plume simulation result: influence area produced by cold water injection in the groundwater by extraction/injection water flowrate 2.5 l/s and simulation time of 150 days.

The analysis was completed by assuming the conservative hypothesis of both hydraulic and thermal interference between the extraction and injection wells. Literature gives analytical instruments to [6]compute both hydraulic and thermal times that are needed to reach the extraction wells starting from injection wells. The results are shown in Table 2 (computed by considering a total extraction water flowrate of 2.5 l/s and of 6.0 l/s).

Table 2. Hydraulic and thermal interference estimation between injection and extraction wells.

	ATES system water flowrate (l/s)	
	2.5	**6.0**
Critical distance d (m)	34	81
Hydraulic return time (days)	29	13
Thermal return time (days)	75	34
Percentage of short-circuit flowrate[7]	4%	18%

[6] $d > Q/(b*K*i*\pi)$ between extraction/injection wells to avoid thermal short-circuit.
[7] Defined as the ratio between the water flowrate that flows back from the injection well to the extraction well and the injection water flowrate.

Effect on extraction temperature[8] (°C)	-0.1	-0.6

According to the design distances (about 35 meters) between the nearest injection and extraction wells, and considering also the configuration of the wells field that is coherent with the natural flow direction of the groundwater, a risk of hydraulic interference between the wells is very low with 2.5 l/s water flowrate, while may occur at the maximum water flowrate of 6.0 l/s.

Table 3 summarizes the monthly estimation of extracted and injected groundwater based on thermal and cooling energy need of the buildings served by the pilot plant. Since more than 80% of the energy is needed in wintertime, the thermal plume has been characterized according only to this condition, thus introducing an error that can be considered as acceptable in such a preliminary analysis. It should be noted that, in this case (i.e. by neglecting the summertime operation contribution) the thermal plume is a “cold plume”, i.e. groundwater is cooled with regard to its natural temperature.

Table 3. Thermal and cooling energy demand and related volume of groundwater extracted and injected month by month.

Month	**Thermal energy [MWh]**	**Cooling energy [MWh]**	**Groundwater volume [m^3]**
Jan	57	0	7,182
Feb	35	0	4,410
Mar	20	0	2,520
Apr	3	0	378
May	0	2	252
Jun	0	12	1,512
Jul	0	19	2,394
Aug	0	9	1,134
Sep	0	2	252
Oct	4	0	504
Nov	27	0	3,402
Dec	51	0	6,426
Total	**197**	**44**	**30,366**

3.1.3 Final pumping test

Figure 29 shows the results of depth monitoring during variable pumping tests (i.e. 1.0 lt/s, 1.5 lt/s and 2.0 lt/s, each 30 minutes long) for one of the three extraction-injection wells tested. Figure 29 shows how groundwater level decreases in the wells located near the groundwater extraction well, while it increases in the wells close to the groundwater injection well. Then, Figure 30 shows the natural phreatic level of the groundwater before the test, while Figures 31 and 32 shows, respectively, the absolute variation and the relative variation of groundwater depth during the test at 2 lt/s flowrate.

[8] Decreasing of groundwater extracted temperature due to thermal short-circuit.

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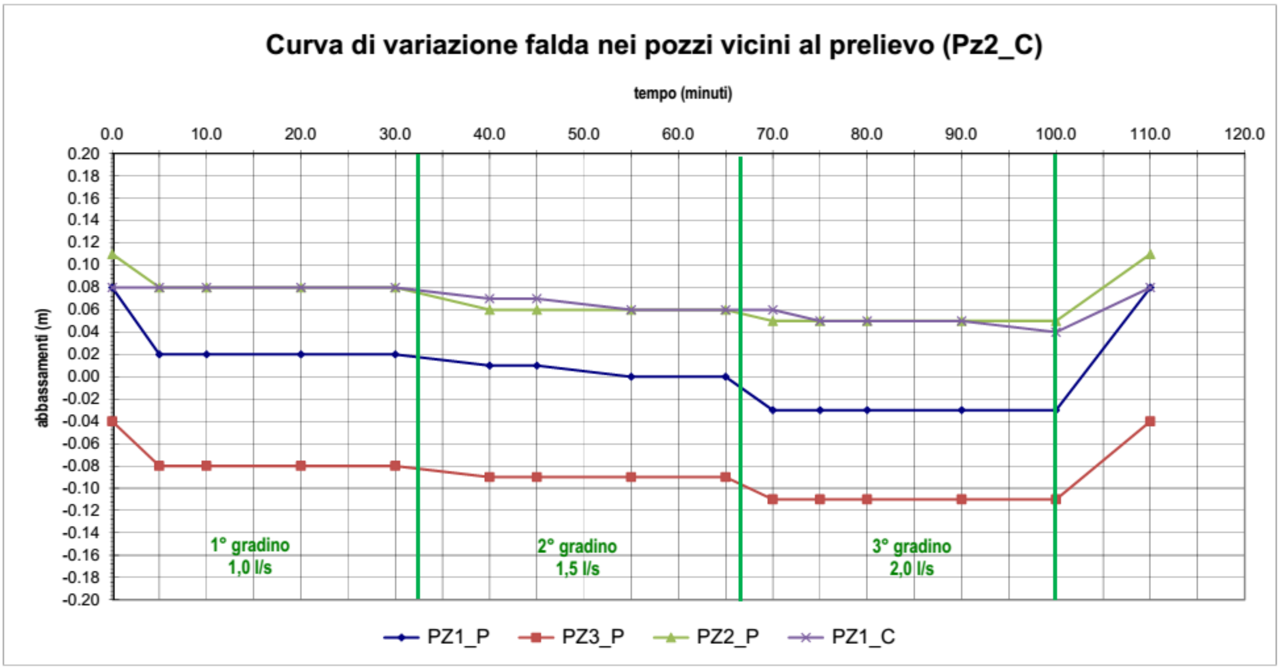

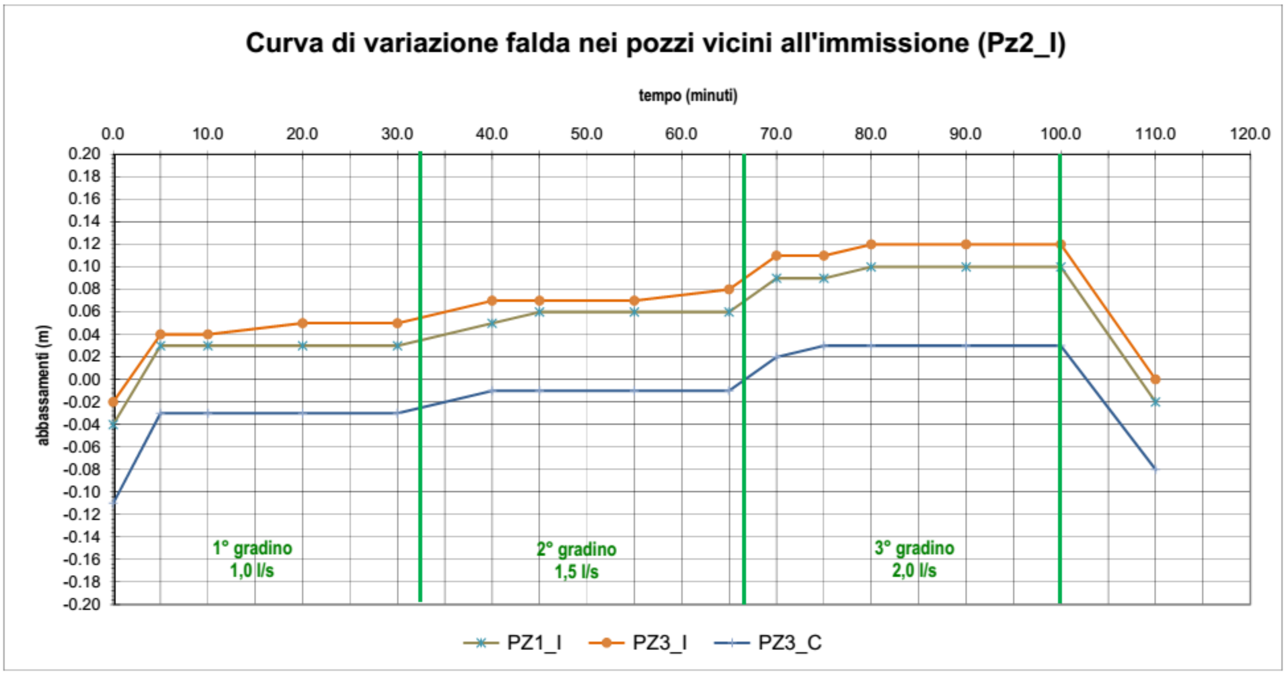

Figure 29. Phreatic level variation in the wells near the injection well (*curva di variazione falda nei pozzi vicini all'immissione*) and in the wells near the extraction well (*curva di variazione falda nei pozzi vicini al prelievo*).

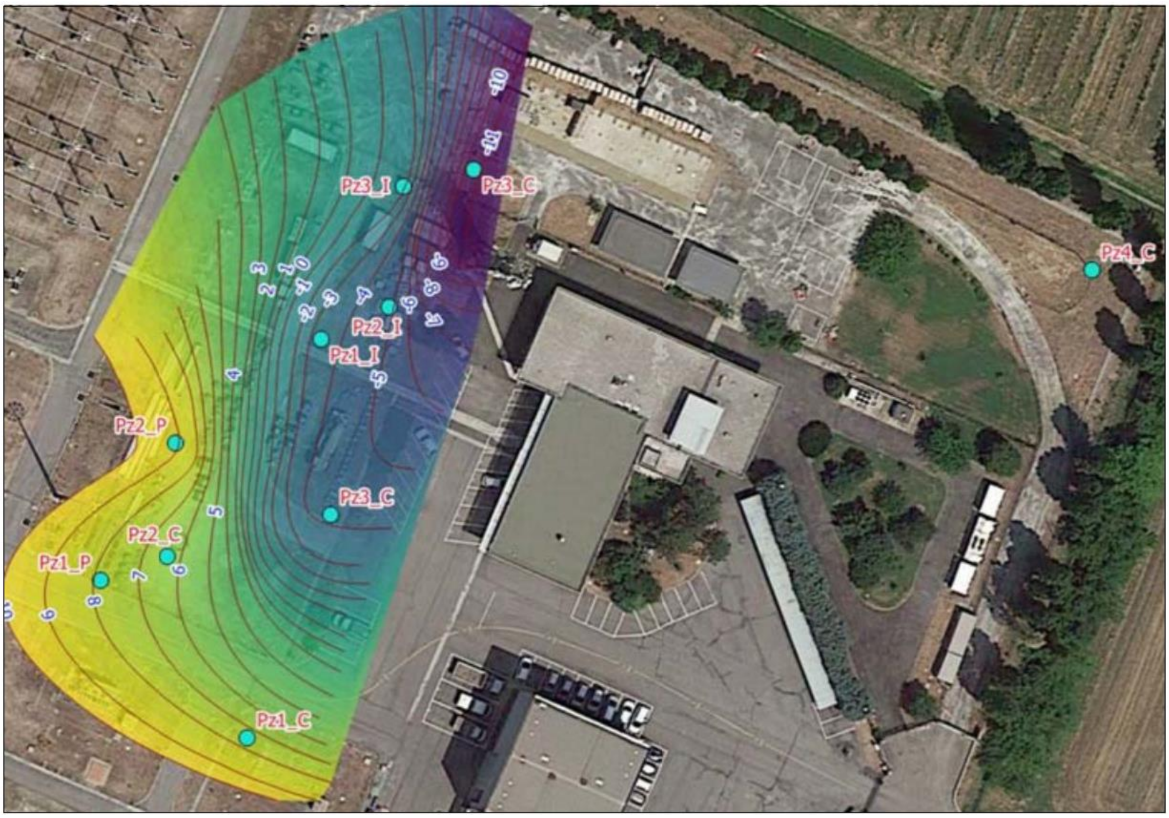

Figure 30. Static phreatic level of the aquifer.

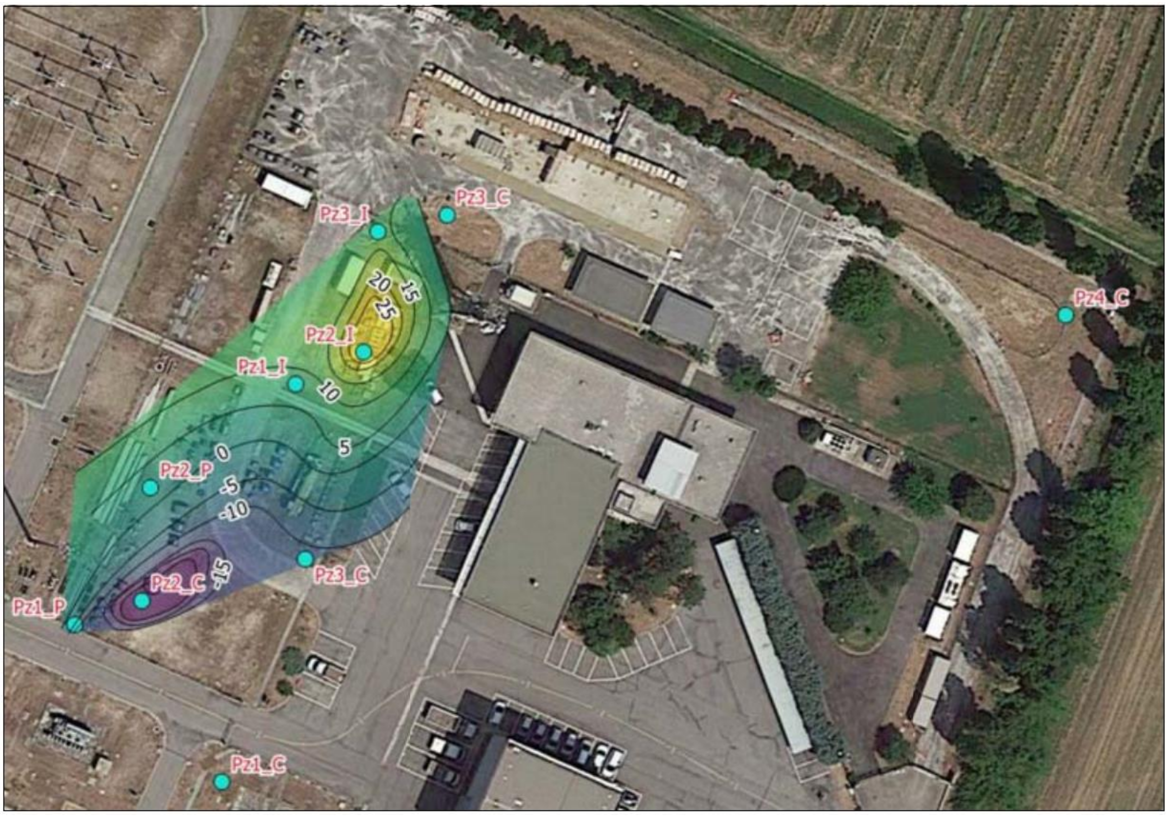

Figure 31. Modification of the phreatic level of the aquifer during variable pumping test.

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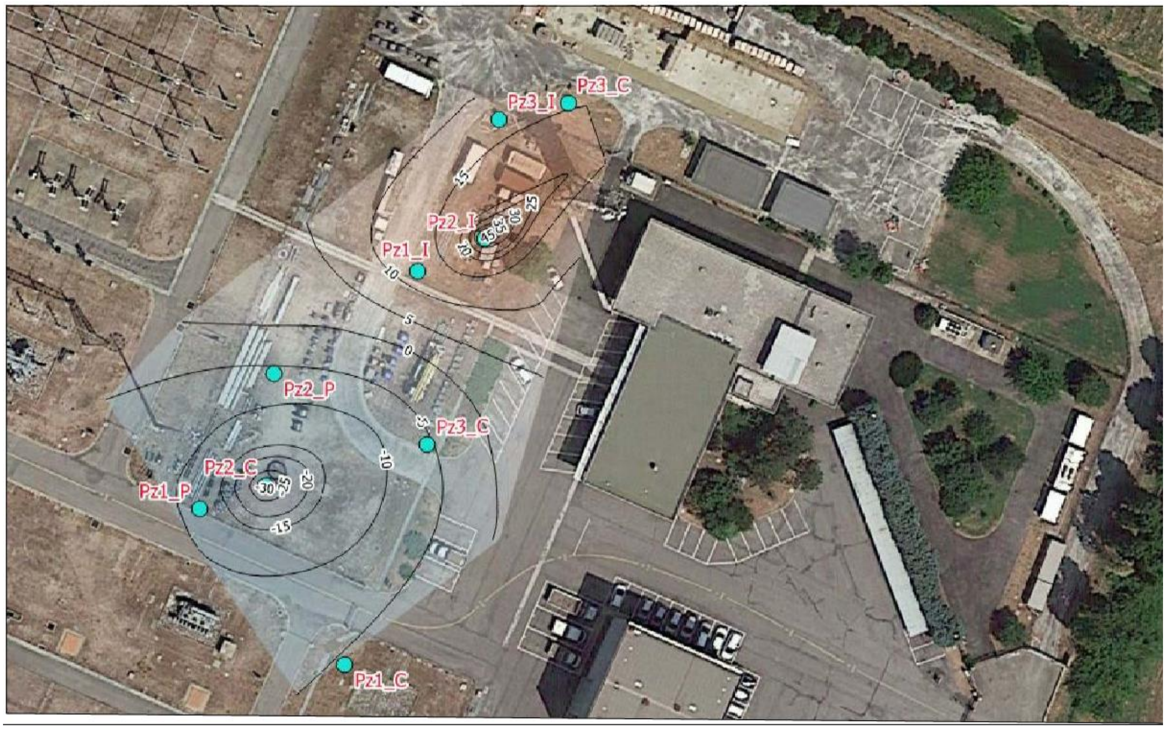

Figure 32. Modification of the phreatic level of the aquifer normalized with the starting values.

Figure 32 shows that a groundwater level depression area is formed with a circular shape near the extraction well, while an asymmetric groundwater elevation 'hump' in the SW-NE direction can be observed around the injection well. The section of the line that connect the two wells (extraction and injection) is shown in Figure 33.

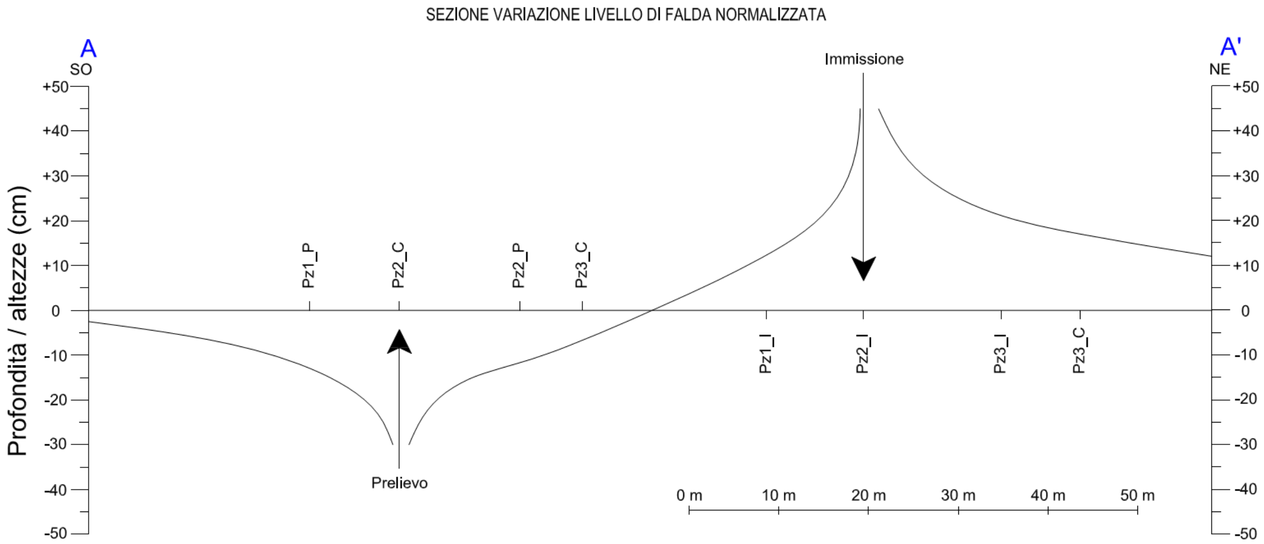

Figure 33. Variation of the phreatic level and hydraulic gradient during extraction-injection pumping test at 2.0 lt/s constant flowrate.

Then, in February 2018 further tests have been organized with simultaneous extraction and re-injection from each well, thus simulating the real plant working condition. The total flowrate has been fixed at 5.5 lt/s – about 1.8 lt/s per well – and kept constant for 96 hours. Unfortunately, after 36 hours from test starting one pump failed, and so the test was concluded with a total flowrate of

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approximately 3.5 l/s from two wells. Figure 34 shows the phreatic level variation in the monitoring wells during the test.

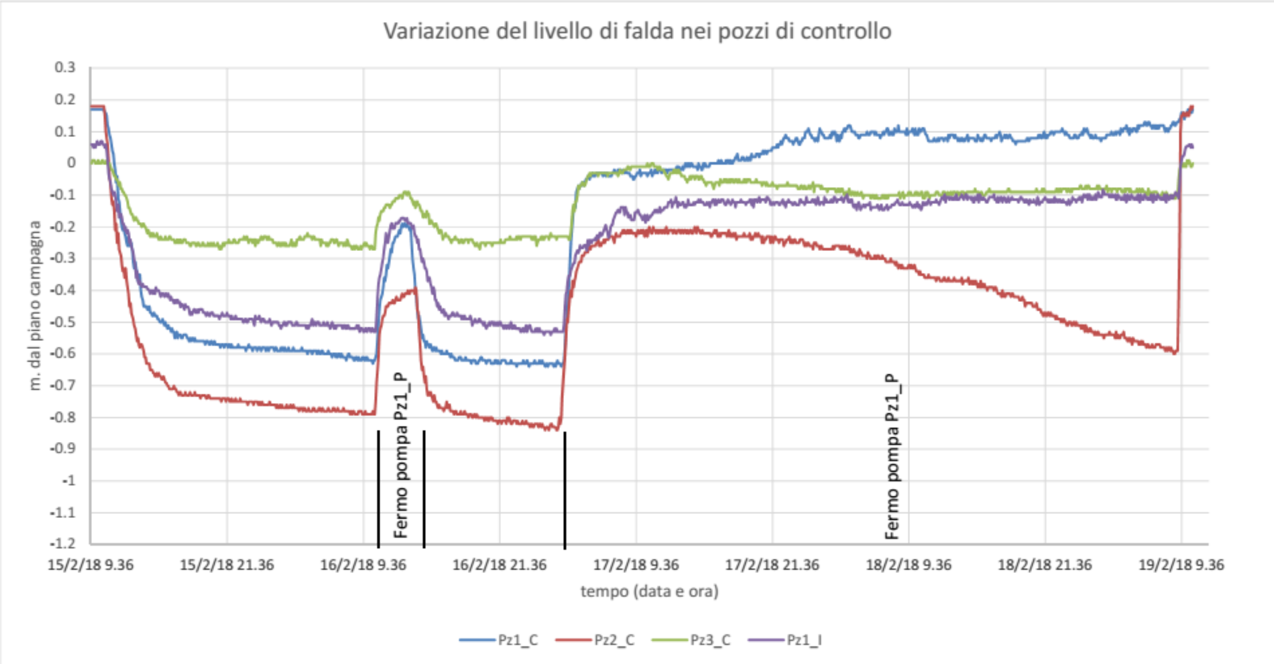

Figure 34. Phreatic level variation in the monitoring wells during the test at constant flowrate.

The monitoring well placed upstream (PZ1_C) is affected by a phreatic level decrease of about 0.7-0.8 m with a pumping flowrate of about 5.5 lt/s, while at flowrate of about 3.5 lt/s there is a re-charging of the aquifer followed by a substantial coming back to the starting condition. This fact should confirm the hypothesis of groundwater flowing in the S-N direction. The monitoring well placed in the middle of the three extraction wells (PZ2_C) is highly affected, with a measured phreatic level decrease of less than one meter at 5.5 lt/s flowrate. After the pumping flowrate variation there is a rapid increase of the phreatic level, followed by a constant decrease which does not reach a stationary point. The remaining monitoring wells (PZ3_C and PZ1_I) are placed downstream and measure a stabilization of phreatic level at two different levels corresponding to the two different pumping flowrate. It should be underlined that after 10 minutes from pumps shut-off the initial conditions were reached.

Darcy equation describes how groundwater flows in a porous media; the groundwater flowrate Q can be expressed as:

$$Q = K \cdot A \cdot i$$

where K is the hydraulic conductivity, A is the theoretical cross-section of the aquifer and i is the hydraulic gradient. So, the groundwater flow velocity V can be expressed as:

$$V = K \cdot i$$

Hydraulic conductivity K has been computed on the basis of Figure 35 data, which includes data from the pumping tests carried out in October 2017. K resulted equal to 10^{-4} m/s, that is in line with previous results (see thermal plume hypothesis).

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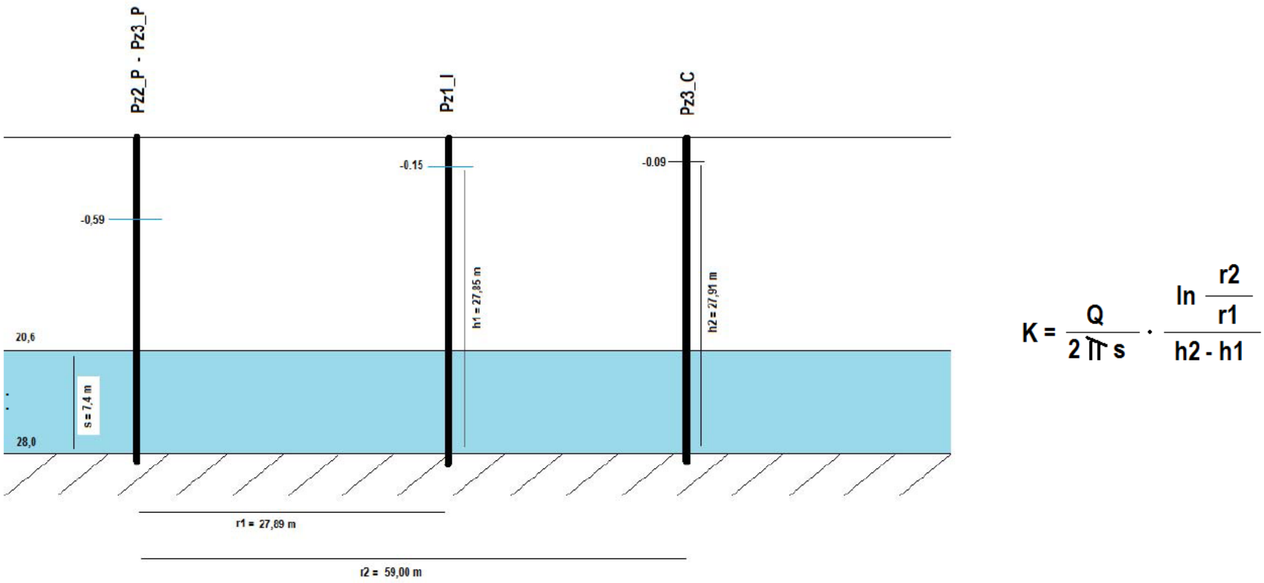

Figure 35. Computation scheme adopted for hydraulic conductivity K estimation. Q was the flowrate extracted from Pz2_P and Pz3_P wells during the tests carried out in October 2017.

3.1.4 Tracer test

After approximatively 20 hours from the end of tracer application within the injection well, a variation in the electrical conductivity started to be observed in the extraction well (Figure 36). A minimum value of 800 mΩ/cm was measured (i.e. a 11% reduction if compared to the nominal value of 900 mΩ/cm measured before the test). Then, after about 18 hours, the electrical conductivity rises and turns back to the nominal value measured before the test started.

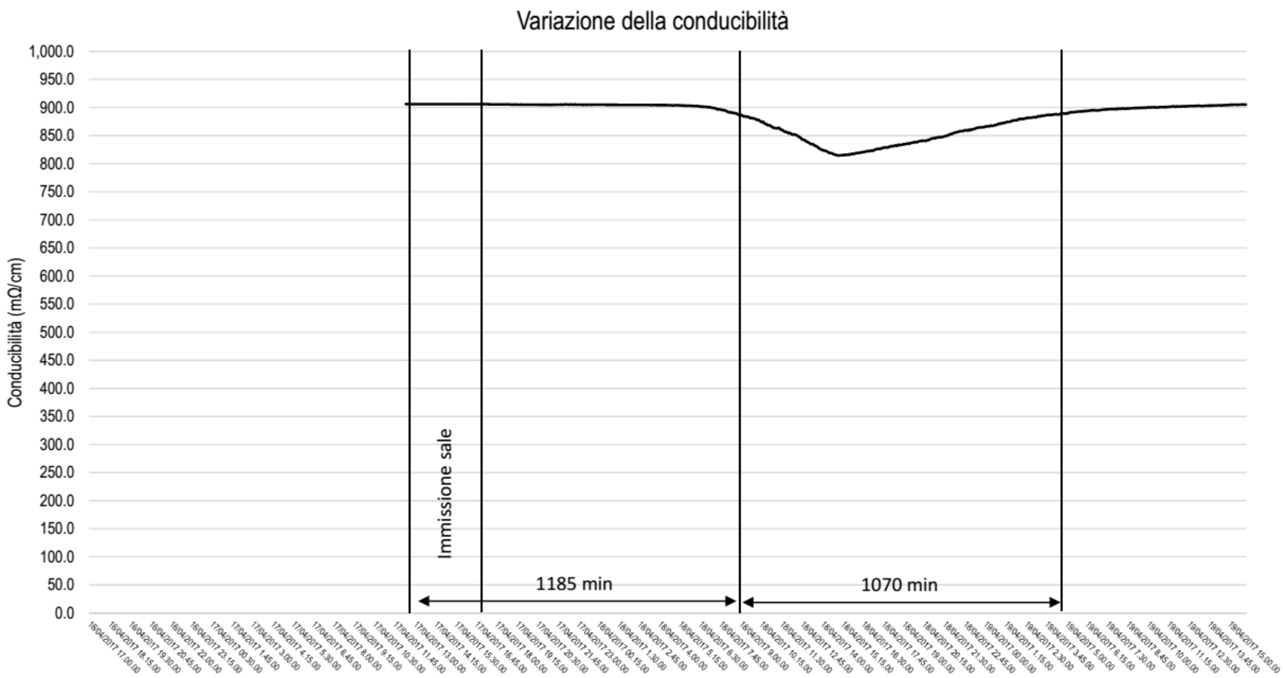

Figure 36. Electric conductivity variation within the well n°5 (see Figure 9 for reference).

Therefore, a short-thermal circuit can occur at maximum water flowrate and for a long operation time, but it is confined to the nearest extraction-injection wells and with limited impact in terms of water flow. Nevertheless, it was decided to use the nearest of the foreseen injection well (well n°5

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in Figure 9) as monitoring well, and to use the close monitoring well (well n°4 in Figure 9) as injection well instead. So, the final wells configuration of Figure 9 has been adopted.

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3.2 Monitoring

3.2.1 Groundwater samples chemical-physical characterization

Table 4 provides a summarize of all water sample analysis results.

Table 4. Results of water samples chemical-physical analysis. Underlined in yellow the values that exceed law limits. Reference for wells numeration is Figure 9.

				Date: 13/07/2016	Date: 09/11/2016	Date: 16/05/2017	Date: 16/05/2017	Date: 16/05/2017
				Well: Existing	Well: Well #5	Well: Well #5	Well: Well #1	Well: Well #10
				Pump: Off	Pump: On	Pump: Off	Pump: Off	Pump: Off
Test	**Quantity**	**Method**	**Allowed limits**	**Result**	**Result**	**Result**	**Result**	**Result**
pH	u pH	APAT CNR IRSA 2060 Man 29 2003		7.5	6.9	6.8	6.9	6.9
Conductivity	µS/cm	APAT CNR IRSA 2030 Man 29 2003		1200	1200	1300	1200	1200
Fixed residue at 180°C	mg/l	APAT CNR IRSA 2090 A Man 29 2003		560	770	670	680	620
Total hardness	mg/l CaCO3	APAT CNR IRSA 2040 B Man 29 2003		560	590	630	610	640
Nitrites	mg/l	MI 118 rev 9 2013		100	130	98	92	100
Nitrates	µg/l	MI 119 rev 7 2013	500	< 200	<200	230	860	<200
Ammonia nitrogen	mg/l NH4	M.U. 2363:09 A		< 0,10	0.14	<0,1	0.12	<0,1
Chlorides	mg/l	MI 120 rev 8 2013		48	50	53	49	56
Sulphates	mg/l	MI 123 rev 9 2015	250	90	76	40	72	48
Iron	µg/l	DIN EN ISO 11885:2009	200	< 10	60	20	790	100
Manganese	µg/l	DIN EN ISO 11885:2009	50	1200	1300	1300	1300	1400
Lead	µg/l	DIN EN ISO 11885:2009	10	< 5	<5	<5	<5	<5
Mercury	µg/l	DIN EN 1483:2007	1	< 0,1	<0,1	<0,1	<0,1	<0,1
Cadmium	µg/l	DIN EN ISO 11885:2009	5	< 1	<1	<1	<1	<1
Total hydrocarbons	µg/l	ISO 9377-2:2000	350	< 100	<100	<100	<100	<100
Escherichia coli	UFC/100 ml	UNI EN ISO 9308-1:2014	0	none	none	none	none	none
Total coliform bacteria at 37°C	UFC/100 ml	UNI EN ISO 9308-1:2014		none	3700	410	32	5
Enterococcus	UFC/100 ml	UNI EN ISO 7899-2:2003	0	none	none	none	none	none
Dissolved oxygen	mg/l	MI 191 rev 1 2015		1.8	2	1.4	1.9	1.9
Sodium	mg/l	DIN EN ISO 11885:2009		29	33	29	37	29
Potassium	mg/l	DIN EN ISO 11885:2009		1.8	2	1.6	1.5	1.7
Magnesium	mg/l	DIN EN ISO 11885:2009		30	32	32	34	32
Calcium	mg/l	DIN EN ISO 11885:2009		200	190	210	190	200
Tribromomethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.3	< 0,03	<0,03	<0,03	<0,03	<0,03
1,2-Dibromethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.001	< 0,001	<0,001	<0,001	<0,001	<0,001
Dibromochloromethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.13	< 0,013	<0,013	<0,013	<0,013	<0,013
Bromodichloromethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.17	< 0,017	<0,017	<0,017	<0,017	<0,017
Chloromethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	1.5	< 0,04	<0,04	<0,04	<0,04	<0,04
Trichloromethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.15	< 0,015	<0,015	<0,015	<0,015	<0,015
Vinyl chloride	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.5	< 0,05	<0,05	<0,05	<0,05	<0,05
1,2-Dichloroethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	3	< 0,03	<0,03	<0,03	<0,03	<0,03
1,1-Dichloroethylene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.05	< 0,005	<0,005	<0,005	<0,005	<0,005
Trichloroethylene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	1.5	< 0,03	<0,03	<0,03	<0,03	<0,03
Tetrachloroethylene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	1.1	< 0,05	<0,05	<0,05	<0,05	<0,05
Hexachlorobutadiene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.15	< 0,015	<0,015	<0,015	<0,015	<0,015
Total aliphatic carcinogenic	µg/l	EPA 5030C 2003 + EPA 8260C 2006	10	< 0,235	<0,235	<0,235	<0,235	<0,235
1,1-Dichloroethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	810	< 0,04	<0,04	<0,04	<0,04	<0,04
1,2-Dichloroethylene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	60	< 0,11	<0,08	<0,08	<0,08	<0,08
1,2-Dichloropropane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.15	< 0,05	<0,05	<0,01	<0,01	<0,01
1,1,2-Trichloroethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.2	< 0,02	<0,02	<0,02	<0,02	<0,02
1,2,3-Trichloropropane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.001	< 0,001	<0,005	<0,001	<0,001	<0,001
1,1,2,2-Tetrachloroethane	µg/l	EPA 5030C 2003 + EPA 8260C 2006	0.05	< 0,005	<0,005	<0,005	<0,005	<0,005
Benzene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	1	< 0,1	1.1	< 0,1	< 0,1	< 0,1
Toluene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	15	< 0,1	1.7	< 0,1	< 0,1	< 0,1
Ethilbenzene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	50	< 0,1	1.4	< 0,1	< 0,1	< 0,1
Styrene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	25	< 0,1	1.2	< 0,1	< 0,1	< 0,1
m-xylene+p-xylene	µg/l	EPA 5030C 2003 + EPA 8260C 2006	10	< 0,2	2.6	< 0,2	< 0,2	< 0,2
Anionic surfactants	mg/l	MI 131 rev 8 2015		0.2	0.27	< 0,2	< 0,2	0.32
Non ionic surfactants	mg/l	MI 132 rev 7 2013		< 0,5	0.04	< 0,5	< 0,5	<0,5
Cationic surfactants	mg/l	MI 134 rev 2 2008		< 0,2	<0,2	< 0,2	< 0,2	0.32

Data analysis of repeated sampling confirms that manganese remains present at a very high concentration. After a brief literature survey, it was found that high concentrations of manganese and/or iron are quite common in the area and that this is not of anthropogenic origin. Moreover, the analysis shows that some parameters, including benzene, had fluctuations over the time and are probably influenced also by well position.

The absence of benzene in the next monitoring round allowed submitting the authorization request to the regional authority with no environmental issues regarding aquifer contamination risk. Nevertheless, all the parameters listed in Table 4 (benzene included) will be seasonally monitored.

Three further samples were withdrawn from the three extraction wells during the last pumping test in 2017 to complete the manganese characterization. Two different tests have been realized, accordingly to Johan Valstar (Deltares) advices (results in Table 5):

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- redox potential;
- manganese concentration in the sample and manganese concentration in the filtered portion of the sample, to estimate percentage of manganese presence in colloidal form.

Table 5. Further groundwater samples analysis on redox potential and manganese form.

Sample	**Total Manganese**	**Manganese after filtration (with 0.45 micron filter)**	**% Unfiltered Manganese**	**Redox potential**
1	1251 µg/l	1145 µg/l	91,5%	178 mV
2	1149 µg/l	1136 µg/l	98,9%	162 mV
3	1019 µg/l	953 µg/l	93,5%	138 mV

Data show that manganese concentrations do not decrease after filtering, thus a relevant fraction of not dissolved manganese is present. Therefore, the risk of clogging cannot be excluded. Nevertheless, considering the covering layer and limited thickness of the aquifer, chances for manganese precipitation should be very limited. Furthermore, the groundwater has been already extracted and injected at the site during the pumping tests and no problems related to clogging were observed. So, manganese precipitation, if any, is probably not a fast process, but biological enhanced oxidation of manganese may develop over time. Further analysis may be realized with nano-filters or centrifuges with nano-separators, but still an Italian laboratory[9] has to be identified able to perform such analysis. Furthermore, oxygen concentration measurements should be repeated to verify redox potential values.

In conclusion, it can be stated that manganese presence may increase the clogging risk in the injection wells, even if the risk seems to be marginal. In the first months of pilot plant operation the groundwater injection will be monitored with particular attention.

3.2.2 Energy audit

The peak requirement of thermal power in wintertime was estimated by applying the UNI EN 12831. The external design temperature was fixed at -5°C, while conditioned room temperature was set at 20°C. On the basis of rooms volume and surface, as well as by an estimation of buildings characteristics, the following estimation was found, summarized in Table 6.

Table 6. Estimated peak requirement of thermal power in wintertime.

Building A (changing rooms building)	**Thermal power [kW]**	**Notes**
Tooling	16.8	Room temperature of 18°C; heat fed through ceiling panels.
Changing room	11.8	The one with heat fed through heat pumps.
Other rooms	28.3	
Total	*56.9*	
Building B (office building)	**Thermal power [kW]**	**Notes**

[9] A local laboratory should be identified since one sample should be analysed as soon as possible after sampling to limit groundwater characteristics modification.

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Total ground floor	43.1	
Total second floor	44.7	
Total	*87.8*	
TOTAL (A+B)	144.7	

Then, on the basis of mean annual environmental data, an estimation of primary energy consumption for heating has been estimated too (UNI EN ISO 13790 and UNI TS 11300-1). Due to the oversizing of existing plants (methane boilers), a seasonal efficiency of about 80% has been attributed to the existing plants, taking into account heat generation, distribution, regulation and emission. The methane consumption has been estimated as summarized in Table 7.

Table 7. Estimated annual methane consumption for thermal power feeding in wintertime.

Building	**Methane consumption [Nm^3/year]**
Building A	11,000
Building B – ground floor	6,700
Building B – first floor	7,500
Total	25,200

The computation of past energy consumption faced different technical obstacles. First of all, there is no separated measurements of electric energy consumption, i.e. there is one electric energy meter for the whole Martignone station. The presence of one meter is justified by the fact that Terna has a special contract for energy consumption, so there was no need to measure the consumption of different subsystems fed by electric energy in the station. Moreover, the major quantity of electricity is consumed by the electric station, and not by the buildings' facilities, so there is no chance to make a seasonal analysis of the whole electric consumption to identify summertime consumption increasing due to space cooling impact. Secondary, in the last years different implementations have been carried out on the structure of the buildings to increase their efficiency. Finally, a back-up electric boiler has been installed in 2014 for building B heating, so it is difficult to know what is the contribution of this new boiler to the whole thermal energy production. Nevertheless, by analyzing methane consumption it is possible to have a rough comparison between estimation and real consumption. The whole methane consumption of Martignone station has been summarized in Table 8 starting from 2013.

Table 8. Whole measured methane consumption in Martignone station.

Year	**Methane consumption [Nm^3]**
2013	24,160
2014	20,020
2015	21,830

Real consumption shows that only a limited overestimation had been made through the estimation model with regard to year 2013, when the electric boiler was not installed yet. So, the model used for the estimation of peak power as well as annual energy request can be considered as a good approximation of real data.

The peak requirement of cooling power in summertime was estimated by applying the UNI EN 12831. The design has been done by considering an external air temperature of 33°C, while conditioned room temperature was set at 24°C. On the basis of rooms volume and surface, as well as by an estimation of buildings characteristics, the following estimation was found, summarized in Table 9.

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Table 9. Estimated peak requirement of cooling power in summertime. (*) no cooling terminal.

Building A (changing rooms building)	**Cooling power [kW]**
Tooling room (*)	0.0
Changing room	13.1
Other rooms	2.7
Total	*15.8*
Building B (office building)	**Cooling power [kW]**
Total ground floor	68.7
Total second floor	71.2
Total	*139.9*
TOTAL (A+B)	**155.7**

One interesting result, relevant for plant design, is that cooling peak demand is higher than thermal one, and that this is concentrated in the office building, this should be taken into account for the heat pump/chiller sizing.

On the basis of summertime peak demand estimation, and considering seasonal environmental data of the site, an annual cooling energy demand of 49,000 kWh per year has been estimated. So, an estimation of current electric consumptions can be done: by considering a mean energy efficiency ratio (EER) of about 3.0 for the existing chillers, a yearly electric consumption of 16,300 kWh can be estimated.

4. Evaluation of system performance

The current thermal energy consumption can be estimated on the basis of the energy audit carried out by UniBo in 2016 and 2017. The yearly energy consumption for buildings heating is estimated to be about 170,000 kWh and it is generated by methane boilers. Mean annual energy consumption of methane is about 24,000 Nm^3/year (a seasonal boilers efficiency of 70% has been considered).

On the basis of summertime peak demand estimations, and considering seasonal environmental data of the site, an annual cooling energy demand of 49,000 kWh per year has been computed. So, an estimation of current electrical consumption can be done: by considering a mean energy efficiency ratio (EER) of about 3.0 for the existing chillers, a yearly electric consumption of 16,300 kWh can be estimated.

The assumption of energy savings estimations is that the pilot plant can completely substitute methane consumption for space heating and existing chillers' electric consumption for space cooling. Heat is now produced via heat pumps with an estimated coefficient of performance (COP) of 4.0. So, electric energy consumption for space heating can be estimated to be about 42,500 kWh. Instead, cooling is generated via chillers (reversible heat pumps) with an estimated EER of about 8.5. The value is very high if compared with air-to-water chiller since in summertime the air can reach temperatures up to 35-40°C, while groundwater is more or less constant at 14-16°C. So, electrical energy consumption for cooling is about 5,800 kWh.

Thus, total electric energy consumption for both space heating and cooling in the new pilot plant configuration can be estimated in 48,300 kWh.

The energy savings can be estimated as follows:

- methane consumption (old plant): 24 x 0.82 = 19.68 TOE (1,000 Nm3 of methane = 0,82 ton of oil equivalent, TOE);
- electric energy consumption (old plant): 16.3 x 0.25 = 4.08 TOE (1 MWh electricity = 0.25 TOE);
- electric energy consumption (new plant): 48.3 x 0.25 = 12.08 TOE.

The result is a yearly energy saving of 11.68 tons of oil equivalent. The reduction of equivalent CO_2 emission can be computed as follows:

- CO_2 equivalent emissions due to methane consumption (old plant): 24,000 x 1.96 = 47,040 kg of equivalent CO_2 (1.96 kg di CO_2 per Nm^3 of methane);
- CO_2 equivalent emissions due to electric energy consumption (old plant): 16,300 x 0.35 = 5,705 kg of equivalent CO_2 (0.35 kg di CO_2 per kWh of electric energy);
- CO_2 equivalent emissions due to electric energy consumption (new plant): 48,300 x 0.35 = 16,905 kg of equivalent CO_2.

The new plant configuration leads to an emission reduction of about 35.8 tons of equivalent CO_2 per year. Table 10 summarizes the energy and CO_2 savings.

Table 10. Summary of estimated energy and $CO_{2\ eq}$ emission savings.

	Old plant	**Pilot plant**	**Net savings**
Methane + electric energy consumption (TOE)	19.68 (methane) 4.08 (electric energy)	12.08 (electric energy)	11.68
CO_2 emissions (tons $CO_{2\ eq}$)	47 (methane) 5,7 (electric energy)	16.9	35.8

Based on the available information, the impact on groundwater quality can be considered as negligible, due to high groundwater natural flowrate velocity and the adoption of a recirculation ATES system.

5. Conclusions related to barriers and issues addressed

Monitoring actions on the aquifer and on the existing plants/buildings demonstrated to be fundamentals to overcome the existing barriers to ATES systems development in Italy (Table 11) and to achieve an optimal design approach, including both below and above ground pilot plant sections. Moreover, monitoring actions are precious to make the authorization process as quick as possible and allow the realization of more accurate simulation of the plant impact (i.e. thermal plume study). In particular, data coming from monitoring actions have been used for the implementation of the executive project of the pilot plant, for the computation of the thermal plume and for the authorization/permit obtaining.

Table 11. Summary of improvements at Terna site due to project consortium support.

Critical barriers detected	**Solution implemented by Terna through the support of E-USE(aq) consortium support**
Lack of technology knowledge: the original	Installation of reversible heat pumps to produce

project made by Terna does not include cooling.	both heat and cold, plus chiller dedicated to rooms that require space cooling all over the year.
Lack of technology knowledge: the original project made by Terna does not include monitoring devices and a centralized system for monitoring and control of the plant.	Implementation of the project to measure the impact on groundwater and the efficiency and effectiveness of the ATES plant.
Lack of knowledge about aquifer characteristics.	Realization of preliminary pumping test to properly design groundwater extraction and injection wells.
	Aquifer samples chemical-physical analysis to investigate potential critical conditions (i.e. clogging risk).
	Realization of pumping test simulating waterflow extraction and injection as in operation to evaluate the impact of ATES system operation on the aquifer equilibrium.
	Realization of salt tracer tests to evaluate thermal short-circuit risk.
Different skills requested for the proper design of the system.	Identification of local partners for the design and realization of the plant: Subsoil and Omega Associati for design, Subsoil for wells realization, Medielettra for heating/cooling plant realization, plus Terna (pilot plant owner). UniBo, Deltares, WUR and TU Delft contributed to the implementation of the executive project.
Authorization/permit process not clearly defined	Continuous and pro-active involvement of the regional environmental agency (ARPAE) in the design process of the ATES plant.
	Realization of thermal plume study to evaluate the impact of ATES plant.
	Design of a robust and complex monitoring system able to evaluate continuously the impact of the ATES plant on the aquifer.

Annex list, annexes available on request

Annex 01	Regional authorization for groundwater extraction
Annex 02	Regional authorization for groundwater injection
Annex 03	Preliminary techno-economic evaluation of potential demo sites
Annex 04	New blue print for the new site under investigation for pilot plant realization in Italy
Annex 05	Analysis and design of energy scenarios including ATES for an anaerobic digestion plant