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Groundwater flow modeling supporting a remediation project within a chemical facility

Modello di flusso della falda utilizzato nell'ambito di un progetto di bonifica di un sito industriale

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ABSTRACT - Environmental characterization activities and hydraulic testing were conducted at a chemical plant located in Lombardy, in the upper portion of the Po Plain, in close proximity to a river. The subsoil consists of fluvial and glaciofluvial deposits (sand and gravel mixtures) about 30 m thick and hosting the unconfined aquifer, followed by mixed continental-marine deposits (sandy gravels, interbedded with silty layers) about 50 m thick, hosting a confined aquifer, which is separated from the hydrogeologic unit above by a silty and clayey level and is delimited at its bottom by marine clays representing a regional aquiclude. No further details can be provided on the geographical and geological description of the site, because of their confidential nature.

The purpose of the characterization activities, requested to comply with Italian environmental regulation, was to identify the presence and extent of suspected contamination. One of the investigated areas was a man-made basin (or basin), excavated in the central portion of the facility and used in the past to collect post-process cooling water. Chemical analyses confirmed the presence of constituents within both the sediments at the bottom and the first 0.5 m of native subsoil beneath the basin. The area, notified as contaminated to the Italian Authorities had to be remediated.

Hydrogeological tests were thus conducted to evaluate the local hydrogeological properties of the aquifer beneath the plant and set up a groundwater model to be used as a supporting tool for the remediation of the area. In fact, the bottom of the basin, which was not sealed with any impermeable layer, was located at about 2.5 m of depth and resulted below the local groundwater level, generally found at about 2.2-2.3 m below ground surface. Pumping wells were necessary to decrease the local groundwater level in order to excavate sediments and soil and restore the site by means of clean material and the construction of a concrete basin, in dry and safe conditions.

The local hydraulic properties (Transmissivity, Hydraulic Conductivity and Storativity) obtained from the interpretation of the pumping activities and the general response of the aquifer system to the hydraulic tests were used to calibrate a groundwater flow model, which was built using the mathematical code MicroFEM©, version 3.60.66, a hybrid finite element-finite difference method for the calculation of heads.

The purpose of the model was to determine the minimum number and the location of pumping wells required to meet the project objectives (namely, impose a groundwater level necessary to conduct field works required for the site remediation at an optimized pumping rate). Based on the model's prediction, two pumping wells were actually installed and operated at the pumping rates defined after several runs of the model. The groundwater levels in the working area could be lowered to the desired level and excavation works were safely completed. The model was therefore a useful tool to support the site-specific remediation plan.

KEY WORDS: aquifer testing, finite element method, pumping configuration optimization, remediation, transmissivity, unconfined aquifer.

RIASSUNTO - Attività di caratterizzazione ambientale e test idraulici sono stati condotti presso uno stabilimento chimico situato in Lombardia, nella porzione superiore della Pianura Padana, collocato in prossimità di un fiume. Il sottosuolo dell'area è costituito da depositi fluviali e fluvioglaciali (miscele di ghiaia e sabbia) spesso circa 30 m, al cui interno si trova l'acquifero freatico. Ad essi fanno seguito depositi misti continentali e marini (ghiaie sabbiose intercalate da strati limosi) spessi circa 50 m, al cui interno si trova un acquifero confinato, separato dall'unità idrogeologica soprastante da un livello di argilla limosa e delimitato alla base da argille marine che rappresentano l'acquicludo a scala regionale. Per ragioni di riservatezza non vengono forniti ulteriori dettagli in merito all'ubicazione geografica e alla descrizione geologica del sito.

Le attività di caratterizzazione sono state condotte per identificare la presenza e l'estensione di una possibile contaminazione all'interno del sito. Tra le aree indagate era compreso un bacino artificiale, realizzato nella porzione centrale dello stabilimento e che, in passato, veniva utilizzato per raccogliere la acque di raffreddamento utilizzate nei processi industriali svolti in sito. Le analisi chimiche hanno confermato

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la presenza di composti chimici sia nei sedimenti al fondo che nei primi 0,5 m di terreno naturale al di sotto del bacino artificiale. L'area, notificata alle autorità italiane come contaminata, necessitava di interventi di bonfica.

Sono state successivamente svolte delle prove idrauliche allo scopo di valutare le proprietà idrogeologiche dell'acquifero nell'area dello stabilimento, e sviluppare un modello idrogeologico della falda da utilizzare come strumento decisionale nell'ambito delle operazioni di bonifica pianificate per il sito. Infatti, il fondo del bacino artificiale, non impermeabilizzato, era posto a circa 2,5 m di profondità e risultava più basso di circa 0,2-0,3 rispetto al livello medio di falda. Era dunque necessario utilizzare dei pozzi di pompaggio per deprimere localmente il livello della falda in modo da poter eseguire, in condizioni di sicurezza e all'asciutto, attività di scavo per rimuovere i sedimenti e il terreno naturale e ripristinare il sito mediante la stesura di terreno pulito e la costruzione di una vasca di cemento.

Le proprietà idrauliche locali (trasmissività, conducibilità idraulica e coefficiente di immagazzinamento) ottenute dall'interpretazione delle prove idrauliche e la risposta in generale dell'acquifero ai test condotti sono state utilizzate per la calibrazione del modello idrogeologico della falda, realizzato utilizzando il codice matematico MicroFEM© 3.60.66, che utilizza un metodo ibrido (elementi finiti-differenze finite) per il calcolo del livello potenziometrico.

Lo scopo del modello era determinare il numero minimo di pozzi di pompaggio, la loro ubicazione ideale e la portata ottimale di emungimento, necessari a raggiungere gli obiettivi del progetto, cioè ad abbassare il livello della falda in modo da poter svolgere le attività richieste per la bonifica del sito.

In base alle risposte fornite dal modello sono stati perciò installati due pozzi di pompaggio, emunti alle portate indicate a seguito di diverse iterazioni del modello. È stato così possibile abbassare la falda al di sotto del bacino artificiale fino a raggiungere il livello desiderato per poter eseguire le operazioni di scavo e rimozione in condizioni di sicurezza e all'asciutto. Il modello si è perciò rivelato uno strumento molto efficace a supporto delle attività di bonifica pianificate per il sito.

PAROLE CHIAVE: acquifero non confinato, bonifica, metodo di calcolo agli elementi finiti, ottimizzazione dello schema di pompaggio, test di pompaggio, trasmissività.

1. - INTRODUCTION AND STUDY - LIMITATIONS

The present paper describes a case-study of groundwater modeling applied to the remediation of a contaminated site identified inside a chemical facility, operating in Lombardy since the late sixties.

After the direct investigation results confirmed the presence of chemical compounds above regulatory standards in both in the subsoil and within groundwater, the site was notified to the Italian Authorities as requested by the environmental regulation.

During a formal meeting (*Conferenza di Servizi*) the characterization activities conducted at the site were discussed and a series of prescriptions were made by the Authorities, including the execution of additional investigations and the remediation of the contaminated areas.

As part of the remediation, excavation activities were required in an area (a man-made basin) where contamination was found in the saturated portion of subsoil; groundwater level had to be locally decreased to allow remediation of the subsoil. Consequently, a groundwater model was developed in order to design a suitable pumping scheme. In addition to the definition of number of pumping wells and optimization of pumping rate, however, the groundwater flow model was also used as a tool to minimize both the interferences with production activities conducted at the facility and costs related to the site remediation activities.

Given the short timing previewed by the law for the preparation of a Preliminary Remedial Design, a detailed study of the hydrogeological conditions of the unconfined aquifer could not be conducted. Time and cost constraints, unfortunately, represented one of the drivers in the groundwater flow model development; the accuracy and precision of the model's prediction, however, were considered satisfactory under the remediation perspective and allowed for the achievement of the overall project goals, as the excavation activities conducted as part of the remediation, could be conducted under safe and dry conditions.

2. - SITE SETTING AND STUDY AREA DESCRIPTION

The investigation site is a chemical facility, extending over an area of about 160,000 m^2 and located in Lombardy, within the northern portion of the Po Plain and in proximity of a river (that will be indicated here as River Alpha).

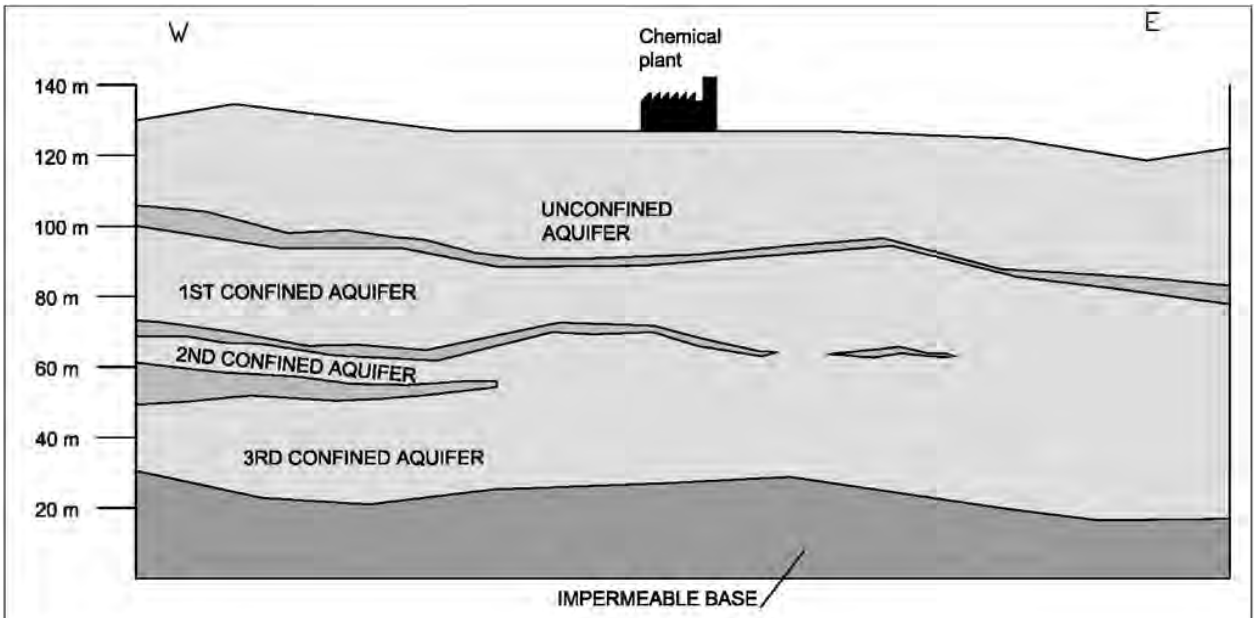
In order to accomplish with Italian environmental regulations requirements and as a response to local Authorities requests, an environmental characterization study was conducted across the entire facility by means of direct investigations, in order to evaluate the presence, magnitude and extent of contamination related to current and past activities conducted by the plant.

Given the production history, the type and mobility of the chemical compounds of concern and the local geological features, the investigations mainly focused on the shallow portion of subsoil and included the execution of soil borings (mainly drilled to 3-3.5 m of depth, to characterize the unsaturated soil) and the installation of 2" and 3" monitoring wells, generally advanced to a depth of 10-15 m and screened in the upper portion of the unconfined aquifer.

Field investigations described above, combined with the findings of a literature search conducted at a wider scale (logs of deep public and private wells retrieved at the local Municipality) helped identifying the local geologic features of the subsoil between ground surface and about 45 m below ground surface, which consists of coarse-grained sediments, mainly gravels and sandy gravels, locally interbedded with thin layers of silt. The geological sequence reconstructed based on the logs of the deep wells presented several features similar to those described for the Po river plain by regional studies (AIROLDI & CASATI, 1989; AIROLDI *et alii*, 1997; BARNABA, 1998) and summarized by GIUDICI *et alii*, 2000.

In detail, at a regional scale the following stratigraphic sequence, here presented from the surface down (fig. 1), can be described:

- Upper unit composed of sandy gravels corresponding to recent alluvial and fluvioglacial sedi-



LEGEND / *LEGENDA*

Coarse-grained deposits (sandy gravels) interpreted as recent alluvial and fluvioglacial sediments deposited by River Alpha (unconfined aquifer) or mixed continental-marine deposits (confined aquifers)
Depositi grossolani (ghiaie sabbiose) interpretate come depositi alluvionali recenti e sedimenti fluvioglaciali depositati dal Fiume Alfa (acquifero freatico) e depositi di origine mista continentale-marina (acquiferi confinati)

Silt and clay lenses locally representing aquitard units
Limi e argille che costituiscono locali acquitardi

Marine clays (aquiclude)
Argille marine (acquicludo)

Note / *Nota*:
The simplified regional geologic sequence represented above was derived from / *La sequenza geologica regionale semplificata rappresentata in figura è stata tratta da:*
GIUDICI M., FOGLIA L., PARRAVICINI G., PONZINI G. & SINCICH B. (2000) – A quasi three dimensional model of water flow in the subsurface of Milano (Italy): the stationary flow. Hydrology and Earth System Sciences, 4(1), 113-124 (2000)

Fig. 1 - Regional stratigraphic sequence.
- *Successione stratigrafica regionale.*

ments deposited by River Alpha (upper Pleistocene-Holocene). These deposits host an unconfined aquifer. The lower limit of this unit is an erosive surface, located at a depth ranging between 30 and 40 meters;

- Second unit, composed of mixed continental-marine deposits, consisting of sandy gravel layers separated by silt and clay lenses, which subdivide the unit into minor sub-units from an hydrogeological point of view. Two superimposed confined aquifers are identified. The overall thickness of this unit varies between 50 and 90 meters; and
- Basal unit composed of silty-clayey sediments deposited in a marine environment during the lower Pleistocene and Pliocene; these sediments represent the regional aquiclude.

At a regional scale, as confirmed by a piezometric surface map obtained at the local Municipality, groundwater in the unconfined aquifer flows from north to south; groundwater level measurements conducted at the facility indicated that at the local scale the unconfined aquifer flows from northwest to the southeast, with an average hydraulic gradient of 0.0035 beneath the facility, and is locally drained by the River Alpha.

The depth to groundwater at the site ranges from 1.5 to 4.8 m below ground surface (bgs). Within the basin's area the average depth to groundwater is in the order of 2.2 m bgs; the water table is, thus, above the actual bottom of the basin.

The facility currently includes a network of sampling locations used to monitor the local groundwater quality (fig. 2) and consisting of:

- 4 piezometers and 23 monitoring wells screened in the upper portion of the unconfined aquifer (between 3 and 10 m bgs);
- one monitoring well screened in a wider portion of the unconfined aquifer (between 2.5 and 15.5 m bgs); and
- one monitoring well screened in the upper portion of the first confined aquifer (between 47.5 and 52.5 m bgs).

In addition, four pumping wells, P1, P3, P4 and P5 (fig. 2), mainly screened in the confined aquifer, are used by the site for industrial water supply.

The analytical results of collected samples identified the following environmental conditions:

- Groundwater contamination identified in the unconfined aquifer only (sample taken from production wells presented concentrations below the method detection limits), mainly affecting the downgradient areas of the facility;
- A "hot spot"-type subsoil contamination, identified in the shallow layers (within 2 m of depth) of unsaturated soil, at selected locations only, whose position was related to the presence of productive areas or warehouses.

Based on a detailed review of the operational processes formerly conducted in the facility, the presence of contamination within a man-made basin excavated in the central portion of the facility was suspected and direct characterization activities, conducted after the preliminary investigation on soil and groundwater, confirmed that concentrations of chemical compounds detected in the basin's sediments and in the first meter of native soil were above regulatory standards.

The man-made basin, 35 m wide by 35 m long and 2.5 m deep, covering a surface of about 1200 m^2 is located in the central portion of the facility. Even though the basin currently represents a reservoir of clean water kept for fire-fighting purposes, in the past it received cooling water used for the industrial processes, which was discharged into the basin before being channeled outside the facility by means of a pipeline connected to an external canal.

The bottom and walls of the basin were represented by the boundaries of the excavation made to create the basin's depression. Native soil was not protected by any kind of impermeable layer. Therefore, any constituent present in the post-process cooling water was free to accumulate first in the sediments at the bottom of the basin, infiltrate into the natural soil and finally leach into the groundwater. Also, due to the relative depths of the bottom of the basin and the groundwater table (2.5 and 2.2 m below ground surface, respectively), the unconfined aquifer resulted always in contact with the basin's sediments and water. Under normal site use conditions, the basin was about 75% full of water (thus the basin surface resulted about 0.6-0.7 m bgs but nearly 1.7 m above the groundwater level. The basin acted as a recharge source.

3. - THE PROBLEM

Soil sampling within the basin indicated the presence of chemical compounds in both the sediments at the bottom and in the upper 0.3-0.4 meters of native soil beneath the basin. A remedial action, as requested by the Italian Authorities during a *Conferenza di Servizi* meeting, was therefore considered necessary and the planned intervention included the removal of the contaminated portion of subsoil.

Because of the relative depths of the bottom of the basin (2.5 m bgs) and the groundwater table in the study area (2.2 m bgs), it was deemed necessary to temporarily lower the groundwater level, in order to allow excavating and removing the soils in safe and dry conditions.

For the purpose of designing the dewatering system, a groundwater flow model of the site was

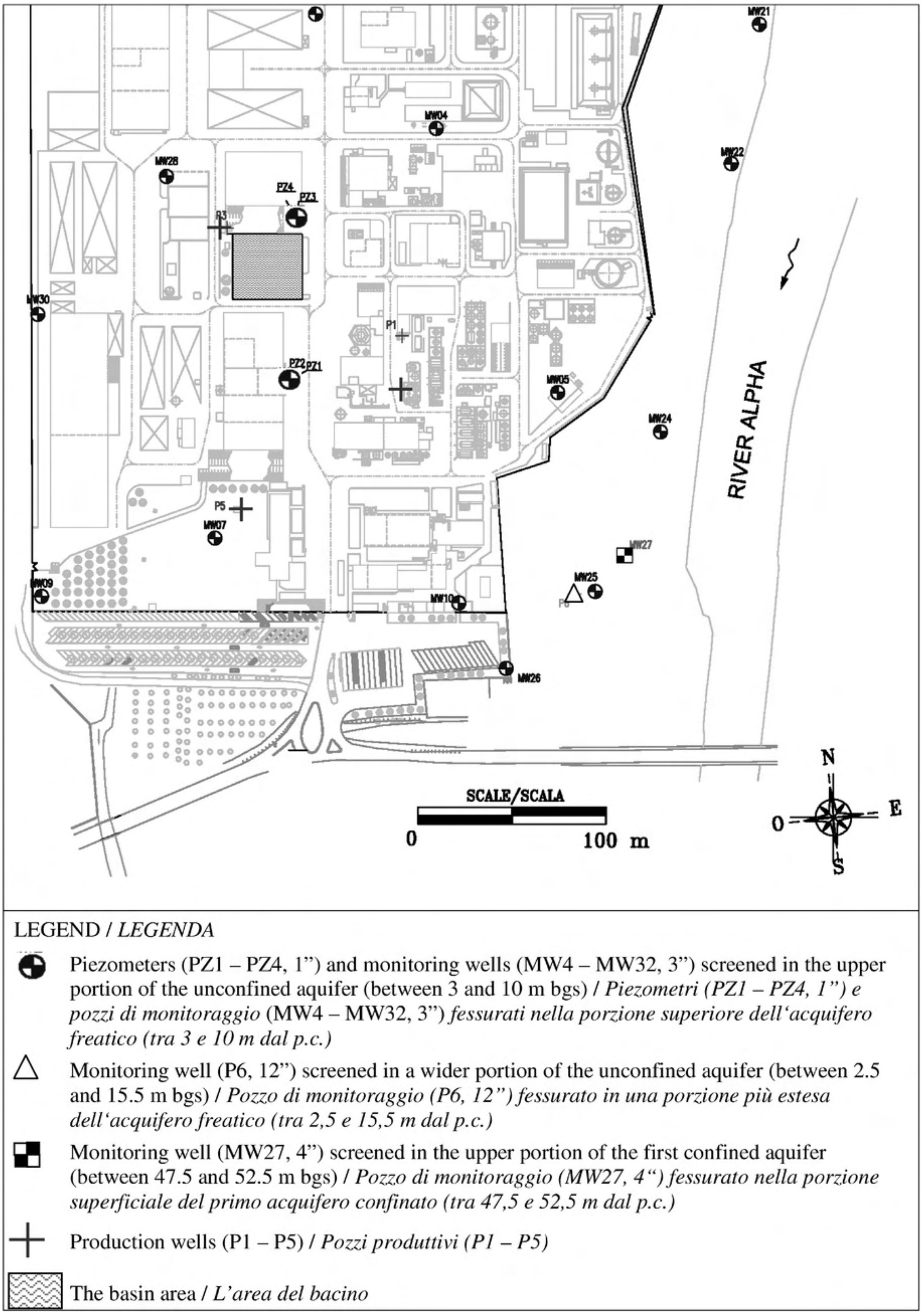


Fig. 2 - Groundwater monitoring network within the chemical plant.
- *Rete di monitoraggio della falda all'interno dello stabilimento chimico.*

used as a supporting tool for the design of pumping wells required to meet the project objectives, which included:

- For the basin's area: quantification of the amount of water that had to be extracted to decrease the groundwater surface to the desired level (about 0.6-0.7 m below the undisturbed head conditions), definition of the minimum number and location of pumping wells necessary to obtain the desired groundwater level and optimization of the pumping rates;
- For the area downgradient of the basin and the production areas: evaluate the effectiveness of existing pumping wells on the hydraulic containment of the upper portion of the unconfined aquifer, especially in the southeastern corner of the facility and identify a pumping wells configuration (position and pumping rate) possibly required for the hydraulic containment.

In addition, the following site constraints had to be taken into consideration:

- The number and position of pumping wells required for the basin's remediation had to be selected so that interferences with the plant's operations could be minimized, avoiding interruptions of production activities or damages to underground utilities, and the overall remediation costs could be affordable;
- Groundwater extracted in view of the remediation, possibly contaminated by the chemical compounds leaching from the sediments in the basin, had to be discharged into the on-site wastewater treatment plant prior to being discharged off site. The total amount of groundwater that the wastewater treatment plant was able to process on a daily basis could not be exceeded; a small reduction in the facility's inflow into the plant was agreed to allow for the treatment of the extracted groundwater (which, however, could not exceed 250 m^3/h);
- The design of the pumping system was required in a very short time, in order to respond to the local Authorities prescriptions within the times established by the law.

4. - THE GROUNDWATER FLOW MODEL

A groundwater flow model of the aquifer was constructed, using the finite element-finite difference code MicroFEM© 3.60.66 (HEMKER C.J. & DE BOER R.G., 1997), which is a hybrid finite element-finite difference method for the calculation of heads. Given the time and budget constraints, a thorough hydrogeological study could not be completed in view of the implementation of the groundwater model.

The modeled area resulted about 7 km wide and 8 km long; the purpose of having such a large area was to minimize the mathematical effects of model boundaries in the area of interest (the facility) and also to include all available hydrogeological features (basically, the Alpha River and regional potentiometric surface contour lines, retrieved from a local Municipality groundwater surface map) to be used as fixed head boundary conditions, in order to minimize assumptions on groundwater flow at the site. Finally, the groundwater flow model was intended as a decisional tool to be possibly used in the future by the facility; therefore, the entire facility boundary was to be covered by the model to allow for any future simulations and hydraulic testing planning and development.

The modeled area was defined by an irregular grid of nodes, with different spacing distances (ranging from 300 meters to 5 meters inside the facility), which were selected in order to have a sufficient detail within the facility, where site-specific data (though pellicular) on geological features and hydrogeological conditions could be obtained by direct observation, and minimize errors at the boundaries, where regional-scale data, retrieved from literature, had to be used.

Given the limited dimensions of the study area (1200 m^2) and the local geological conditions in relation to a quite uniform regional setting and considering the construction schemes of the existing monitoring wells (which were defined for other purposes than investigating the aquifer for hydrogeological studies), the groundwater flow model had to replicate a case that can be simplified as a horizontal formation of constant thickness, infinite extent, discharged by partially penetrating wells, with finite radius and constant discharge rate.

The numerical code MicroFEM© 3.60.66 was applied to simulate the effects of partial penetration on groundwater flow. As described in the paper presented by Hemker (HEMKER C.J., 1999) this was one of the possible applications of the numerical code that is a hybrid finite element-finite difference method for the calculation of heads (HEMKER C.J., 1997).

The theory and solution to account for the effect of partial penetration on flow in a homogeneous unconfined aquifer flow problem, as originally developed by NEUMANN (1974), and extended by MOENCH (1993, 1996), is applied in the paper presented by HEMKER (1999), who suggests an integrated analytical and numerical solution of the Laplace transform.

Since on-site production wells, screened in the confined aquifer, were used to conduct part of the hydraulic testing, the presence of confined layers was deemed necessary to replicate the main hydrogeological conditions.

The following configuration, which in the end was confirmed to adequately replicate field observation with the model, was used to model the area in the subsurface (fig. 3):

- a first layer, 20 m thick, representing the saturated portion of the unconfined aquifer, where the majority of the monitoring wells installed at the site is screened;

- a second layer, 50 m thick, represents a lower portion of aquifer, locally confined by discontinuous clayey layers, where the site pumping wells have their screened section;

- the third layer (40 m thick) representing the

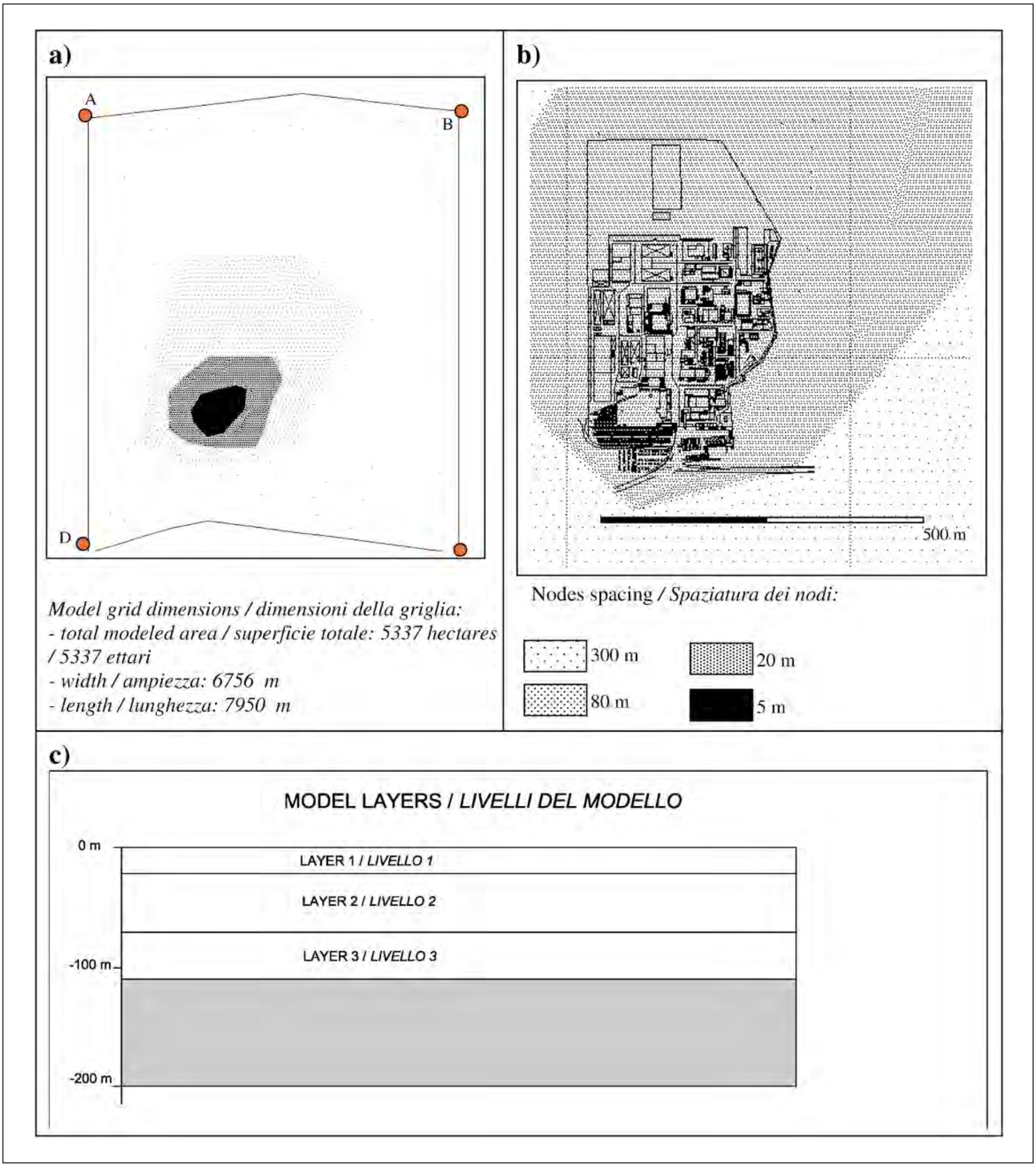


Fig. 3 - Groundwater flow model configuration. a) Model grid dimensions, b) Model grid: detail of the chemical facility area, c) Model layers.
- Configurazione del modello di flusso della falda. a) Dimensioni della griglia del modello, b) Griglia del modello: dettaglio dell'area dello stabilimento chimico, c) Livelli del modello.

confined aquifer. It is estimated from regional geology that the base of model layer 3 corresponds to the top of the regional aquiclude (marine clay layer).

Hydraulic properties, especially for the portion of the model more distant to the facility, with larger nodes spacing, were first assigned to the different layers based on literature values of hydraulic conductivity (GIUDICI *et alii*, 2000) and corresponded to the following:

- First layer: T = 0.04 m^2/s (3456 m^2/day) ;
- Second layer: T = 0.065 m^2/s (5616 m^2/day);
- Third layer: T = 0.0104 m^2/s (898.56 m^2/day).

Fixed head conditions (Dirichelet type) were assigned taking into consideration the regional groundwater surface map retrieved at the local Municipality, where groundwater levels for the Alpha River were also indicated. In order to calibrate model and refine simulations within the facility area, hydraulic testing were conducted at the site.

5. - AQUIFER TESTING

The aquifer tests conducted at the site aimed at determining the local hydrogeological features and the response of the hydrogeological system to pumping activities; these data were necessary to define the specific conditions for the hydraulic containment, to evaluate whether these conditions are achieved with current pumping rates and to optimize the number of pumping wells necessary to reduce the groundwater surface elevation at the basin's area in view of its remediation.

Different types of testing were conducted, in the following order: at two selected locations a step drawdown test was conducted to identify the optimal pumping rate for each well. A constant discharge test followed at both locations, operating the wells at the pumping rates suggested by the previous test. Finally, a pulse test (or interference test) was conducted, using the on-site pumping wells normally used by the facility for industrial purposes. Each test will be described below.

5.1. - STEP DRAWDOWN TESTS AND COSTANT DISCHARGE PUMPING TEST

In order to obtain hydraulic parameters of the aquifer, step drawdown tests (SDTs) and pump and recovery tests (PRTs) were conducted in two wells: P1 and P6. The first well is located in proximity of the basin's area, while the second well was installed in a position suggested by the model as a good location for a future hydraulic containment system.

The SDT for P1 (tab. 1) had three 120 minute steps, while in test conducted on P6, six steps were applied, each with a duration of one hour.

Tab. 1 - *Step drawdown test conducted on P1 and P6.*
- Prova a gradini condotta nei pozzi P1 e P6.

Step drawdown Test at P1			
Step	**Pumping rate**	**Time length of the step**	**Notes**
1	69.3 m^3/hour	2 hours	drawdown was measured by means of a manual water level indicator and was recorded at intervals of 5, 10, 15, 20, 30 40, 60, 90 and 120 minutes
2	108.9 m^3/hour	2 hours	
3	144.7 m^3/hour	2 hours	
Step drawdown Test at P6			
1	56.2 m^3/hour	1 hour	drawdown was measured by means of a manual water level indicator and was recorded at intervals of 5, 10, 15, 20, 30 40, and 60 minutes
2	108 m^3/hour	1 hour	
3	136.2 m^3/hour	1 hour	
4	180 m^3/hour	1 hour	
5	221.7 m^3/hour	1 hour	
6	252 m^3/hour	1 hour	

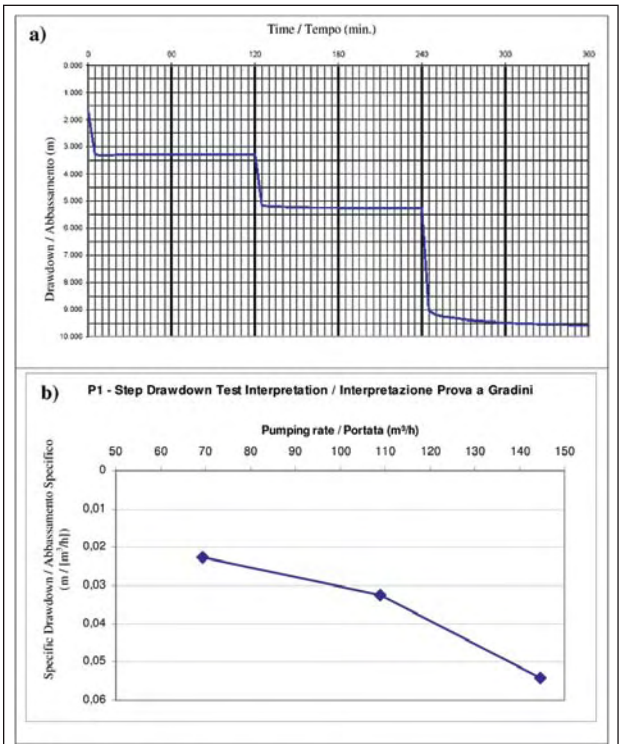
The constant discharge pumping tests (PRTs) were then conducted for both P1 and P6, at the optimal pumping rates, graphically determined for both wells (fig. 4 for P1 and fig. 5 for P6).

A pumping phase was first conducted with duration of 2 days for P1 and 2.8 days for P6, and the corresponding drawdown was measured at significant locations; a recovery phase (one day for P1, 3.1 days for P6), during which the rise of groundwater level was observed at the end of pumping activity, was then completed.

5.2. - PULSE TEST

An interference test (or pulse test) was also conducted and consisted of the observation of groundwater level fluctuations at selected monitoring locations to evaluate the response to different pumping schemes (tab. 2), obtained by turning on and off the existing site production wells. The objective of the test was to verify the effectiveness of pumping system present on-site on hydraulic containment and assess the existence of any hydraulic connections between the unconfined aquifer and the confined layers below (since most of the pumping wells resulted to be screened in both types of unit).

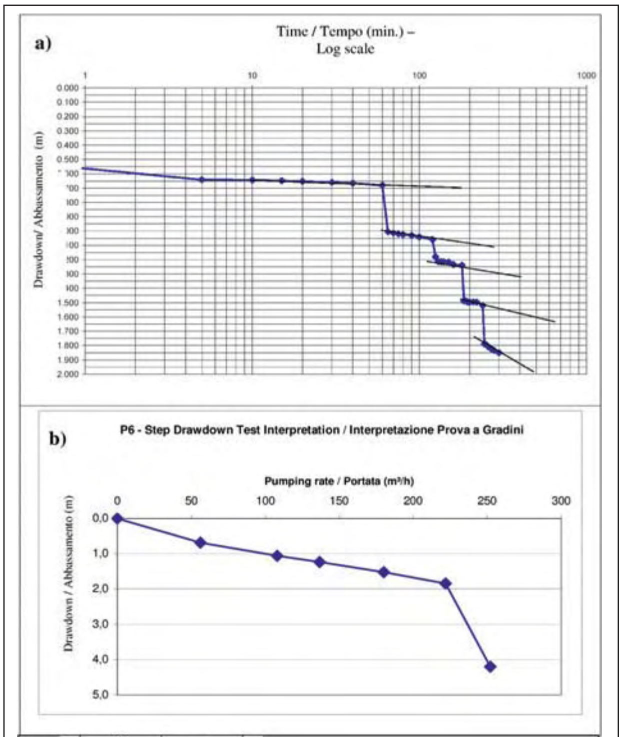
This type of pulse testing (using the normal fluctuations in pumping from supply wells) represents a very low cost method of determining aquifer properties because dedicated wells are not needed and water supply needs of the facility can be ade-



c)

Q	s	s/Q
m3/h	m	m/[m3/h]
0	0	0
69.3	1.565	0.0225
108.9	3.55	0.0326
144.7	7.85	0.0542

Fig. 4 - Step Drawdown Test (SDT) in pumping well P1. a) Field data: drawdowns vs. time, b) Interpretation of SDT, c) Flow rates, drawdown and specific drawdown measured during the test.
- *Prova di portata a gradini nel pozzo produttivo P1: a) Dati di campo: abbassamenti rispetto al tempo, b) Interpretazione della prova a gradini, c) Portate, abbassamenti e abbassamenti specifici misurati durante la prova.*



c)

Q	s
m3/h	m
0	0
56.2	0.68
108	1.06
136.8	1.238
180	1.52
221.8	1.85
252	4.205

Fig. 5 - Step Drawdown Test in well P6. a) Field data: drawdowns vs. time, b) Interpretation of SDT, c) Flow rates and drawdowns measured during the test.
- *Prova di portata a gradini nel pozzo P6. a) Dati di campo: abbassamenti rispetto al tempo, b) Interpretazione della prova a gradini, c) Portate e abbassamenti misurati durante la prova.*

quately satisfied, avoiding an interruption of pumping, possibly required by other types of testing.

The observation points were selected to monitor the central portion of the site, around the three production wells P1, P3 and P5, where the water level response to changes in pumping rates was expected to be detectable and where most of the hydrogeological data gaps were identified. In addition, observation wells were selected in the southeastern portion of the site including monitoring locations, in order to evaluate the influence of the site pumping activities and the extent of the capture zone created by the existing production wells with the current pumping rates.

Groundwater level fluctuations were recorded by means of pressure transducers, with readings taken at 1-minute intervals, and by manual measurements, taken at a 15-minute or 30-minute frequency depending on the location.

The pulse-test was implemented not only to estimate the Zone of Capture (ZOC) of existing production wells and evaluate the preliminary data to quantify the response of the unconfined aquifer to different pumping schemes, but also to evaluate the relationships between the unconfined aquifer and the confined aquifer and verify whether the hydraulic control of the unconfined aquifer was effective to guarantee containment also in the southeastern portion of the site.

5.3. - Hydraulic tests interpretation

The outcomes of the STD and PRT tests were analyzed using the software Aqtesolv to evaluate the local aquifer properties. The average transmissivity (T), vertical resistance (c) and storativity (S) values estimated by the interpretation of the test, applying the Neumann delayed-yield solution (Neumann, 1972, 1975), were initially obtained from the interpretation of the pumping, and recovery tests conducted in P1 and P6 were processed using a software application specifically dedicated to the interpretation of aquifer tests in multi-layer systems, MLU (Multi-Layer Unsteady state).

Tab. 2 – *Pulse Test operation scheme.*
- Schema operativo del Test a Impulsi.

Step	Time	P1 ON/ OFF Pumping rate (m^3/h)		P3 ON/ OFF Pumping rate (m^3/h)		P4 ON/ OFF Pumping rate (m^3/h)		P5 ON/ OFF Pumping rate (m^3/h)	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
1	12:00 ÷ 13:00	114	116	0	0	168	134	0	0
2	13:00 ÷ 14:00	112	115	115	180	161	137	180	190
3	14:00 ÷ 15:00	111	114	109	182	163	134	181	188
4	15:00 ÷ 16:00	0	0	165	180	160	135	180	185
5	16:00 ÷ 17:00	0	0	173	183	160	135	0	0
6	17:00 ÷ 18:00	114	113	174	183	162	133	0	0
7	18:00 ÷ 19:00	112	111	145	149	0	0	0	187
8	19:00 ÷ 20:00	0	0	137	149	0	0	185	186

Subsequent optimization phases were conducted until a good match between simulated and observed drawdown could be found (fig. 6, fig. 7).

The values obtained for the three layers considered in MLU resulted:
- Layer 1: T = 2453 m^2/day, S = 0.3;
- Layer 2: T =1200 m^2/day, c = 14 days, S = $6x10^{-5}$;
- Layer 3: T = 960 m^2/day, c = 23 days, S = $6x10^{-5}$.

The storativity coefficients defined for layers 2 and 3 resulted in the range of values typical of confined aquifers. Since the second layer represents a deep portion of the aquifer that can be locally confined by discontinuous clayey layers, and the third layer represents the confined aquifer delimited at its bottom by marine clays, the result was considered satisfactory.

The layers considered in MLU replicated those adopted for the large-scale groundwater flow model; therefore, the values reported above were finally used in the large-scale groundwater flow model. The optimized values were assigned only to the nodes of the unconfined aquifer, corresponding to the area of influence of the wells (considering the position of the observation wells where pumping caused drawdown effects, though limited). For remaining nodes of the unconfined aquifer and for remaining layers, the initial T values were not modified. The groundwater model developed using the MicroFEM©, version 3.60.66 mathematical code was then calibrated trying to simulate the potentiometric surface contour under undisturbed conditions and to replicate both the results of the pulse test and the PRT. Several runs were conducted until a good match between field observations, tests results, and the software simulations was obtained (fig. 8).

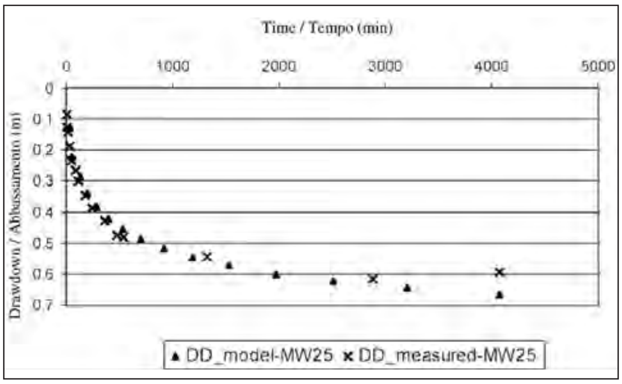


Fig. 6 - Comparison between simulated and measured drawdown during constant discharge (Pump and Recovery Test – PRT) at P6.
- *Confronto tra gli abbassamenti simulati e quelli osservati durante le prove di lunga durata al pozzo P6.*

Once calibrated, the model was used to both evaluate the hydraulic containment under current conditions, and to define the best pumping scheme (number of wells and pumping rates) required for the dewatering of the basin's area.

6. - GROUNDWATER FLOW MODEL APPLICATIONS

6.1. - Hydraulic containment evaluation

A groundwater elevation map of the unconfined aquifer under undisturbed conditions was first obtained considering measured data from monitoring wells only (pumping wells data were excluded because no sufficient data were available to delineate, by interpolation, the drawdown cone in the pumped aquifer).

The following observations were made:
- two production wells were pumping at the time of measurement (P3 and P4), as indicated by the water levels in the wells;

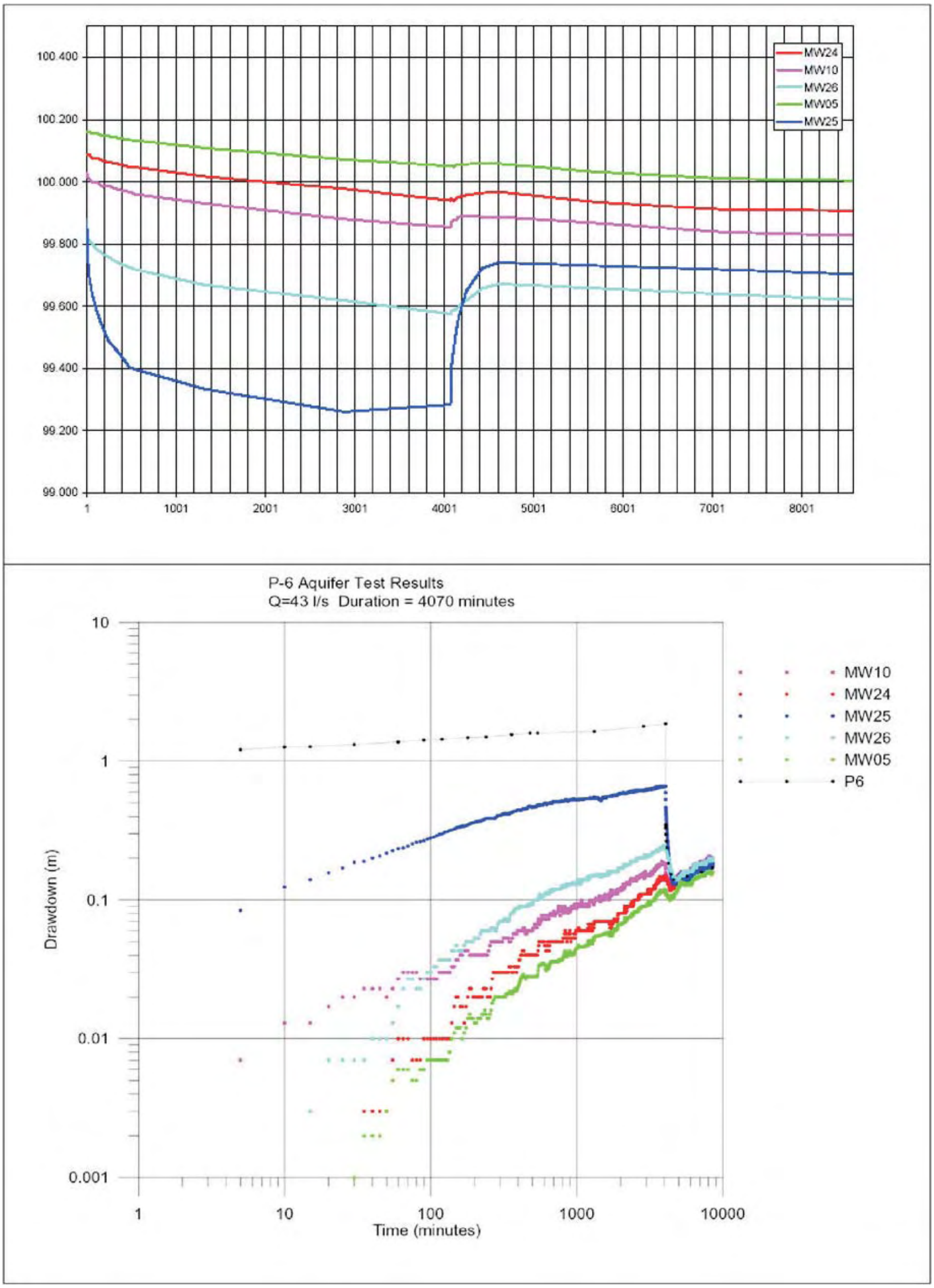


Fig. 7 - Comparison between measured drawdown (above) and simulated drawdown (below) – PRT interpretation using the MLU software.
- Confronto tra gli abbassamenti osservati (in alto) e quelli simulati(in basso) – Interpretazione della prova di lunga durata mediante il software MLU.

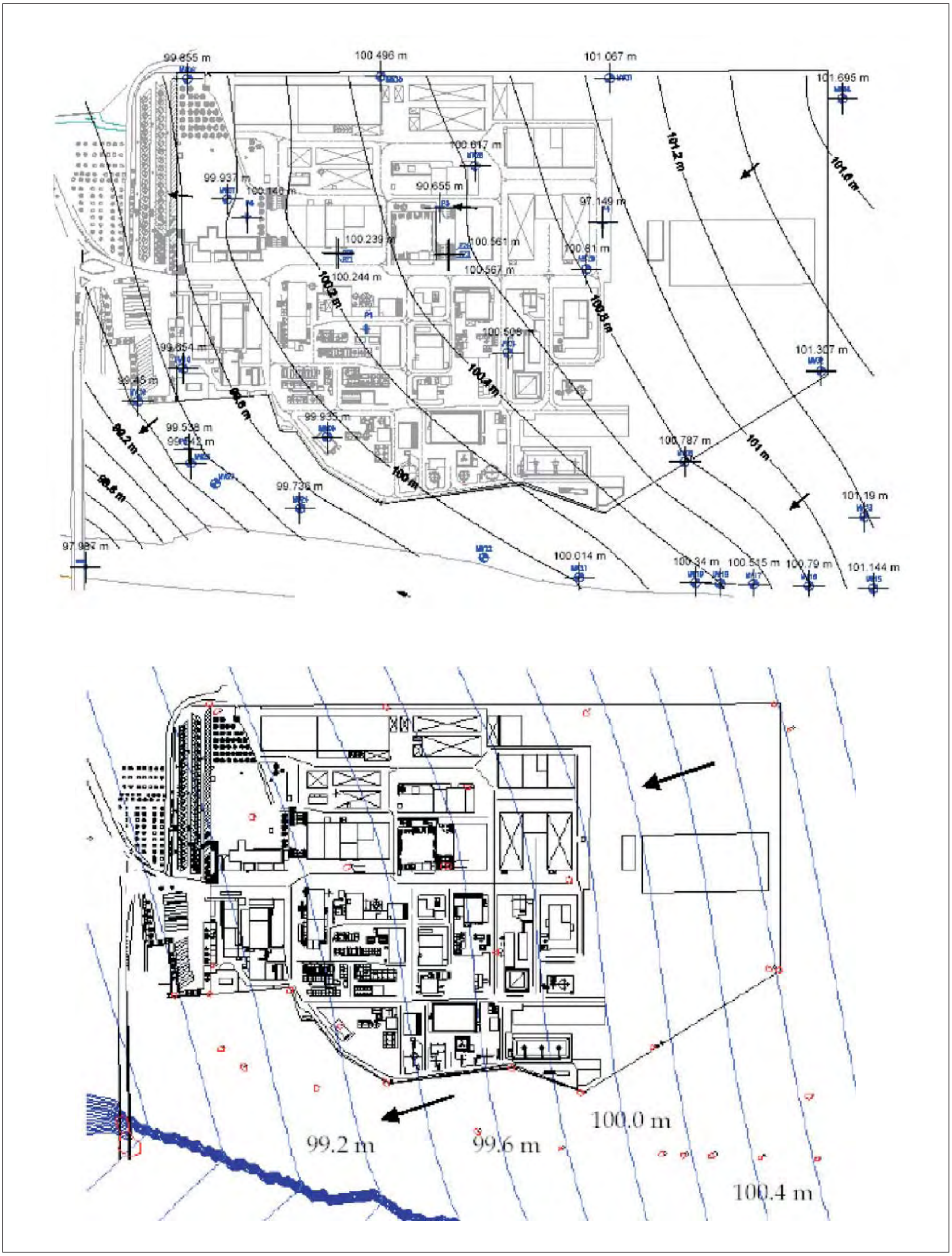


Fig. 8 - Comparison between measured data (above) and simulated data (below) – Groundwater surface map for the unconfined aquifer.
- Confronto tra dati misurati(in alto) e simulati(in basso) – Carta potenziometrica dell'acquifero freatico.

- based on the interpolation, the pumping activity seemed to have a minimum effect on the upper unconfined aquifer in the central portion of the facility (as indicated by the inflections in the potentiometric surface contour lines); and
- the southeastern corner of the facility was not affected by the pumping wells.

Subsequently the outcomes of the pulse-test, which was conducted to verify whether different pumping schemes could modify the response in the unconfined aquifer, were considered. The results are discussed below:

- Monitoring well MW7 was the only location where groundwater level fluctuations presented a clear correlation with pumping activity of well P5 (about 20.5 m distant). The maximum drawdown, associated with an average pumping rate of 180 m^3/hour, was 0.115 m. The effects of pumping at other production wells on MW7 seemed to be negligible (0.005 m);
- Groundwater level fluctuations measured in the central portion of the site, especially in the piezometer pairs PZ1-PZ2 and PZ3-PZ4 located in proximity of the basin's area, seemed to be the result of pumping activity of P3 and P5; the combined effects of the two pumping wells created a maximum drawdown in the order of 0.02-0.03 m, with a maximum response of about 0.06 m. The influence of P1 on observed drawdowns was quite limited and was not consistent and clearly defined: for instance, a rise in the level, apparently associated with the interruption of pumping activities in P1, can be observed in the intermediate portion of the test in the piezometer pairs. However, different response to pumping interruption were observed at the end of the pulse test in the two days of measurements;
- The southeastern portion of the site seemed to be scarcely or not influenced by the pumping activities at the site; the groundwater level fluctuations measured at the different monitoring wells (on average 150 to 250 m distant from the pumping wells) presented time-trends independent at each location, and not corresponding to on/off cycles of the site pumping wells;
- In summary, the pulse testing showed that the effects of normal pumping operation have only a small and local effect on groundwater levels in the shallow aquifer.

As a subsequent step, the site groundwater flow model was used to evaluate the extent of the capture zone created by the site production wells. In order to achieve this goal, the software was used to draw the flowlines (the ideal paths of groundwater particles in the subsoil) corresponding to the following pumping configuration (using pumping rates that provided the highest response during the pulse test):

- P3: 160 m^3/hour (3840 m^3/day);
- P4: 160 m^3/hour (3840 m^3/day);
- P5: 180 m^3/hour (4320 m^3/day).

All of the above indicated wells are screened in the lower portion of the unconfined aquifer as well as in the confined aquifer. The flowlines drawn by the software indicated that the pumping is not containing the upper portion of the unconfined aquifer (fig. 9).

As a further step, the model was run including in the pumping scheme the newly installed well P6, which is screened in the upper portion of the unconfined aquifer, considering a flow rate similar to the one applied during the PRT (140 m^3/hour).

As a final result, it was concluded that:

- the hydraulic containment of the southeastern corner of the site can be achieved using well P6, if it is operated at a pumping rate similar to the one adopted for hydraulic testing (140-150 m^3/hour, corresponding to about 43 l/s). At lower pumping rates (2500 m^3/day – 30 l/s), the hydraulic containment of the southeastern corner (possibly receiving chemicals released in groundwater at the basin's area) would not be complete;
- the theoretical pumping rate necessary to contain, using P6, the upper portion of the unconfined aquifer over the entire site (10000 m^3/day – above 115 l/s) would not be sustainable both considering the characteristics of the well, of the pump that can be installed in it and the volumes of pumped water that the site can treat and discharge daily;
- the theoretical pumping rates necessary to achieve the hydraulic containment of the unconfined aquifer using the production wells (320 m^3/hour for P3; 320 m^3/hour for P4 and 350 m^3/hour for P5) would be again not sustainable, nor feasible. In fact the total extracted volume could not be treated by the wastewater treatment plant, and the technical characteristics of the pumps installed in the wells would not allow reaching the required pumping rates.

Considering the conclusions presented above, a hydraulic containment system for the southeastern corner of the site was developed based on P6 well pumping at 140-150 m^3/hour (fig. 10).

6.2. - Dewatering of the basin area and pumping scheme configuration

The groundwater flow model was subsequently run in transient mode, in order to forecast groundwater level changes over time, and simulations were conducted based on the following assumptions:

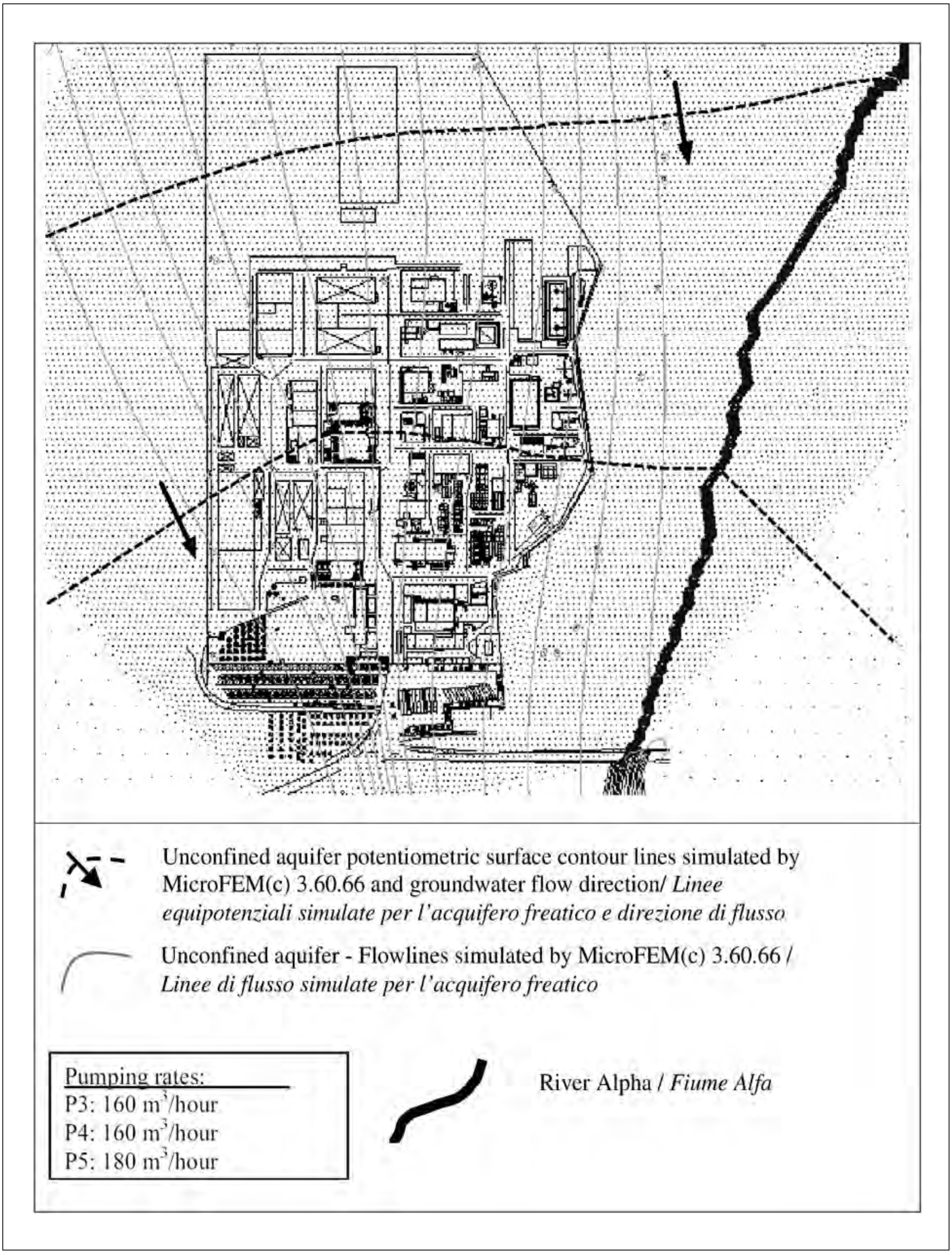


Fig. 9 - Simulated flowlines in the upper unconfined aquifer with pumping wells P3, P4 and P5 operating.
- Linee di flusso simulate per la porzione superficiale dell'acquifero freatico, con i pozzi produttivi P3, P4 e P5 in pompaggio.

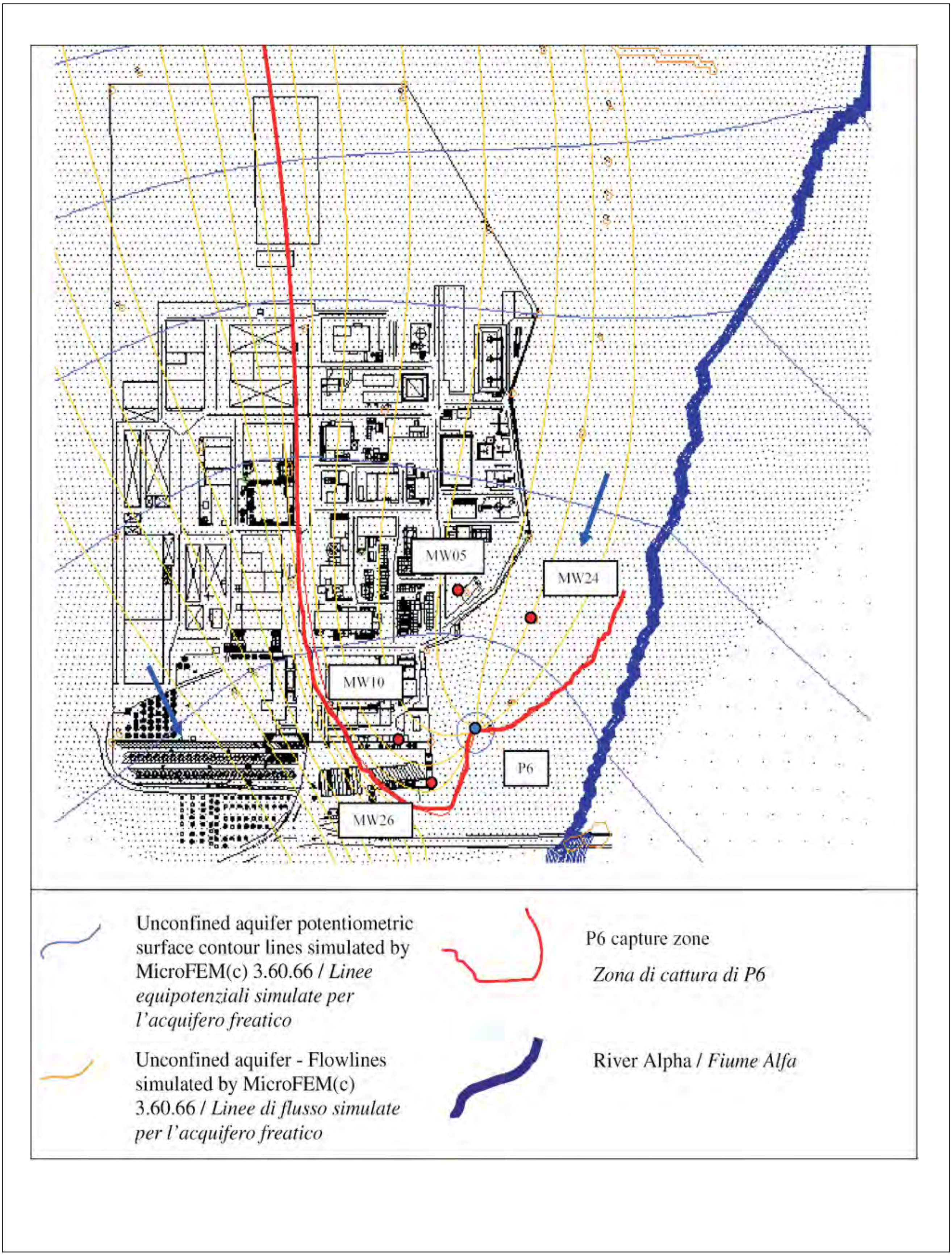


Fig. 10 - Simulated flowlines in the upper unconfined aquifer with well P6 pumping at 140 m³/hour.
- Linee di flusso simulate per la porzione superficiale dell'acquifero freatico, con il pozzo P6 in pompaggio a 140 m³/ora.

- Initial conditions represented by the use of the study area prior to remediation. The water level of the basin was artificially maintained about 1.5 m above the natural potentiometric level of the unconfined aquifer, due to the discharge of water extracted from P3. Based on the simulation results, the water level inside the basin could locally affect groundwater level measurements conducted in piezometers located close to the basin itself (PZ3-PZ4).
- The map obtained considering an artificial recharge of the basin shows bending of the potentiometric surface contour lines which is in agreement with groundwater surface maps obtained from the interpolation of field measurements.

A first run of simulations was conducted to evaluate the time necessary for the basin to naturally discharge water and restore equilibrium with the unconfined potentiometric surface, in the hypothesis that the discharge of water extracted from P3 should be interrupted (see upper diagram in fig. 11).

The presence of the basin was simulated assigning to the basin's area an initial head value 1.5 m higher than the one indicated by the model under steady-state conditions, without the artificial recharge of the basin. The model was then run in transient mode; according to the simulation results, the natural discharge would have taken about 8-10 days to reach the equilibrium (which is assumed to be at about the same depth as the bottom of the basin). Therefore, this drawdown would not have been sufficient to ensure to have the first 0.5 m of native soil below the bottom of the basin above the groundwater level.

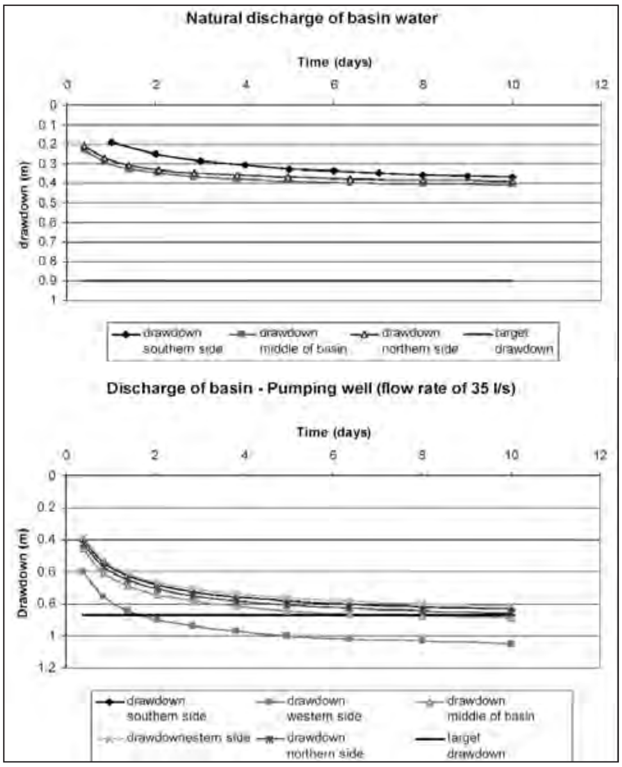


Fig. 11- Simulated discharge of the basin under natural conditions (diagram above) and with a pumping well (diagram below).
- *Simulazioni di svuotamento del bacino in condizioni indistrurbate (grafico superiore) e con un pozzo in pompaggio (grafico inferiore).*

Subsequently, a simulation was conducted considering the same initial conditions (water level in the basin higher than the natural groundwater level), to evaluate the time-frame required for the dewatering of the basin conducted using one pumping well installed west of the basin and pumping at a flow rate of 35 l/s.

Figure 12 shows the location suggested for the pumping well, while the lower diagram in figure 11 shows the simulated drawdown measured at the center of the basin and along each of the four sides. The location of the well was selected along the western side, cross-gradient of the basin, considering both the site characteristics (logistic) and the hydrogeological features of the area, in order to avoid pumping groundwater from other portions beneath the facility.

- Based on the simulation outcomes, it was initially assumed that a single pumping well could be used to increase the dewatering of the basin to the equilibrium with the natural potentiometric surface level (estimated time required for this phase: about 1 day).
- In case pumping should be continued for further 2-3 days, the groundwater level would be further decreased and the target drawdown would be almost reached.

There was however one data gap that needed to be addressed before the execution of soil removal operation: the actual groundwater level beneath the basin needed to be estimated more accurately, by means of simple groundwater level measurements to be conducted at selected monitoring wells (PZ1, PZ2, PZ3 and PZ4, MW28, MW30, MW7 and MW9), together with the discharge rate of P3 water into the basin and depth to water inside the basin, with respect to the ground surface.

Once gathered, the above mentioned data were used to refine and calibrate the existing groundwater flow model in correspondence of the basin; one pumping well was actually installed west of the basin and operated at a flow rate of 35 l/s in order to evaluate observed results against predictions.

As a subsequent step, a preliminary pumping test was run in correspondence of the location suggested by the model, to evaluate the actual response of the aquifer/basin system to the pumping. The calibrated groundwater model was used in transient mode to replicate the dewatering test conducted on site; the dewatering test was simulated with the following steps:

STEP 1 (duration: 9 hours):

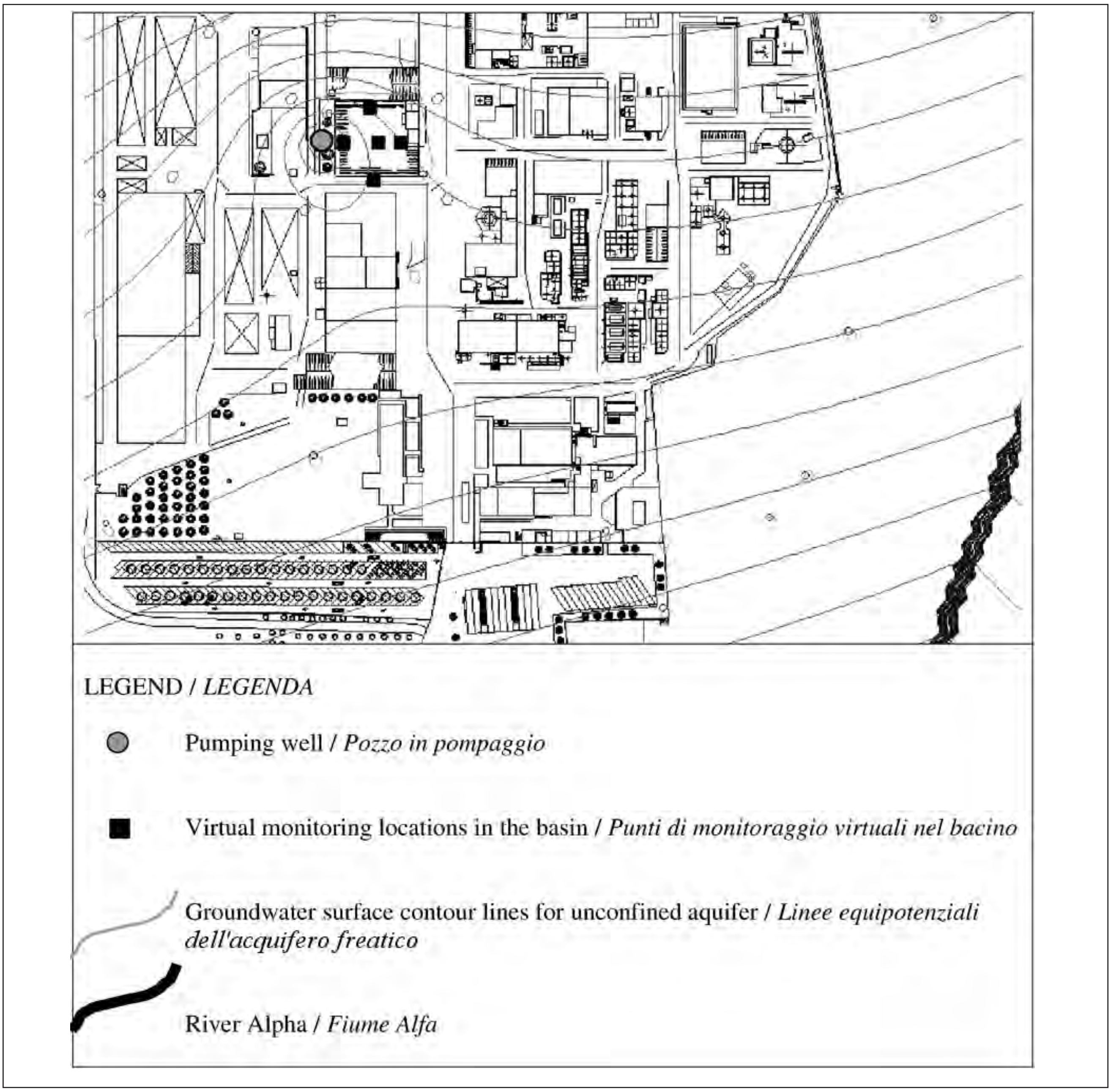


Fig. 12 - Location of pumping well and virtual monitoring locations selected to simulate drawdown inside the basin.
- Ubicazione del pozzo di pompaggio e dei punti di monitoraggio virtuali selezionati per simulare l'abbassamento indotto all'interno del bacino.

The basin is full of water and, at the beginning of the test, discharges to groundwater as no impermeable layer is present at the bottom. Two pumping wells are turned on with the following pumping rates:

- P7 = 108 m^3/hour (30 l/s);
- P8 = 144 m^3/ hour (40 l/s)

Drawdown recorded at observation wells PZ2 and PZ3 is compared to simulated values.

STEP 2 (duration 17 hours):

The basin is nearly empty and does not discharge to groundwater. The external pumping is interrupted, while the two wells keep pumping at the same rate. Drawdown is simulated at observation wells PZ2 and PZ3 (no measurement was taken)

STEP 3 (duration 3 hours):

Pumping is interrupted and the groundwater level is observed for three hours. Drawdown recorded at observation wells PZ2 and PZ3 is compared to simulated values (tab. 3).

At the end of the pumping period (26 hours), the model overestimates the drawdown at PZ3, upgradient of the pumping wells, but replicates a similar response to the interruption of pumping activities (in 3 hours, the system recovers about 20 cm in the

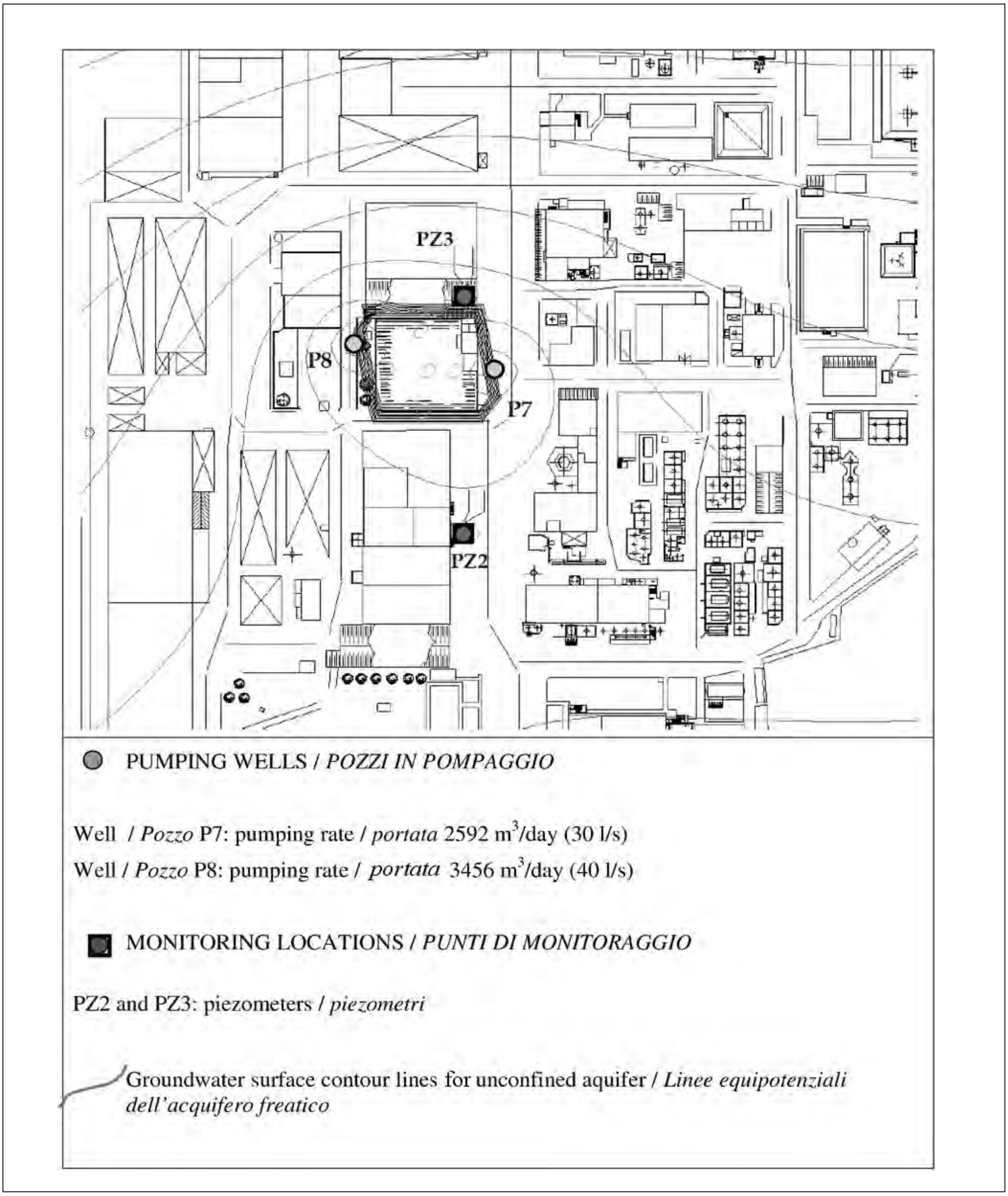


Fig. 13 - Groundwater surface map simulated for the unconfined aquifer at the end of the 26 hours-pumping test.
- *Carta potenziometrica dell’acquifero freatico simulata al termine della prova di pompaggio di 26 ore.*

simulation and 16 cm in the observed test).

On the opposite, the simulation better represent the drawdown at PZ2, downgradient of the basin (maximum observed drawdown: 31 cm; maximum simulated drawdown: 32 cm) but the response to the interruption of pumping is different (in 3 hours the system recovers 4 cm in the simulation and 16 cm in the observed test).

Tab. 3 – *Pilot pumping test - Simulated versus observed drawdowns.*
– Test pilota di pompaggio - Confronto tra abbassamenti simulati e osservati.

Step	**Time (from the beginning of pumping)**	**Drawdown at PZ2**		**Drawdown at PZ3**	
		measured	**simulated**	**measured**	**simulated**
		(m)	**(m)**	**(m)**	**(m)**
1	2 hours (0.083 days)	0.19	0.03	0.10	0.14
	5 hours (0.21 days)	0.22	0.10	0.17	0.27
	8 hours (0.34 days)	0.27	0.16	0.20	0.37
3	26 hours (1.08 days)	0.31	0.32	0.24	0.55

Though not extremely accurate, the model predictions (fig. 13) were, however, considered adequate for the actual implementation of the pumping system and the execution of remediation works.

The optimized pumping configuration finally defined based on the pumping test outcomes (tab. 4) consisted in two pumping wells (P7 and P8), installed along the east and west sides of the basin. The average pumping rate adopted in the field was 125 m^3/hour for both wells.

7. - CONCLUSIONS

Field works started at the beginning of July 2007 and were completed in about 3 months; due to site constraints, both wells could not always be operated at the optimized pumping rate for the whole period, but groundwater was pumped out at flow rates ranging between 95 and 145 m^3/h.

The dynamic groundwater levels inside the wells were stable at 7.2 to 8.7 m bgs, while the dynamical level measured at close monitoring points was 2.6 m bgs (at piezometers PZ3 and PZ4, upgradient of the site) and 2.96 (at piezometers PZ1 and PZ2, downgradient of the site). The dynamic level inside the basin was stable at 2.85 at 2.95 m bgs.

The dynamic groundwater level obtained as a consequence of pumping activities (fig. 14) was sufficient to allow excavating machines to enter the working area and remove sediments and native soil to the desired depth and to build an impermeable concrete basin.

The original basin area was first reshaped and the western and southern banks pulled back. In-place soil reshaping was also necessary to ensure safe working conditions, particularly acceptable banks slopes (35° to 40° maximum). The concrete basin basement was comprised of a 30-cm-thick gravel layer laid from 2.95 to 2.65 m bgs and properly compacted, followed by a 20-cm-high concrete underpinning casting (lean concrete) equipped with a 5-mm-diameter arc-welded net (20x20 cm mesh) and a 40-cm-high concrete bed, installed from 2.45 to 2.05 m bgs. Upon the basin concrete basement installation, 25-cm-thick concrete waterproof walls were finally installed at the all basin sides.

The groundwater flow model specifically developed for the site was thus successfully used to support the remediation throughout the entire duration of the works (fig 14).

Tab. 4 – *Optimized pumping configuration.*
– Schema di pompaggio ottimale.

Well ID	**Well Diameter**	**Well Depth**	**Screen Interval**	**Pump depth**	**Average pumping rate**
	(mm)	(m bgs)	(m bgs)	(m bgs)	(m^3/h)
P7	323	12	2 - 12	11	125
P8	323	12	2 - 12	11	125

Acknowledgements

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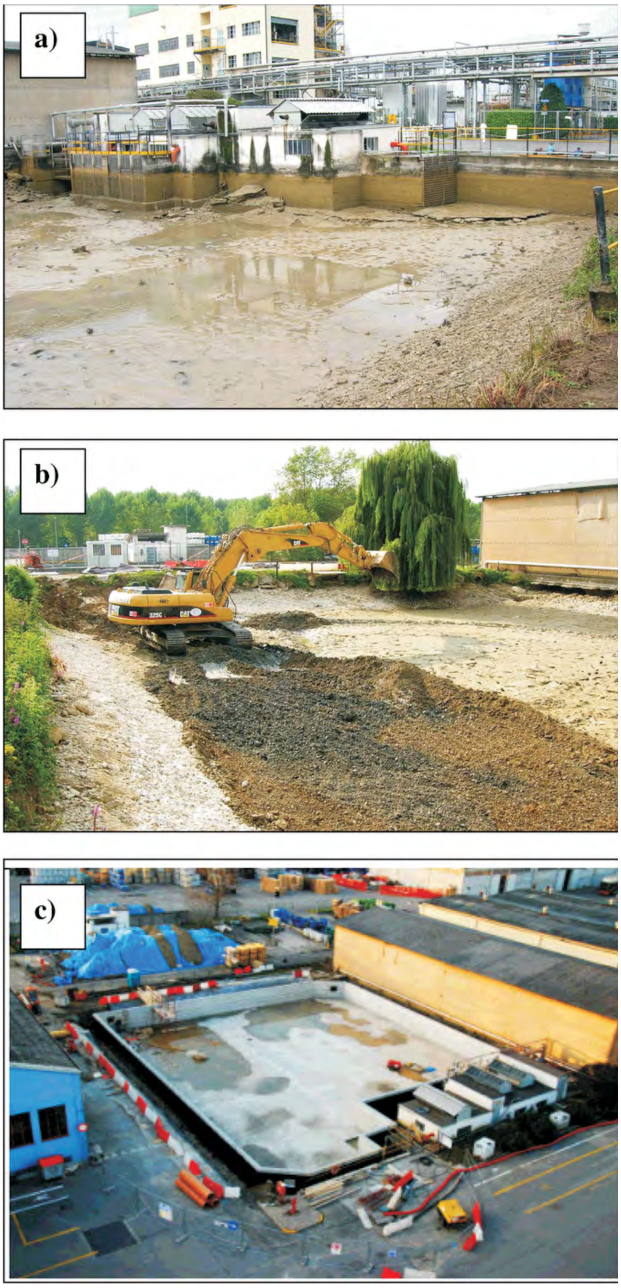

Fig. 14 - Pictures from the remediation works: a) Dewatering of the basin before the beginning of the pumping activity, b) Excavation activities and c) Concrete basing installation.

- Fotografie di varie fasi della bonifica: a) Svuotamento artificiale del bacino precedente la fase di pompaggio, b) Attività di scavo, c) Installazione della vasca di calcestruzzo.

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