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APPLICATION OF BOREHOLE FLOW MEASUREMENTS TO CHARACTERIZE HYDRAULIC HETEROGENEITIES AND THEIR IMPACT ON THE LOCAL GROUNDWATER FLOW NETWORK

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EXTENDED ABSTRACT

Il presente studio sperimenta un metodo d'indagine per l'identificazione e la caratterizzazione delle eterogeneità idrauliche presenti in sistemi acquiferi complessi. L'interesse scientifico ed applicativo per la tematica deriva dal fatto che le modalità di implementazione di queste eterogeneità all'interno dei modelli matematici, usualmente utilizzati per simulare il comportamento e l'evoluzione dei sistemi acquiferi, condizionano fortemente i risultati della modellazione stessa. In effetti, il miglioramento del dettaglio e della precisione con il quale si tiene conto delle eterogeneità all'interno del dominio dà risultati molto positivi, soprattutto nel caso di spiccata eterogeneità lungo il profilo verticale e per analisi a scala di grande dettaglio (sito specifiche).

Obiettivo del presente studio è quindi quello di verificare l'opportunità di integrare i metodi d'indagine tradizionale (log stratigrafici, prove di portata e monitoraggio piezometrico) con misure di flusso in foro tramite flowmeter, in grado di completare il quadro conoscitivo locale attraverso l'individuazione e la caratterizzazione delle eterogeneità. Più in dettaglio, nel presente studio si sono eseguite misure di flusso sia orizzontale che verticale in foro; tali misure sono state condotte su un caso di studio nel quale l'eterogeneità geologica dell'acquifero (acquifero multistrato caratterizzato da una trasmissività dell'ordine di 0.04 m^2/s) si somma alla presenza di strutture antropiche interrate, che rendono il sistema particolarmente complesso da caratterizzare con le tecniche di indagine tradizionali.

In particolare le misure di flusso verticale sono state condotte sia in condizioni di flusso indisturbate sia in presenza di pompaggio e hanno permesso una dettagliata ricostruzione della successione idro-stratigrafica, con l'individuazione di vari livelli ad elevata permeabilità nella porzione inferiore di una unità precedentemente ritenuta omogenea, e soprattutto di un livello acquifero confinato in grado di originare flussi diretti verso l'alto. Nei livelli a maggiore permeabilità sono poi state eseguite delle letture piezometriche tramite cluster mirati alla definizione del carico idraulico alle profondità nelle quali i test con flowmeter verticale avevano individuato le maggiori portate defluenti.

Infine, le misure di flusso orizzontali sono state condotte nei livelli a maggiore permeabilità precedentemente individuati sia nei piezometri di monitoraggio classici (caratterizzati da lunghe fenestrature) sia nei cluster (aventi fenestrature molto più ridotte); queste ultime misure si sono dimostrate molto più significative al fine di caratterizzare le eterogeneità dell'acquifero ed hanno fornito valori di velocità secondo Darcy dell'ordine di 10^{-4} m/s, permettendo così di quantificare il flusso attraverso i livelli maggiormente produttivi dell'acquifero, anche in conseguenza dell'interazione con le strutture interrate.

I dati e le informazioni ottenuti dai test con flowmeter sono stati utilizzati per aggiornare il modello concettuale del sistema acquifero, inizialmente elaborato sulla base della campagna d'indagine tradizionale. I due modelli concettuali (quello iniziale e quello aggiornato) sono poi stati confrontati tramite l'implementazione di due differenti modelli numerici di flusso 3D, con l'impiego del codice di calcolo alle differenze finite MODFLOW.

I risultati delle simulazioni hanno evidenziato come alla scala locale i metodi di indagine tradizionale non siano in grado di caratterizzare l'acquifero con un sufficiente grado di dettaglio, in quanto la presenza di spiccate eterogeneità lungo il profilo verticale porta alla formazione di livelli acquiferi in pressione lungo gli strati a maggiore permeabilità, che sovrapponendosi agli effetti indotti dalla presenza delle strutture interrate influenzano fortemente la dinamica del sistema acquifero, generando localmente significativi flussi verticali aventi gradiente dal basso verso l'alto.

Lo studio effettuato consente di giungere ad alcune importanti conclusioni; in particolare risulta confermato che l'esecuzione di misure di velocità in foro in punti opportunamente scelti può migliorare significativamente il modello concettuale del sistema acquifero, consentendo una ricostruzione del campo di flusso a scala locale di maggiore dettaglio ed affidabilità non solo in condizioni naturali, ma anche e soprattutto in presenza di strutture antropiche interrate, che esercitino la funzione di barriere impermeabili capaci di deviare in modo significativo il flusso idrico.

ABSTRACT

The focus of this study is to examine the use of borehole flow measuring procedures, in order to support conventional methods and information used to characterize heterogeneous aquifers. In general stratigraphic logs, data from pumping tests and piezometric monitoring are used. In this study a combined approach of vertical and horizontal borehole flow measurements and piezometric monitoring is described, to complete and merge available data for the accurate modeling of a complex aquifer. Vertical thermo-flowmeter logs allowed the detection of noticeable heterogeneities: a leaky aquifer, an upward directed leakage and several layers with higher hydraulic conductivity in the lower part of a hydrostratigraphic unit that appeared almost homogeneous. Horizontal in-hole groundwater flow measurements allowed for quantifying the flow in the more productive layers at the bottom of the aquifer, with observed Darcy velocity up to 10^{-4} m/s in some measuring points. A numerical model was applied to analyze the major differences between a conceptual model of the aquifer obtained by the use of conventional methods of characterization and a model based on the here proposed approach.

Keywords: *groundwater velocity, conceptual models, heterogeneity, flowmeter, numerical modeling, in-hole flow measurements*

INTRODUCTION

Volcanic and alluvial sediments consist of layers of various thickness, partly with large areal extension, characterized by different granulometry and usually a slightly sloping inclination (the slope often ranges between 0.1% and 5%). The presence of lenses with different dimensions and thickness, the occurrence of buried riverbeds and strata acting as aquitard design a groundwater flow network with preferential groundwater flow paths and directions.

In general, structural variations of sediments on a regional scale are due to the alternation of deposition and erosion phases during the formation of the aquifer. Each sedimentation phase is associated to a particular granulometry and different layers are separated by irregular erosion surfaces. In Fig. 1 the structure of the alluvial aquifer of the Milan area is shown as an example. On a local scale, different shapes and hydraulic conductivities of sediment lenses and layers take significant influence on the flow network.

The evaluation of the continuity and hydraulic conductivity of layers and lenses in alluvial and volcanic aquifers is often difficult owing to the lack of suitable data. Nevertheless, the characterization of the mutual role and productivity of different strata and their significance in the hydraulic network can play an important role in understanding the actual flow conditions on a local scale.

It is known that a vertical flow can be naturally induced in a borehole that cuts across hydraulic potential contour lines (Corcho Alvarado *et alii*, 2009; Zinn & Konikow, 2007; Schöttler,1997, Fig. 2). Commonly a downward component of the groundwater flow exists in recharge areas, and an upward component in discharge areas. Vertical flows occur within long-screen wells, even in homogeneous aquifers with very small vertical head differences (Basiricò *et alii*, 2015).

In general, groundwater flow focuses on layers and structures of high hydraulic conductivity resulting in different hydraulic pressures within the aquifer. This situation can lead to aberrant piezometric heads measured in wells that access layers of different hydraulic pressure. Thus, water table contour lines based on piezometric well head measurements can show deformations that are caused by these heterogeneities.

Phillips (1991) analytically described the role of permeable lenses on the flow network in some simple cases. Francani e*t alii* (2002) applied similar relations to evaluate the flow and piezometric head distribution near lenses of different hydraulic conductivity. Numerical models can describe in 3D the effect of heterogeneities on piezometric head distribution and flow lines (Eaton, 2006; Gattinoni, 2011). Nevertheless, in real cases the substantial issue is to locate the significant heterogeneities in reference to the studied problem and characterize them, from a geometrical and hydrogeological point of view, to formulate a reliable conceptual model of the aquifer with the suitable level of detail. The possibility to identify and to characterize the hydraulic impact of individual lenses and layers on the local flow network depends on the numbers, density and quality of available data.

In recent studies, in-hole vertical groundwater measures were used to support the formulation of the groundwater flow conceptual model (Mastrocicco *et alii*, 2013; Petitta *et alii*, 2013).

In order to support conventional methods of aquifer characterization, two direct measuring procedures are proposed and their application discussed in a case study. Vertical and horizontal groundwater velocity and direction are measured in boreholes (free of using artificial tracers) to display the heterogeneity of the aquifer and to evaluate the role of layers with lower hydraulic conductivity. Coupled to a piezometric monitoring program, the gained results can help to identify layers that act as aquitard and help to detect critical hydrogeologic conditions in regard to a studied problem.

A numerical model has been developed to analyze the differences between a conceptual model of the aquifer solely based on conventional methods of characterization and a model that comprises data from the proposed borehole flow measurements.

APPLIED METHODS

The suggested approach is based on in-hole groundwater flow measurements to check the conceptual model of the aquifer. In the presented case study the following survey procedure was proposed and executed:

- Tracer-free measurements of ambient vertical groundwater

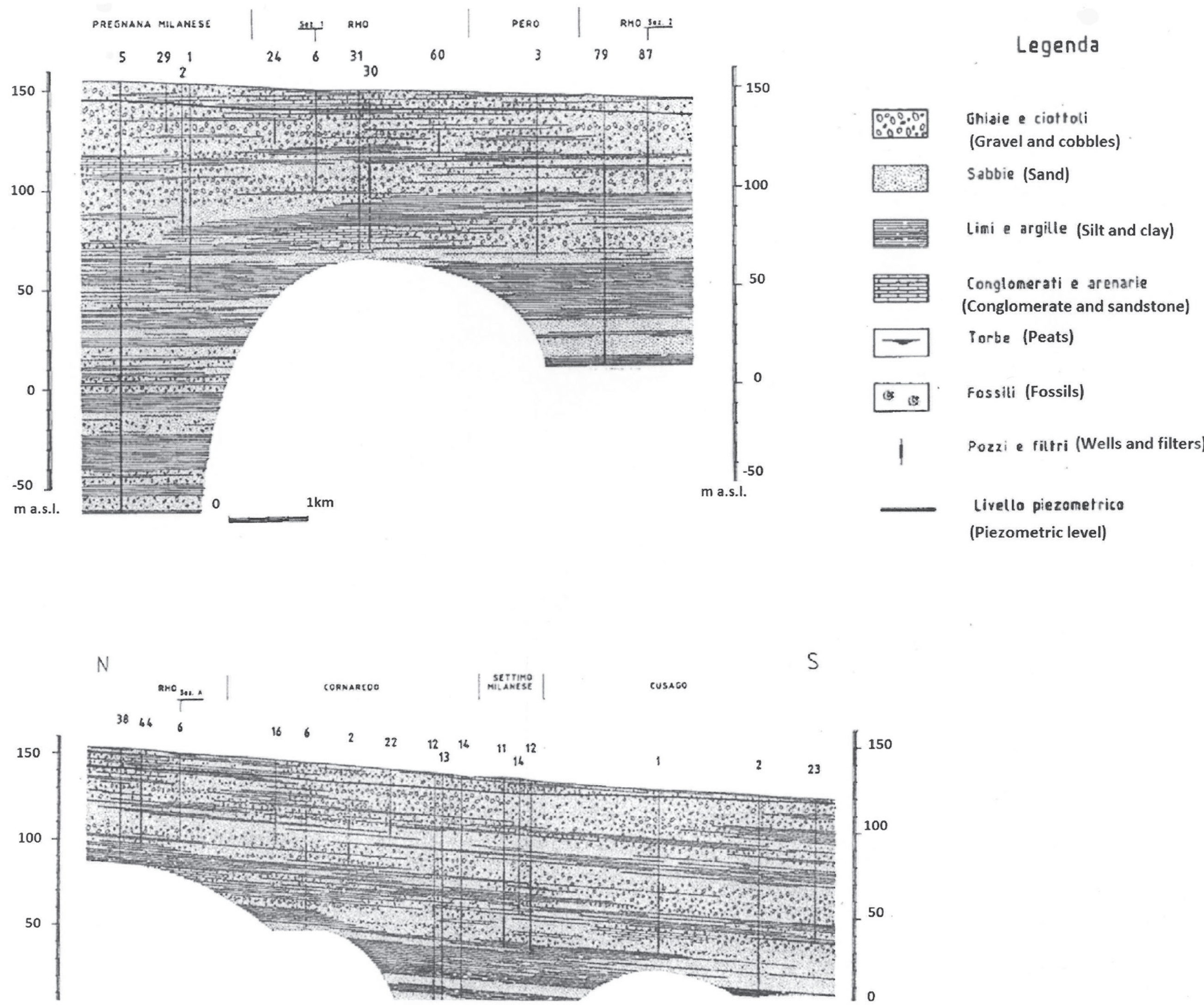

Fig. 1 - Example of hydrogeological sections describing the alluvial aquifer of the Milan area in East-West (OE) and North-South (NS) extension, corresponding with the maximum slope (modified from Denti *et alii, 1993)*

flow in monitoring wells that are screened along the whole aquifer profile. This measurement comprises a flow-log in undisturbed conditions along the screened well section in order to identify hydraulic short cuts and to localize sections of ambient inflow and outflow along the well profile. The aim is to assign different piezometric pressures on the corresponding strata and to identify layers that might act as aquitards. Subsequently, this measurement procedure was repeated under forced flow conditions (low-rate pumping directly below the groundwater level) in order to quantify and assign a hydraulic conductivity profile to the surrounding strata.

- Measurement of piezometric heads in cluster piezometers filtered at depth corresponding with the detected main inflows and outflow sections.
- Tracer-free horizontal in-hole flow velocity measurements in the depth of strata with high hydraulic potential, both in piezometers with long screens and in cluster piezometers with short screens. Measurement taken in piezometers with short screen intervals are more representative, as the natural hydraulic situation of the individual layer is less disturbed.

Vertical groundwater velocity measurements

If aquifer layers with different pressure potentials are connected by a well bore, a hydraulic short circuit is induced in the well and a permanent vertical groundwater flow in the well bore is the result. The flow velocity varies along the well profile in regard

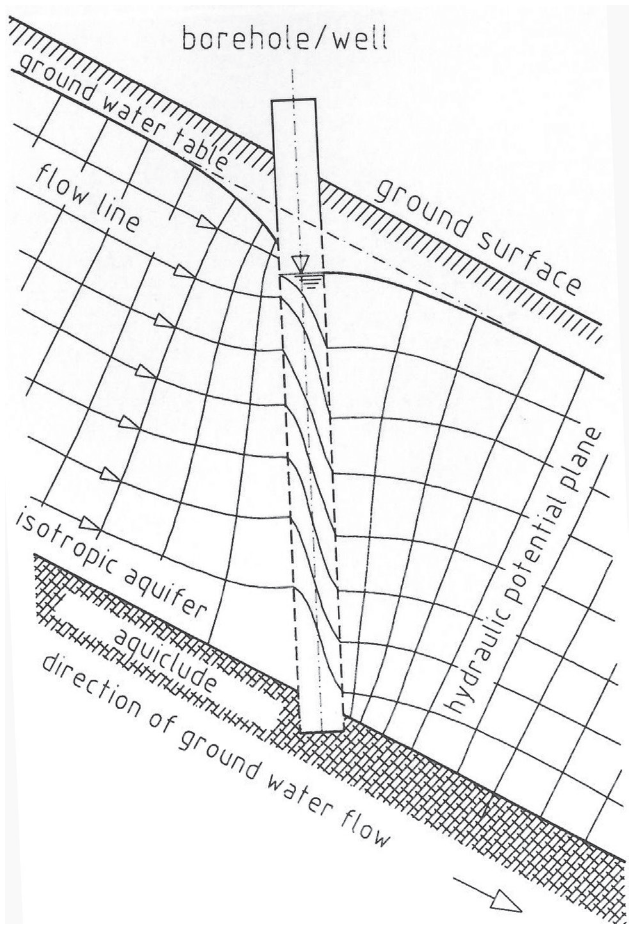

Fig. 2 - Extreme heightened proportions of a potential flow field disturbed by a fully screened well (Schöttler, 1997, modified after Bergmann, 1970)

to the hydraulic potential of individual horizons. To detect the presence of a hydraulic short-circuit, to quantify the vertical flow and to characterize the variability of hydraulic conductivity along the aquifer profile, a thermo-flowmeter was used. The Berghof Thermo-Flowmeter is capable of sensing very small flow motion in water (down to less than 1 mm/s) by the principle of Constant Temperature Anemometry (CTA) measurements (Halla, 2006). It is similar to a Fluid-log with the advantage that no artificial tracers are needed. The working principle is based on the cooling effect of a flow on a heated body. The CTA measures velocity along the axial well profile and provides continuous velocity readings that are processed into amplitude and time-domain statistics.

Thermo-flowmeter measurements were carried out both under natural undisturbed hydraulic conditions and under forced hydraulic conditions (low-rate pumping directly below the groundwater table). In the former, hydraulic short circuits are detected and inflows/outflow horizons are identified. In the latter, groundwater inflow is forced along the well screen profile: the inflow quantity from the different horizons corresponds with their hydraulic conductivity, that can be quantified by the inflow/withdrawal ratio in the well profile. The precondition for this calculation is that the average hydraulic conductivity over the whole aquifer profile is known (i.e. from pumping tests).

Horizontal groundwater velocity measurements

Horizontal groundwater flow velocity measurements were carried out with the Phrealog measuring system. This technology is based on the observation and optical recording of the movement of natural microscopic particles that are present in the groundwater and carried as suspension along with the natural groundwater flow. The measurements are carried out in selected intervals in the well bore. The in-hole flow rate can be tracked within a velocity range from $1x10^{-2}$ m/s (0.01 m/s) to lower than $1x10^{-6}$ m/s (0.08 m/d). Depending on lithological conditions, velocities lower than $6x10^{-7}$ m/s (0.05 m/d) are generally set to zero or to "no flow movement". Naturally occurring particles are carried along by the in-hole flow that corresponds with the ground water flow system in the aquifer (Schöttler, 2004). The observed particles often consist of aggregations of i.e. organic and inorganic material as clay minerals. At high flow rates the transportation of silt particles and even fine sand fractions can be observed.

In order to measure groundwater flow direction and velocity, images of a illuminated focal plane in the axial centre of the measuring section are continuously recorded by camera. The image sequences are computed in real time by a particle tracking software calculating the drift of the particle patterns. The flow direction is determined with the probe-integrated compass and the flow velocity is calculated by timing the movement of particle patterns across the cameras field of view. To calculate the Darcy Velocity based on the measured in-hole flow, two correction factors are used: the factor α and the factor γ (Oglivi, 1958; Krätzschmar & Luckner, 1966; Klotz, 1977, 1978). The product between α and γ is equal to V_H/V_f, where V_H is is the flow velocity along the median flow line within the well, and V_f is the Darcy velocity. The factor α compensates the influence of the flow geometry caused by well construction. This factor is calculated by the hydraulic conductivity K of the aquifer, the filter pack and filter screen as well as the diameter of the bore and the well. The factor γ considers the influence of the probe on the in-hole flow (see the following references for the complete formula of these correction parameters: Drost *et alii,* 1968; Schöttler, 1997; 2004; 2007). Furthermore, the hydraulic influence of the well geometry in the investigated sections can be simulated and the data aligned with a respective simulated flow scenario (Driessen *et alii*, 2015). Simultaneous to flow tracking, the particle load is quantified. This additional information can be used to support the identification and estimation of possible piping effects at an early stage as it can help to prove and quantify the outwash/relocation of fine grain material within the aquifer.

CASE STUDY

Background and framework description

The discussed survey procedure was applied to a case study; the location and site details are undisclosed in order to meet privacy protection requirements.

An underground structure had to be realized at the bottom of a hill slope, in a heterogeneous aquifer, with the following schematic stratigraphy:

- from ground surface to 10 m depth: gravel to sandy silt;
- from 10 m to 28/40 m depth: fine-medium sand and silty sand to medium-coarse sand, from loose to moderately packed;
- from 28-40 m depth: rock, from friable to compact (slightly consolidated), 2-3 mm joints filled with calcium carbonate.

The hydrogeological setting of the area is characterized by a multilayer aquifer having a groundwater flow directed North to South (Fig. 3).

In the first phase of characterization, a pumping test was conducted to quantify the transmissivity along the aquifer profile and a mean overall transmissivity T of 0.04 m^2/s was calculated. Moreover, Lugeon tests were available referred to the rock formation at the bottom of the hydrogeologic system, whose results show a permeability range from 2 x 10^{-7} m/s to 3 x 10^{-6} m/s. As a consequence, the rock formation is considered as a bedrock, with a hydraulic conductivity that can vary locally, depending on the degree of fracturing and alteration of the rocks.

A supplementary hydrogeologic survey was conducted to improve the existing conceptual model of the aquifer in the vicinity of the underground construction.

Results

In order to verify the on-site hydraulic situation and to determine ground water flow direction and velocities, in-situ vertical and horizontal ground water flow measurements were initially conducted in four monitoring wells realized with long filter screen intervals of more than 25 m (LF1, LF2, LF3 and LF4, Fig. 3).

With regard to the heterogeneous lithology of the aquifer, groundwater head variations along the vertical aquifer profile were assumed. Consequently, thermo flowmeter logs (vertical velocity measurements) were conducted:

1. under the normal, undisturbed conditions, in order to detect

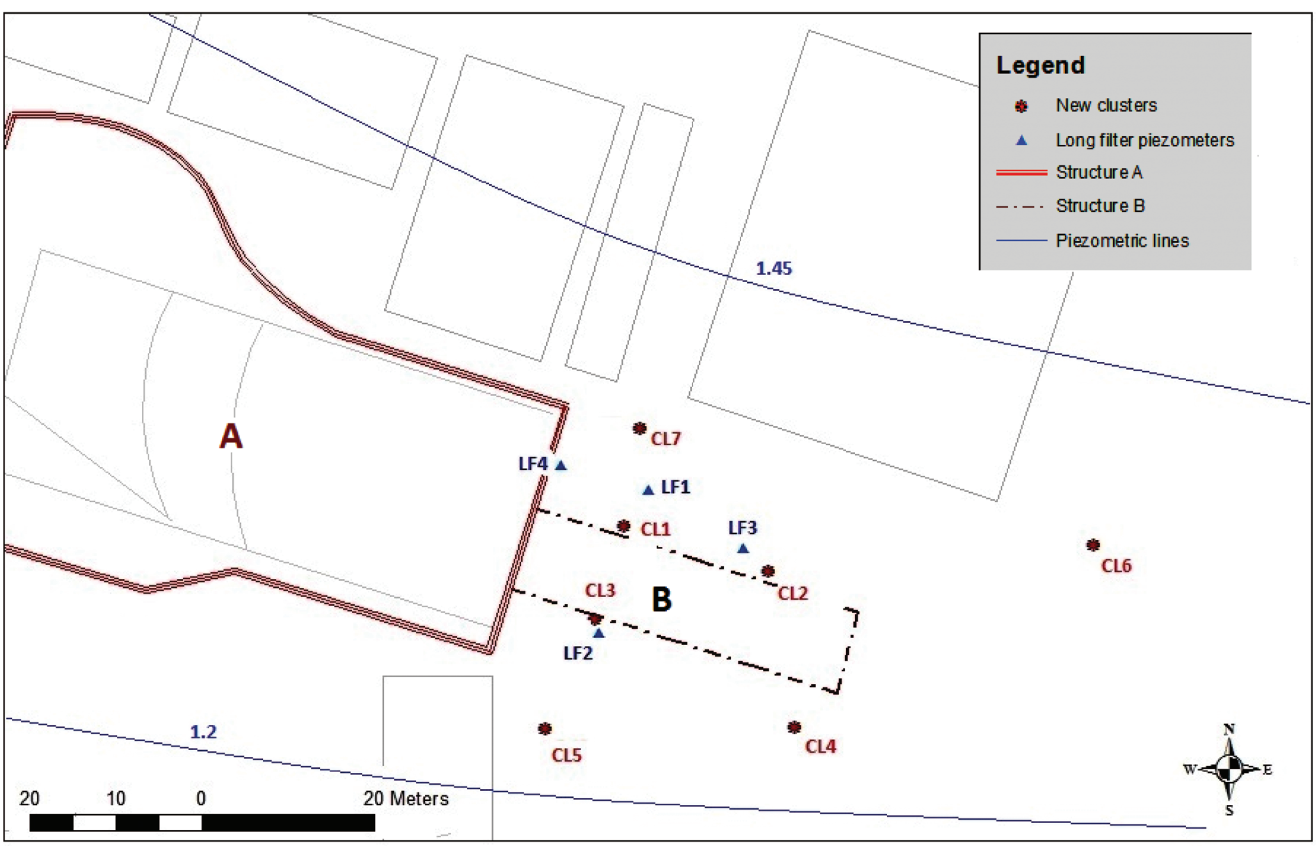

Fig. 3 - Monitoring wells with long filter screens (LF) and cluster monitoring wells (CL) available on site. Structure A is bound by diaphragm walls, driven down into the bedrock to 40-45 m. Structure B is an underground structure located at aquifer depht from 18 to 27 m b.g.s., which may be considered as an impermeable barrier to underground flow. The depicted piezometric lines are inferred by bibliographic studies on a large scale, previous to underground working activities

short-cuts (as effect of different hydraulic heads in the layers), depth and productivity of inflow horizons along the well profile

2. while pumping with a low rate, in order to quantify the hydraulic conductivity profile of the aquifer (the pump was positioned directly below ground water level).

The profiles of the Thermo-Flowmeter logs conducted under undisturbed hydraulic conditions revealed significant upward flow in the wells, indicating a hydraulic short-cut from the lower into the upper part of the aquifer, and revealed confined hydraulic conditions in the lower section of the aquifer. The same situation was registered in all four wells in similar depth sections: from around 20 m b.g.l. and down to 33 m b.g.l. the aquifer in the area of piezometers LF1-LF4 is characterized by several horizons with confined groundwater and with high hydraulic conductivity. These horizons vary in thickness from 0.5 m up to 4 m. The piezometric head in the depth section from approximately 20 m down to 36 m b.g.l. is higher than the piezometric head in the overlying layers, thus resulting in an upward infiltration from the lower into the upper aquifer and an upward flow in the wells via hydraulic short-cuts.

The profiles of thermo-flowmeter logs conducted under forced hydraulic conditions (while pumping) in all the four monitoring wells revealed a sequence of high and low permeable horizons, varying from 1.7 x 10^{-5} m/s (LF1, 0-8 m b.g.s) to 3.3 x 10^{-2} m/s (LF3, 9-9.3 m b.g.s).

As upward flow was recorded in all four proximate wells, a intermediate layer sequence acting as an aquitard must be assumed for this site section. This situation can be characterized as a "leaky aquifer", in the sense of an upward directed leakage. Moreover the thermo-flowmeter logs identified the presence of layers with high hydraulic conductivity in the bottom section of the aquifer that act as main discharge horizons.

Subsequently, new cluster monitoring wells were realized (named CL in Fig. 3), with short screen sections of 3 to 6 m length, to avoid hydraulic short-cuts, placed at depth corresponding with the detected main inflow and outflow horizons. The new monitoring points confirmed higher piezometric heads for the lower part of the aquifer (in particular cluster CL7, CL6, CL2, placed upstream of the underground structures, Fig. 4), locally perturbed or amplified by the presence of impermeable underground structures in the upper layers of the aquifer (cluster CL1, CL5, CL4, CL3, Fig. 4).

To quantify the flow in the more productive layer detected at the bottom of the aquifer, horizontal flow measurements in LF1, LF2, LF3 and LF4 were performed in sections approximately from 25 m b.g.l. down to 34 m b.g.l.. The order of magnitude of the calculated mean horizontal flow velocity (Darcy velocity) in wells upstream of the underground structure B (LF1 and LF3) is 10^{-4} m/s (Tab. 1). These monitoring wells connect all the aquifer layers and the upward gradient monitored on site produces upward flows in the wells. In spite of the hydraulic isolation of the measuring cell with packers, for some depths the enhanced velocity caused by vertical flow in the vicinity of the well (skin effect) affects the horizontal velocity flow measurements.

In the new cluster piezometers with short filter screens (CL, Tab. 1), the horizontal in-hole flow measurements are not affected by upward flow and the results are more representative to display the undisturbed situation of the aquifer. For example, CL2-1 taps the lower part of the aquifer from 29 m to 33 m b.g.l. and the calculated mean Darcy-velocity over all measured depth is 1.4 x 10^{-5} m/s, significantly lower than documented for the near well LF3 (3.3 x 10^{-4} m/s).

The horizontal velocity measures conducted in short screened monitoring wells show that in the deeper aquifer layers the steady horizontal flow can generally be assumed as low (order of magnitude 10^{-5} m/s to 10^{-6} m/s) under undisturbed natural conditions. Higher velocities have been monitored in clusters CL3, CL4 and CL5, placed downstream to the structure B, that is an impermeable barrier from 18 to 27 m b.g.s. This result indicates enhanced groundwater flow below structure B, as the permeability of the underlying layers allow a higher groundwater passage than it was formerly given by the natural underground structure of the aquifer without the barrier function of structure B.

Discussion

A simple numerical model of groundwater flow was developed in order to compare two conceptual models of the aquifer: one obtained by conventional methods of characterization and the other obtained by data from the new proposed survey. In particular, two model configurations were used in this study. The first, referred as scenario 1, was developed to describe the conceptual model obtained by conventional methods of characterization (meaning, in this case, stratigraphic logs, pumping tests and Lugeon tests). The second (scenario 2) updated the parameter value (hydraulic

Id point	Depth of measures [range m b.g.s]	Mean DARCY-velocity (m/s)
LF1	26.6 – 34.6	**2.40 x 10^{-4}**
LF2	25.65 – 35.65	6.00 x 10^{-5}
LF3	24.65 – 33.5	**3.30 x 10^{-4}**
LF4	19.65 – 31.5	5.60 x 10^{-5}
CL1-2	29.5 – 31.5	1.7 x 10^{-5}
Cl2-1	29.5 – 32.5	1.4 x 10^{-5}
CL3-1	27.5 – 29.75	**1.2 x 10^{-4}**
CL3-2	22.5 – 24.5	6. 7 x 10^{-6}
CL4-1	26.65 – 30.65	**1.4 x 10^{-4}**
CL5-1	32.25 – 35.25	8.7 x 10^{-6}
CL5-2	26.5 – 30.5	**1.3 x 10^{-4}**
CL6-1	26 – 27.5	4. 7 x 10^{-6}

Tab. 1 - Mean horizontal Darcy velocity recorded in monitoring

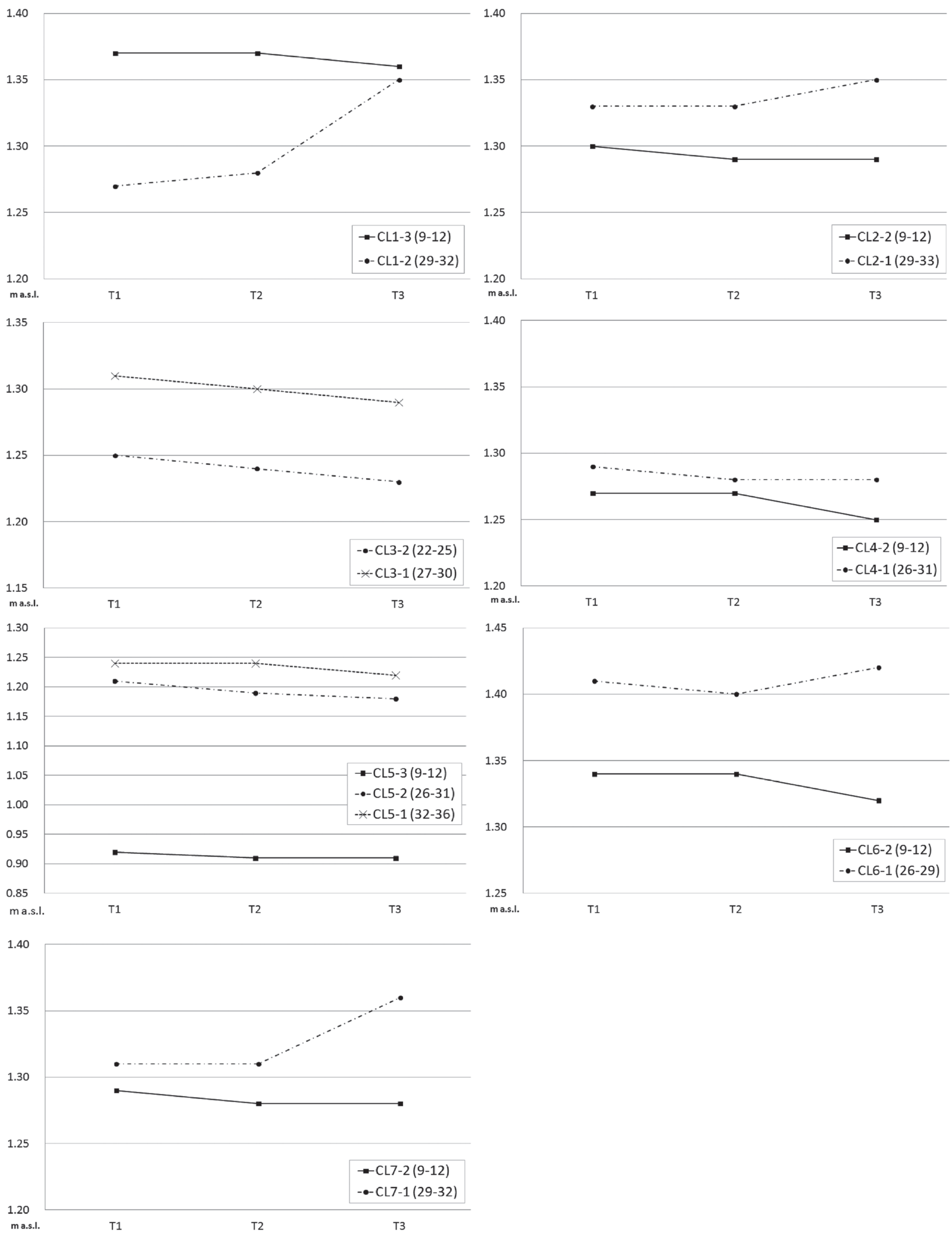

Fig. 4 - Piezometric heads (m. a.s.l.) monitored in cluster piezometers for T1 (February 14th), T2 (February 15th) and T3 (March 7th) . In brackets: filters screen depth below ground level. The position of cluster piezometers is shown in Fig. 3

conductivity) in the base model to match field data collected during flowmeter surveys.

The USGS computer program MODFLOW (Harbaugh *et alii*, 2000; Harbaugh, 2005) was used for this analysis. The model was not detailed enough to be fully calibrated by on site-data, but it was useful to analyze the major differences in the conceptual models of the aquifer.

The finite-difference grid for the numerical model consisted of uniformly spaced model cells that were 5 m on one side. The grid consisted of 88 rows, 60 columns and 12 layers that covered an area of around 0.13 km^2 (0.3 x 0.44 km).

The following boundary conditions were set: no recharge via ground surface and constant heads (CH) at the upstream and downstream sides of the system representing the piezometric level monitored in available piezometers (1.9 m a.s.l at the North side and 0.3 m a.s.l at South). The ground surface was reproduced according to the data obtained by stratigraphic logs and monitoring points available on site. The layers were not sloping between the South end of the studied area and the North end of the underground structure, while they had a slope equal to the one of the ground level between the North end of the underground structure and the upstream end of the model. As a consequence of the morphological characteristics of the area, the North CH condition was placed only in saturated layers.

In scenario 1 the aquifer was represented as an equivalent porous media with uniform properties: hydraulic conductivity value of all layers corresponding with incoherent aquifer materials (Tab. 2 and Fig. 5, K_x=K_y, layers 1-10) was constant

Layer number	Schematic stratigraphy	Scenario 1: Aquifer scheme according to conventional methods of characterization			Scenario 2: Aquifer scheme according to new approach of characterization		
		Depth		k [m/s]	Depth		k [m/s]
		from [m b.g.l.]	to [m b.g.l.]		from [m b.g.l.]	to [m b.g.l.]	
1	Incoherent aquifer materials (from 0 to 10 m depth: gravel to sandy silt:from 10m to 34 m depth: fine-medium sand and silty sand to medium-coarse sand, from loose to moderately packed)	0	34	1.1×10^{-3}	0	6.2	2.40×10^{-5}
2					6.2	9	2.20×10^{-3}
3					9	9.3	3.30×10^{-2}
4					9.3	16.7	7.90×10^{-4}
5					16.7	18.1	2.30×10^{-3}
6					18.1	23.7	6.10×10^{-5}
7					23.7	28.9	2.30×10^{-3}
8					28.9	31.8	4.40×10^{-5}
9					31.8	32.8	2.20×10^{-3}
10					32.8	34	8.50×10^{-5}
11	Bedrock (rock, from friable to compact /slightly consolidated), 2-3 mm joints filled with calcium carbonate	34	42	1.1×10^{-6}	34	42	1.00×10^{-6}
12		42	60	1.1×10^{-7}	42	60	1.00×10^{-7}

Tab. 2 - *Comparison between the aquifer hydraulic conductivity scheme according to conventional methods of characterization (scenario 1) and data from the new proposed approach (scenario 2, k data referred to LF3) umulative curve showing the grain size composition of the soil sampled in the excavation for the permeability test in situ*

and equal to the K obtained by the pumping test (1.1 x 10^{-3} m/s). Hydraulic conductivity values of the two layers at the bottom of the model were equal to 1 x 10^{-6} m/s and 1 x 10^{-7} m/s, represented the bedrock, and they were differentiated according to the results of Lugeon tests. The vertical hydraulic conductivity of layers (K_z) was always equal to 1/10 of K_x.

In Fig. 5, the flow net along a section was represented; the more superficial layers of the model were unsaturated at the North side; the piezometric lines showed some deformations in layers corresponding with the bedrock but did not show vertical gradient in layers corresponding with incoherent aquifer materials.

Subsequently, the numerical model was modified to represent the changes in the conceptual model of the aquifer introduced by the results of the thermo-flowmeter logs.

In scenario 2 the layers represented the heterogeneities of individual strata, each with different hydraulic proprieties: data measured by thermo-flow meter log of LF3 were used to modify the hydraulic conductivity values of layers corresponding with the incoherent aquifer materials (Tab. 2 and Fig. 6, K_x=K_y, layers 1 to 10).

This approach includes the assumption of extension of the hydraulic conductivity measured at LF3 monitoring well to the whole domain of the model, with the aim of evaluating how such variability of K values could modify the hydraulic network. The two layers at the bottom of the model had the same hydraulic conductivity as the previous model and the vertical hydraulic conductivity of layers (K_z) was always equal to 1/10 of K_x. In Fig. 6 the flow net along the same section as Fig. 5 was represented and showed significant upward gradient in strata corresponding with incoherent aquifer materials. This change was due to the presence of strata with lower hydraulic conductivity (for example 6.1 x 10^{-5} m/s from 18 to 23 m depth) that act as an aquitard. The upward gradient caused the upward flows detected on-site in monitoring wells with long filter screen that connect all the aquifer layers.

The results of the study modified the conceptual model of the aquifer and illustrated a potentially critical hydrogeological situation: if the lower, partially confined layers of the aquifer are intercepted by structures that modify the local hydraulic situation, the high permeability of these horizons could lead to an increase of the groundwater flow velocity to a degree that might not be compatible with the technical parameter of soils. For example, Della Rossa *et alii* (2003), Gattinoni & Francani (2009) stated that the overcoming of the critical speed of groundwater flow introduces erosion effects that can lead to a destabilization of soil structures.

The proposed methodical approach can be applied for site investigations prior to, or in the course of, ongoing underground construction activities in order to identify hydrogeologic circumstances that can be critical to construction works in aquifers.

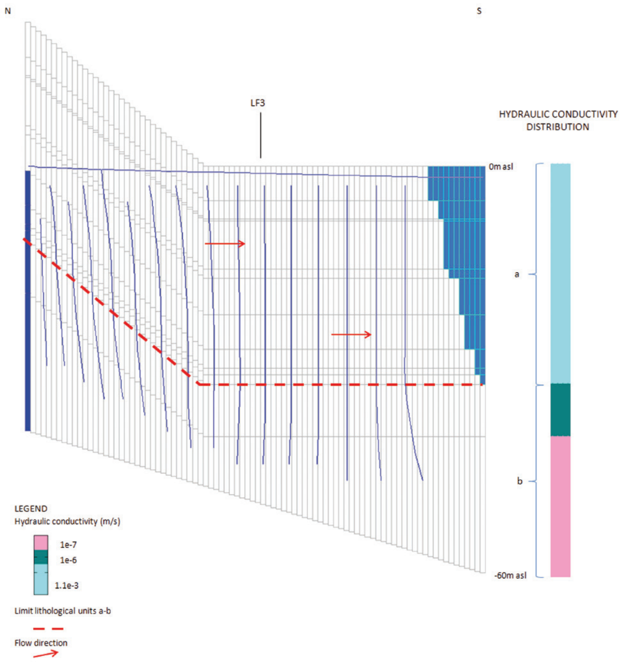

Fig. 5 - Piezometric lines (side view, NS section) and flow directions resulting from the conceptual model of the aquifer obtained in scenario 1 (a = incoherent aquifer materials; b = bedrock)

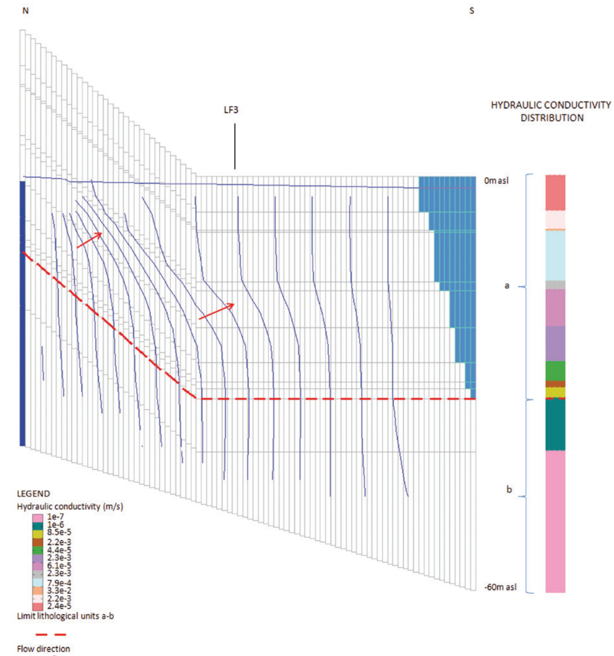

Fig. 6 - Piezometric lines (side view, NS section) and flow directions resulting from the conceptual model of the aquifer obtained in scenario 2 (a = incoherent aquifer materials; b = bedrock)

CONCLUSIONS

The subject of this paper is an advanced investigation approach to identify and characterize significant hydraulic heterogeneities in an aquifer, with a suitable level of detail in reference to a studied case. Conventional hydrogeologic characterization is generally based on data from stratigraphic logs, pumping tests and piezometric monitoring. These data, applied on a local scale, are in some cases not sufficient to resolve the hydraulic situation with an appropriate level of detail, especially in the vertical profile of the aquifer. In order to support conventional methods of characterization, two direct in-hole vertical and horizontal groundwater flow velocity measuring procedures are proposed. They were applied in a case study where supplementary hydrogeologic surveys were conducted to improve the existing conceptual model of the aquifer near an underground structure. The additionally provided data completed the information available for modeling the aquifer with sufficient accuracy.

Vertical thermo-flowmeter logs allowed the detection of some noticeable heterogeneities: a leaky aquifer, an upward directed leakage, and several layers with higher hydraulic conductivity in the lower part of a hydrostratigraphic unit that appeared almost homogeneous. Moreover, horizontal in-hole groundwater flow measurements allowed for quantifying the flow in the more productive layers with observed Darcy velocity up to 10^{-4} m/s in some measuring points.

A numerical model was applied in two scenarios, to analyze the main differences in the conceptual model of the aquifer obtained by conventional methods of characterization and in the updated one obtained through the new approach of investigation. The first was characterized by a regular pattern of flow, without vertical gradients in layers corresponding with incoherent aquifer materials. The second, instead, showed significant upward gradients in strata corresponding with incoherent aquifer materials. This change is due to the presence of strata with lower hydraulic conductivity that act as an aquitard and locally confine the more permeable strata detected at the bottom of the aquifer. Even if the numerical model is not fully calibrated by site data, it supports the field study to understand and describe the complex hydrogeological situation.

The survey method proposed in this study leads to accurate results on a local scale, whose significance in the context of the studied issue must be discussed by relating the collected data with other information on the hydrogeological system. Vertical and horizontal groundwater velocity measurements in monitoring points designed ad hoc, can substantially change the conceptual model of the aquifer; they can be integrated with the conventional techniques of characterization of the aquifer, assuming the following operational steps:

1. characterization of soils with hydraulic conductivity tests, piezometric head monitoring and in-hole groundwater flow velocity measurements;
2. processing and merging of collected data with the elaboration of a conceptual model of the aquifer (the evaluation of groundwater

velocity achievable by indirect approaches cannot reach the level of detail of velocity measurements in boreholes);
3. numerical modeling of natural flow and forecast of its variations caused by the planned underground activities.

These stages should be completed by validation of numerical model results, achieved by their comparison with real piezometric and flow variations, for example induced by wells or pilot excavation.

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