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AN EXAMPLE OF AQUIFER HETEROGENEITY SIMULATION TO MODELING WELL-HEAD PROTECTION AREAS

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EXTENDED ABSTRACT

Una gestione appropriata delle risorse idriche sotterranee richiede la delimitazione attorno ai pozzi per l'approvvigionamento idropotabile dell'area entro cui potenziali fonti di contaminazione possono ancora essere prevenute o attenuate. Quest'area è comunemente indicata come area di protezione o Well-Head Protecion Area (WHPA). Si parla inoltre di zona di ricarica, di zona di alimentazione o zona di contributo (Zone of Contribution o ZOC) per indicare la proiezione bidimensionale, sul terreno, del volume di acquifero in cui l'acqua di falda fluisce in tempi variabili, verso un'opera di captazione (Paradis *et alii*, 2007). La zona di tempo di arrivo (Zone of Travel o ZOT) è definita all'interno della ZOC e può essere individuata dall'isocrona indicante il tempo necessario alle acque sotterranee o ad un contaminate conservativo per raggiungere un pozzo da quella posizione. L'U.S. EPA (1994) definisce 4 metodi di complessità progressivamente crescente per l'individuazione della zona di protezione: (i) metodi geometrici, (ii) metodi analitici semplificati, (iii) mappatura idrogeologica e (iv) metodi di modellazione numerica.

Nel 2007 la Commissione Europea (EC) ha pubblicato il documento "Guidance on groundwater in drinking water protected areas" (Guidance Document n. 16) in applicazione della Water Framework Directive (2000/60/EC). Con questo documento l'EC definisce le aree di protezione per le acque destinate al consumo umano (Drinking Water Protection Areas or DWPAs) e ne stabilisce i principi generali per la definizione, sottolineando però che l'istituzione di tali zone è a discrezione degli stati membri (Fileccia, 2015).

In relazione alla legislazione italiana vigente (D.Lgs. 152/06), per le definizione delle zone di protezione sono previsti 3 criteri: (i) criterio geometrico, usato per identificare rispettivamente le zone di tutela assoluta (raggio fisso pari a 10 m) e di rispetto (raggio fisso di 200 m) attorno al punto di captazione; (ii) criterio cronologico, usato per definire una zona di tempo di arrivo per l'isocrona 60 giorni; (iii) criterio idrogeologico, usato per definire la zona di contribuzione dell'opera di captazione.

Tipicamente una delimitazione esaustiva della ZOT richiede la simulazione numerica del flusso delle acque sotterranee e la riproduzione della componente advettiva del processo di trasporto. In questo contesto la stima delle variabilità spaziale dei parametri idrodinamici ed idrodispersivi costituisce un aspetto critico nell'implementazione delle simulazioni numeriche. Solitamente nella fase di caratterizzazione idrogeologica si utilizzano dati provenienti dai pozzi e/o piezometri che molto spesso non sono omogeneamente distribuiti sull'area di interesse oppure ne coprono solo una porzione. Inoltre è pratica comune quella di assumere il sottosuolo come geologicamente omogeneo e di riprodurre le sue eterogeneità attraverso zone a proprietà costante. Tuttavia il sottosuolo presenta forti eterogeneità, come ad esempio nel caso della conducibilità idraulica (K) che può variare di diversi ordini di grandezza su brevi distanze. Per cui, benché nel complesso il comportamento regionale di un acquifero possa essere riprodotto attraverso l'uso di proprietà medie distribuite in modo uniforme, a volte le condizioni locali possono divergere notevolmente da quelle simulate. In particolare l'impatto delle eterogeneità del sottosuolo può essere amplificato dalla presenza di piccole lenti che possono costituire percorsi di flusso preferenziale. Un approccio utile per affrontare il problema dell'eterogeneità del sottosuolo è la simulazione geostatistica (Dell'Arciprete *et alii*, 2012; Trevisani & Fabbri, 2010).

Nel presente articolo la simulazione geostatistica, abbinata al metodo delle probabilità di transizione (Carle & Fogg, 1996), e la modellazione numerica del flusso delle acque sotterranee sono utilizzate per la definizione delle aree di protezione di alcuni pozzi per l'approvvigionamento idropotabile ubicati nella media pianura veneta. Il metodo delle probabilità di transizione con variabili categoriche è stato utilizzato attraverso l'ausilio del software T-PROGS (Carle, 1999), mentre MODFLOW-2005 (Harbaugh, 2005) e PEST-ASP (Doherty, 2005) sono stati utilizzati rispettivamente per la simulazione e la calibrazione di distribuzioni di carico idraulico sito-specifiche. Infine, per la delimitazione delle linee isocrone del tempo d'arrivo a 60 giorni sono state realizzate delle ricostruzioni a ritroso (backward) dei percorsi di migrazione delle particelle con il codice MODPATH (Pollock, 1994).

ABSTRACT

Groundwater management requires the definition of Well-Head Protection Areas (WHPA) for water supply wells. Italian law uses geometrical, chronological and hydrogeological criteria for WHPA identification, providing a groundwater travel time of 60 days for the definition of the Zone of Travel (ZOT). An exhaustive ZOT delineation must involve numerical modeling of groundwater flow together with simulation of the advective component of the transport process. In this context, the spatial variability of hydrogeological and transport parameters has to be critically estimated during numerical modeling implementation.

In the present article, geostatistical simulation using a transition probability approach and groundwater numerical modeling were performed to delineate WHPAs for several supply wells in the middle Venetian Plain, taking into account the lithologic heterogeneity of the aquifer. The transition probability approach for the lithologic data was developed by T-PROGS software, while MODDLOW-2005 and PEST-ASP were used, respectively, to reproduce and calibrate site-specific hydraulic head data. Finally, a backward particle tracking analysis was performed with MODPATH to outline the 60-day ZOT.

Keywords: *Well-Head Protection Area, transition probability, groundwater numerical modeling, automatic calibration, middle Venetian Plain*

INTRODUCTION

Appropriate groundwater management requires the delineation of the area surrounding a production well for the water supply where potential contamination sources should be prevented and managed. This area is commonly referred as the Well-Head Protection Area (WHPA). The most commonly accepted definition of this area is from the U.S. EPA (1991), which defines a WHPA as: "the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field". This zone can also be referred as the Zone of Contribution (ZOC), i.e., the two-dimensional projection to the land surface of the aquifer volume containing all the groundwater that may flow toward a pumping well over an infinite time of period (Paradis *et alii*, 2007). The Zone of Travel (ZOT) is defined within the ZOC, and it can be described as an isochrone indicating the time necessary for water (or a conservative contaminant) to reach the well from that location. The U.S. EPA (1994) classifies the methods for WHPA delineation into four major categories of increasing complexity: (i) geometric methods, which involve the use of a pre-determined fixed radius and aquifer geometry without any special consideration of the flow system, or the use of simplified shapes that have been pre-calculated for a range of pumping and aquifer conditions; (ii) simple analytical methods, which allow the calculation of distance for WHPA using equations that are solvable with a hand calculator or a spreadsheet program; (iii) hydrogeological mapping, which involves the identification of the ZOC based on geological, geomorphological and hydrogeological settings of the area; (iv) numerical modeling methods, which involve the use of more complex analytical or numerical solutions to determine groundwater flow and contaminant transport processes.

In the European Union (EU) in 2007, the European Commission (EC) published the "Guidance on groundwater in drinking water protected areas" (Guidance Document n. 16) as an application of the Water Framework Directive (2000/60/EC). In this document, the EC defines Drinking Water Protection Areas (DWPAs) and the general procedure for their delineation, underlining that the establishment of such zones is at the discretion of member states (Fileccia, 2015).

Considering current Italian law (D.Lgs. 152/06), WPHA delineation includes three criteria: (i) geometrical criterion, used to identify an absolute protection area (fixed radius of 10 m) and a respect area (fixed radius of 200 m) around the well; (ii) chronological criterion, used to define a ZOT for a travel time of 60 days; and (iii) hydrogeological criterion, used to identify the ZOC of the well.

Typically, a complete ZOT identification requires the numerical simulation of groundwater flow and the reproduction of the advective component of the transport process. In this context, assessing the spatial variability of both hydrogeological and transport parameters constitutes a critical aspect of the model's implementation. Generally, site investigations use borehole data, which unfortunately, represents a small percent of the studied area. Therefore, geological homogeneity is assumed, and polygonal zones with uniform properties are constructed. However, soil properties are highly heterogeneous and, for example, hydraulic conductivity (K) can vary over two orders of magnitude within a short distance. As a result, although overall regional aquifer behavior can be represented by mean uniform properties, local conditions can drastically diverge from model representation. The impact of soil heterogeneity can be magnified by the presence of small lenses, which dominate groundwater flow conditions. In such a case, the WHPA delineation can be significantly biased.

To overcome subsoil heterogeneity, geostatistical simulation of categorical data constitutes a useful approach (Fabbri & Trevisani, 2005; Trevisani & Fabbri, 2010; Sartore *et alii*, 2016). Traditional geostatistical methods, such as Sequential Indicator SIMulation (SISIM; Goovaerts, 1997; Deutsch & Journel, 1998) or Transition PRObability simulation (T-PROGS; Carle & Fogg, 1996; Ritzi, 2000; Lee *et alii*, 2007), can be used for this kind of simulation. Although based on random function models, the posterior conditional probability approach is practically used to predict/simulate the lithologic category at every grid node through kriging or cokriging-based methods (Dell'Arciprete *et alii*, 2012). The initial categorical data are derived from the simplification of available stratigraphic logs. Furthermore, T-PROGS, unlike SISIM, take into account different hydrogeological features, such as volumetric proportions, mean lengths and juxtapositional tendencies of the lithofacies, in its prediction/simulation because of transiogram analysis (Carle, 1997; Weissmann & Fogg, 1999; Engdahl *et alii*, 2010; Piccinini *et alii*, 2015). As a matter of fact, the transition probability approach has been successfully applied in many cases to simulate aquifer heterogeneities (Jones *et alii*, 2005; Fleckenstein *et alii*, 2006; Sakaki *et alii*, 2009; Bianchi *et alii*, 2011; He *et alii*, 2013).

In this article, geostatistical simulation by a transition probability approach (Carle & Fogg, 1996) and groundwater numerical modeling were carried out to delineate WHPAs for several water supply wells in the middle Venetian Plain. The transition probability approach for lithologic data was developed by T-PROGS software (Carle, 1999), while simulation and calibration of results through site-specific hydraulic head data were, respectively, performed using MODFLOW-2005 (Harbaugh, 2005) and PEST-ASP (Doherty, 2005). Simulation results were then used to carry out a backward particle tracking analysis with MODPATH (Pollock, 1994) to outline the isochrone of 60 days and its associated ZOT.

GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS

The study area is located between the provinces of Padua, Venice and Treviso in the middle Venetian Plain (Northeastern Italy; Fig. 1). The Venetian Plain is in the eastern part of the foreland basin of the Southern Alps and is characterized by the presence of alluvial megafans developed by the Brenta and Piave rivers during the Late Quaternary (Fontana *et alii*, 2008). The catchment basins of these rivers mainly consist of limestone and dolomite, which supply large amounts of clastic debris forming hundred meters-thick gravel beds in the piedmont plain. This plain sector, a so-called "high plain", is located close to the Prealps, evolves toward the Adriatic Sea in a fine-grained sedimentary sequence of alluvial or marine origin, forming the so-called "low

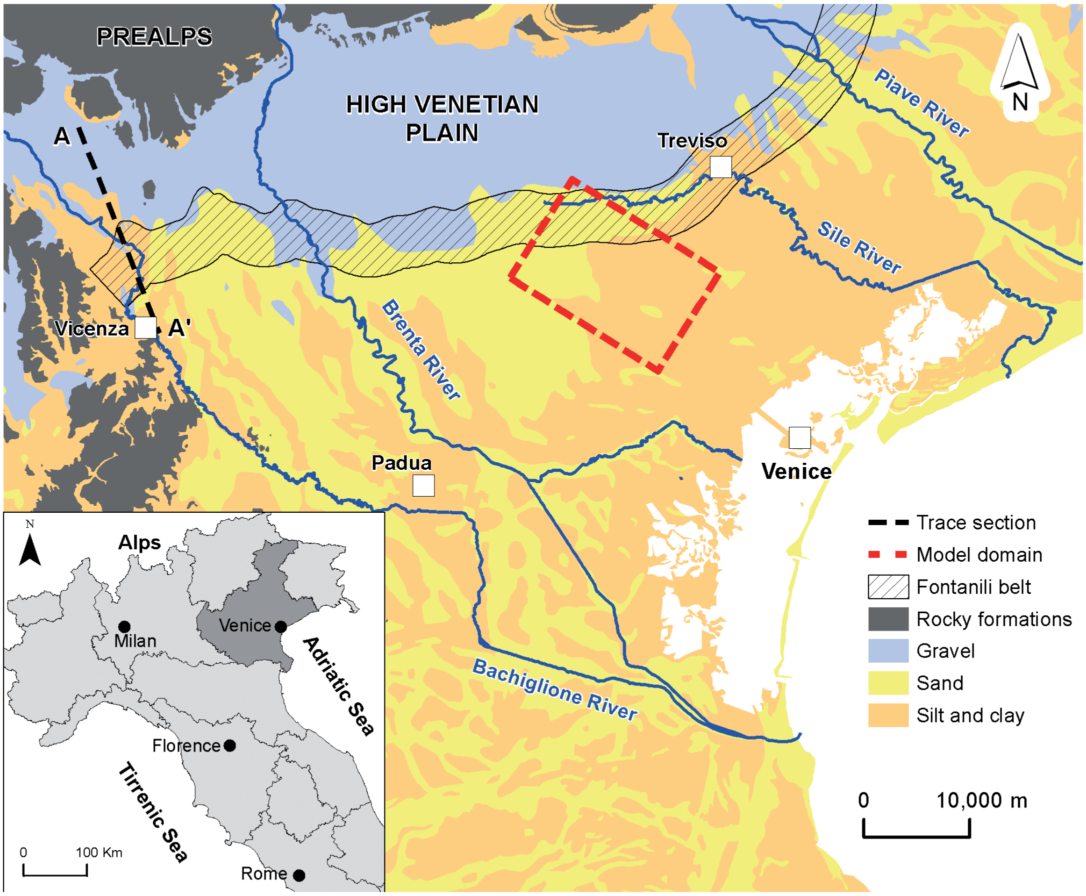

Fig. 1 - *Geological map of the Venetian Plain between the Bachiglione and Piave rivers; the black dashed line A–A' represents the cross-section shown in Fig. 2, while the red dashed line is the model domain of Fig. 4*

plain". This peculiar geological context has led to the formation of two main hydrogeological units: a large unconfined aquifer in the higher-lying part of the plain and a multi-layered confined or semi-confined aquifer system in the lower-lying part of the plain toward the sea. (Fig. 1; Dal Prà *et alii*, 1992; Pola & Fabbri, 2009; Piccinini *et alii*, 2016; Fabbri et alii, 2016; Dalla Libera *et alii*, 2016). The unconfined aquifer evolves into the multi-layered aquifer through a 2-5 km wide band where the gravelly alluvial deposits progressively change to a sequence of impervious or semi-impervious layers interbedded with gravel and sand (Fig. 2; Carraro *et alii*, 2013; Carraro *et alii*, 2015). In this transition zone, defined as the "middle plain", the water table intersects the topographic surface and groundwater emerges on the plain as a numerous spring called the "Fontanili" (Fabbri *et alii*, 1993; Vorlicek *et alii*, 2004).

The study area is situated in the middle Venetian Plain, where the transition from unconfined to confined has already occurred, and the system is characterized by the presence of ten superimposed confined aquifers ranging from 10 to 310 m in depth (Fig. 1; Fig. 3). The analysis is focused on the first one of these aquifers, which is currently the most exploited by both public and private companies. In fact, the groundwater derived from this aquifer is the drinking water supply for the territory of the Venice Municipality. The first confined aquifer is mainly composed of alluvial gravel and sand ranging in depth from 15 to 50 m below ground level (m b.g.l.) resulting in a thickness of approximately 30 m (Fig. 3; Fabbri *et alii*, 2011). This aquifer is supplied by a NW-SE trending groundwater flow coming from the unconfined aquifer located in the high plain, where rainfall, irrigation and river dispersion are the main recharge processes (Cambruzzi *et alii*, 2009; Fabbri *et alii*, 2016). Away from the recharge area, the aquifer becomes progressively artesian with the hydraulic head above the ground surface during the whole year or in the rainy season. This condition has favored an extensive groundwater exploitation in the recent past, with more than one hundred wells drilled in the area for private use. Hydraulic head data were acquired during two field surveys in May and November 2013, and these values range from 24.8 to 7.3 m a.s.l. in accordance with the main groundwater flow direction. Transmissivity (T) and permeability (K) of the first aquifer were evaluated through step drawdown tests (Fabbri & Piccinini, 2013) and through aquifer tests and slug tests performed in private and public wells. Their values range from 4.10×10^{-2} to 6.40×10^{-2} m^2/s and from 1.20×10^{-4} to 3.00×10^{-3} m/s, respectively.

MATERIAL AND METHODS

Model domain and geometrical discretization

The model domain is outlined to reproduce the main groundwater flow direction of the first confined aquifer (NW-SE). The domain is a rectangle of 11,000×16,500 m centered on water supply wells and rotated 126.5° counterclockwise from the N direction (Fig. 1). A high-resolution non-uniform spatial grid is designed using a horizontal cell dimension expansion factor of 1.1 from the pumping wells' location to the edges of the domain (Fig. 4A). The resulting grid is characterized by horizontal cell dimensions ranging from 5 m to 100 m, from which 245 columns (X-dimension) and 385 rows (Y-dimension) derive. Twenty horizontal layers of constant thickness, equal to 2.5 m,

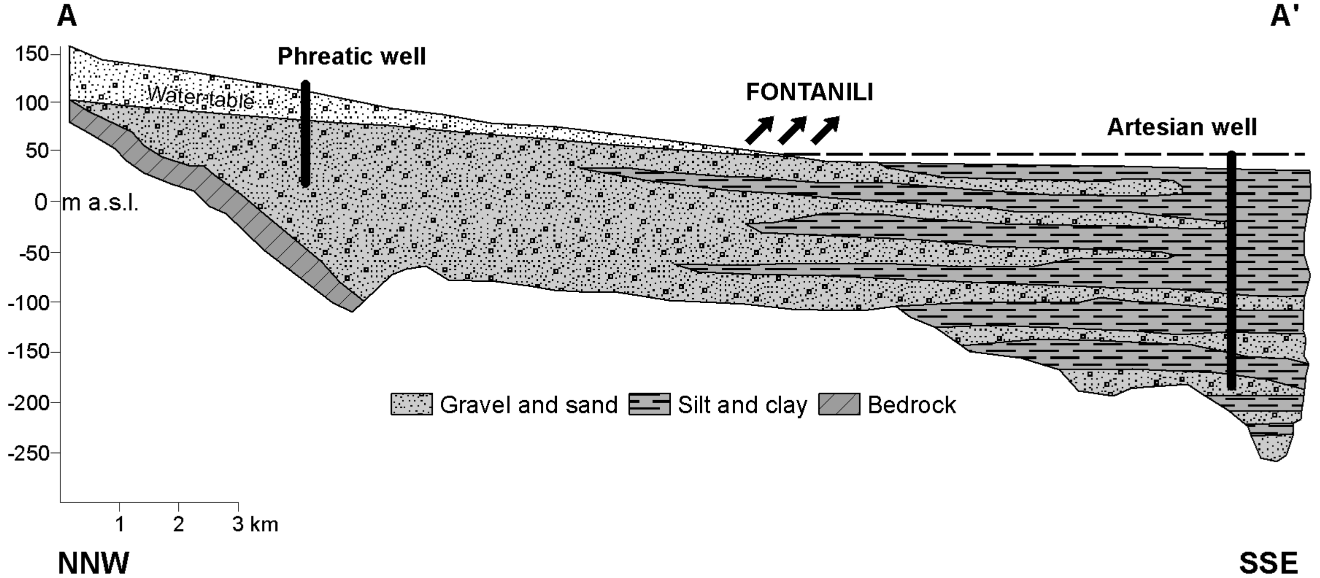

Fig. 2 - Geological cross section across the high and middle Venetian Plain (from Piccinini *et alii, 2016); Fontanili are the plain springs emerging in the middle plain where the water table intersects the topographic surface*

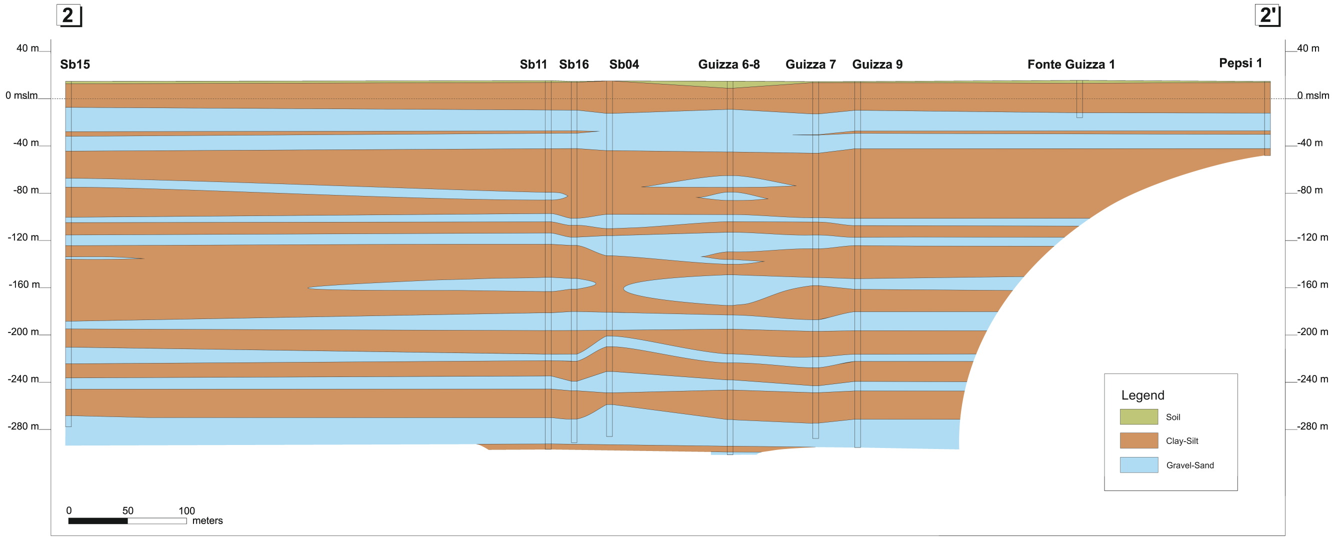

Fig. 3 - Geological cross section in the center of the model domain. The trace of the section is shown in Fig. 5

are represented along the Z-dimension, starting from the top of the first confined aquifer (approximately 0 m a.s.l.; Fig. 4B). This vertical discretization allows for the reproduction of the minimum thicknesses of the lithologic units detectable in stratigraphic logs.

Geostatistical simulation

T-PROGS software simulates categorical variables through the transition probability (TP) of lithologic data modeled as Markov Chain Model (MCM; Krumbein & Dacey, 1969; Carle & Fogg, 1997; Ritzi, 2000). In T-PROGS, TP are used instead of the traditional variogram approach for categorical data owing to their capability to take into account several hydrogeological features of aquifers (He *et alii*, 2014). Four main steps are necessary for simulating the distribution of a categorical variable using T-PROGS: (i) transforming categorical variables (i.e., lithologic data) into indicator variables; (ii) calculating experimental TPs in vertical and horizontal directions; (iii) modeling Markov Chains by fitting experimental TPs; and (iv) generating multiple realizations of the spatial distribution of the categorical variables, approximating the posterior probability by kriging or cokriging-based methods conditioned by on-site available data.

Although lithologic data can be directly read from a borehole log, the number of lithologic units must be reduced to obtain a more computational efficiency for the geostatistical simulation. Thus, borehole data need to be reclassified into a textual categorical system made of fewer categories, in which each category represents a group of lithologic units with similar hydraulic properties. In this study, the lithologic categories were derived from 106 stratigraphic logs recorded during drilling of private and public wells and irregularly distributed inside and immediately outside of the model domain (Fig. 5). The investigated depths range from 12 to 401 m b.g.l. In spite of the uneven data distribution, the high borehole density can be considered sufficient to generate a geostatistical simulation of the lithologic category spatial distribution. The data were reclassified into four main categories, namely: Gravel, Sand, Silt and Clay. The Gravel category was selected as the background category since it is the prevailing lithology in the first confined aquifer. In fact, the background category should be selected as the category that fills in the space not occupied by other categories according to geological interpretation (Carle, 1999)

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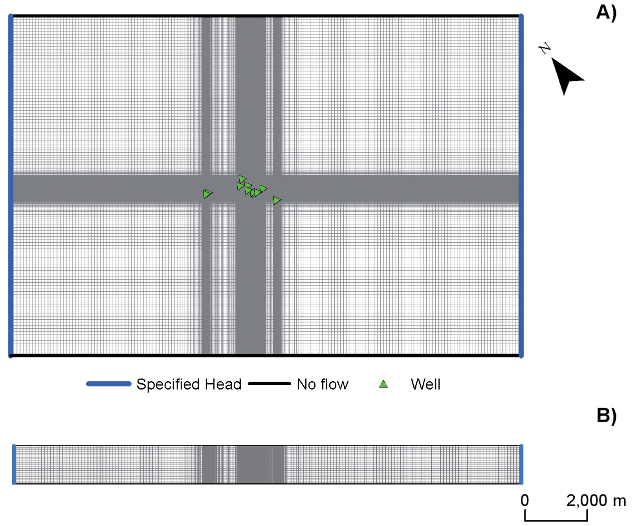

Fig. 4 - Three-dimensional grid used for the geometrical discretization and boundary conditions (BCs) defined in MODFLOW-2005 simulation: in plan view on layer 1 (A) and in section along row 123 with a vertical exaggeration factor of 25 (B)

Groundwater numerical model

Starting from the geostatistical realization of aquifer

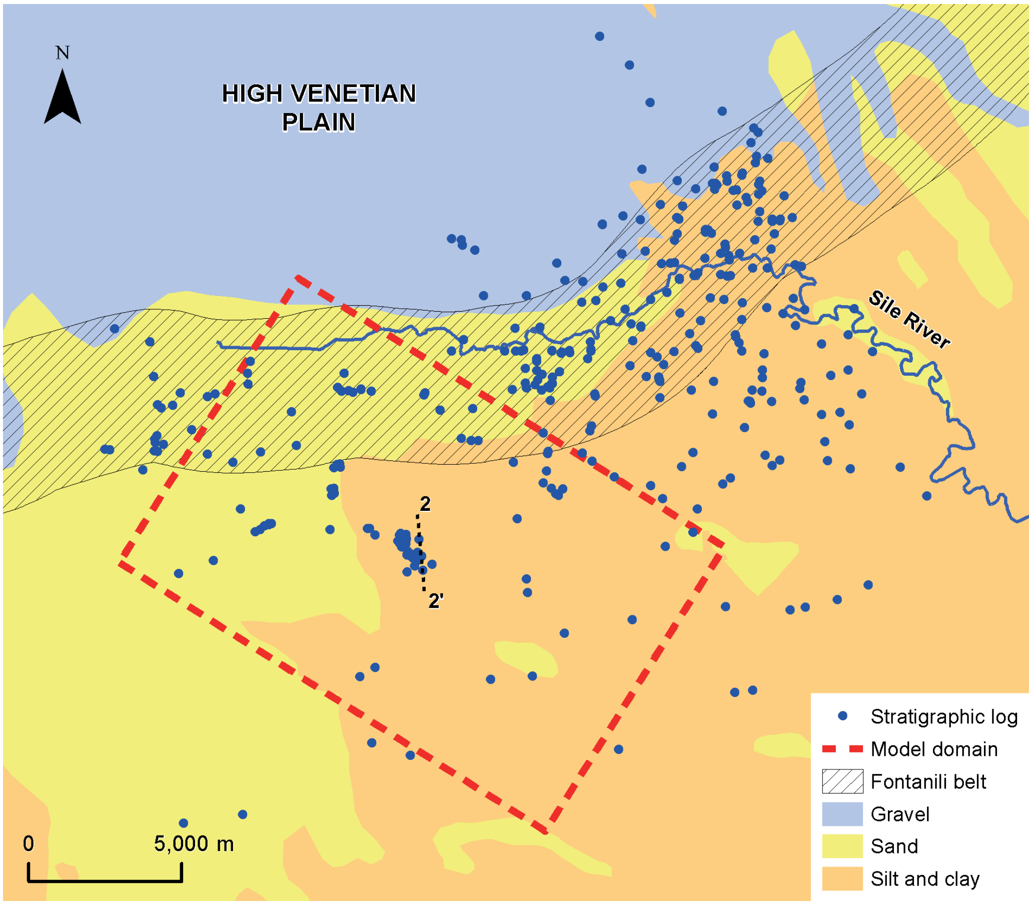

Fig. 5 - Location of the stratigraphic logs around and inside the model domain. The dashed gray line 2-2' is the trace of the cross section in Fig. 3

heterogeneity, two steady-state simulations were carried out using MODFLOW-2005 code (Harbaugh, 2005). MODFLOW-2005 is the modular three-dimensional finite difference groundwater flow model developed by the U.S. Geological Survey (USGS), which has been updated from the original MODFLOW code (McDonald & Harbaugh, 1988). The steady-state simulations were implemented to reproduce the hydraulic head data acquired during the potentiometric survey of May and November 2013. The first simulation was implemented for calibration purposes, while the second simulation was used for model verification (Anderson & Woessner, 1992). To enable an accurate representation of the aquifer heterogeneity derived from the geostatistical simulation, the Hydrogeologic-Unit Flow package (HUF) was used (Anderman & Hill, 2000). The HUF package is an alternative to the traditional Block-Centered Flow Package (BCF) or Layer Property Flow package (LPF), and it allows for defining the vertical stratigraphy independently from the vertical discretization using hydrogeologic units. The WELL package of MODFLOW (McDonald & Harbaugh, 1988) was used to simulate the private and public supply wells inside the model domain, while the Geometric Multigrid Solver (GMG), based on the preconditioned conjugate gradient algorithm (Wilson & Naff, 2004), was adopted for solving the equation system resulting from the finite difference approximation.

An automatic calibration with PEST-ASP (Model-Independent Parameter Estimation; Doherty, 2005) was then performed on the available geostatistical simulation of the lithologic distribution to optimize the hydrodynamic properties associated with the four lithologic categories. PEST-ASP is a nonlinear parameter estimation code that finds parameters minimizing the weighted least square objective function (Φ). PEST-ASP uses the Marquardt-Levenberg algorithm (Marquardt, 1963) to determine the parameter adjustment direction starting from a plausible set of initial parameters inside a specific range for each one.

Finally, a backward particle tracking analysis for steady-state calibration simulation was implemented to define the ZOT of 60 days of travel time for the 11 extraction wells. The advective particle tracking was performed by the MODPATH code (Pollock, 1994) releasing eighteen particles placed in the layers corresponding to the screen depths. In addition to the ZOT delineation, this kind of particle tracking represents an attractive alternative to solving a solute transport model. As a matter of fact, it allows for the estimation of both solute travel paths and the discharge point without involving complex parameters (e.g., dispersion, sorption, chemical reaction) and the related uncertainties (Anderson & Woessner, 1992).

Parameterization

Initial values of horizontal hydraulic conductivity (K_x) and vertical anisotropy (K_x/K_z) were fixed for each lithologic category, while the horizontal anisotropy (K_x/K_y) was equal to 1. Subsequently, parameter estimation was performed using the log-transformation for K_x and K_x/K_z rather than the parameters themselves, resulting in a faster and more stable optimization process. The initial values of these parameters and their variation ranges, which have been used during optimization, are reported in Table 1.

As for hydrodynamic properties, variable values of effective porosity (n_e) were differentiated according to the lithology in the advective particle tracking simulation (Tab. 1).

Boundary conditions (BCs)

The mean hydraulic gradient was reproduced using two specified head boundary conditions (Dirichlet BC or 1st type BC) applied to the northwestern and southwestern sides of the model domain with values of 24 and 7.5 m a.s.l., respectively (Fig. 4). The WELL package (Neumann BC or 2nd type BC) was used to reproduce the 11 wells (6 public and 5 private) present in the model domain (Fig. 4). The pumping rate, assigned to cells corresponding to screen depths, matched the mean annual exploited flow rates and is reported in Table 2.

Material	*K_x initial* (m/s)	*K_x range* (m/s)	*VA initial*	*VA range*	*n_e*
Clay	1.0×10^{-8}	1.0×10^{-9} - 1.0×10^{-7}	10	1 - 100	0.05
Silt	1.0×10^{-6}	1.0×10^{-7} - 1.0×10^{-5}	10	1 - 100	0.07
Sand	1.0×10^{-4}	1.0×10^{-5} - 1.0×10^{-3}	10	1 - 100	0.14
Gravel	1.0×10^{-2}	1.0×10^{-3} - 1.0×10^{-1}	10	1 - 100	0.20

Tab. 1 - Initial values and the range of variation of the horizontal hydraulic conductivity (K_x) and vertical anisotropy (K_x/K_z or VA) used in the automatic calibration. Effective porosity (n_e) used in backward particle tracking analysis

Well	*Type*	*Top screen* (m a.s.l.)	*Bottom screen* (m a.s.l.)	*Q* (m^3/d)
SB-5	private	-32.8	-42.8	103.68
SB-6	private	-30.5	-45.5	604.80
SB-7	private	-27.0	-42.0	1296.00
SB-12	private	-33.1	-45.1	12096.00
PPS-1	private	-32.6	-42.6	432.00
P-1	public	-28.5	-36.5	11232.00
P-2	public	-28.5	-36.5	11232.00
P-17	public	-28.3	-33.8	16416.00
P-27	public	-32.5	-38.5	13824.00
P-28	public	-35.6	-38.7	23328.00
P-29	public	-35.7	-37.7	14688.00

Tab. 2 - Mean annual flow rates (Q) of public and private wells (Type) in the domain area

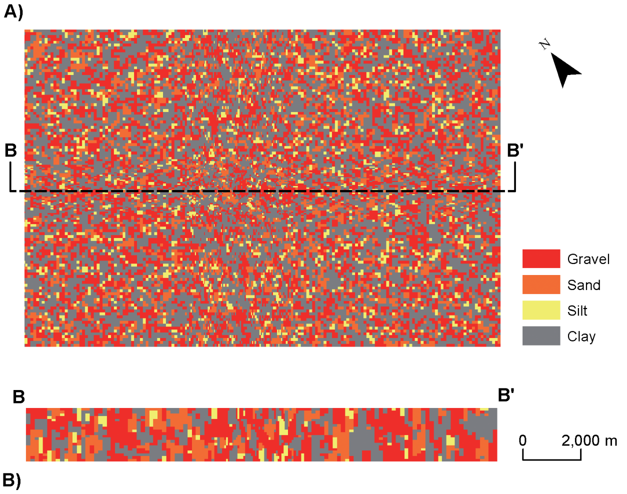

Fig. 6 - Spatial distribution of lithologic categories simulated with T-PROGS in plan view on layer 10 (A) and in the section along row 123 (dashed black line in A) with a vertical exaggeration factor of 25 (B)

RESULTS AND DISCUSSION

Geostatistical analysis and geological simulations

The geostatistical transition probability approach reproduces the borehole input data and simulates the lithologic categories around the borehole in each cell of the grid for every single simulation. It is important to remember that every geostatistical simulation of materials belongs to the same random function, but that different realizations of the same random function can lead to different results in terms of material spatial distribution.

In the present study, only one simulation (random function realization) is performed to take into account aquifer heterogeneity (Fig. 6). The results of this geostatistical simulation are subsequently deterministically treated by the automatic calibration of the hydrodynamic parameters associated with the lithologic categories.

The borehole proportions of lithologies (Tab. 3) confirm that gravel is the dominant lithology in the aquifer (43%), followed by clay (34%). In contrast, sand and silt are minor components, with proportions of 16% and 7%, respectively. Permeable materials constitute as a whole 59% of the lithologies derived from the borehole data. Likewise, gravel and clay are the most continuous lithologies in the vertical direction (Tab. 3), with a mean thickness of 13.83 m and 9.37 m, respectively. In addition, experimental and theoretical transition probabilities (MCM) reach a good fitting in most plots, enhancing the ability of the MCM to estimate experimental transition probabilities along the vertical direction (Fig. 7).

Material	*Volumetric Proportion (%)*	*Lens thickness (m)*
Clay	0.34	9.37
Silt	0.07	5.22
Sand	0.16	8.99
Gravel	0.43	13.83

Tab. 3 - Borehole proportions of lithologies and the mean thickness in the vertical direction

Groundwater numerical model

The quantitative calibration of the geostatistical simulation reaches a good level (Fig. 8). In particular, the Normalized Root Mean Square (NRMS) between the observed and calculated hydraulic head varies from 8.35% in calibration simulation, reproducing the data collected in May 2013 to 7.90% in the verification simulation, which is itself consistent with data collected during the November 2013 survey (Tab. 4). The parameter values producing this match are shown in Table 5. The optimized hydraulic conductivity values of the lithologic categories range over five orders of magnitude, while the vertical anisotropy factor varies from 1 to 29.3. These parameters and their spatial distribution, defined by geostatistical materials simulation, are able to reproduce the two hydraulic head distributions detected in different conditions: late spring (May 2013) and autumn (November 2013). In addition, all parameters derived from the calibration process are consistent with those supporting pieces of information regarding the aquifer and its hydrogeological properties (Vorlicek *et alii*, 2004; Fabbri *et alii*, 2011). In particular, the K_x values for gravel and sand are comparable with those estimated using aquifer and step drawdown tests in the same aquifer (Fabbri & Piccinini, 2013).

The calculated isopotential lines are strongly influenced by the lithologic distribution (Fig. 9), and they differ from the isopotential lines interpolated using observed hydraulic head data or calculated by a classical modeling approach providing few polygonal zones with uniform properties. The flow budget also confirms that the solution satisfies the continuity equation at a

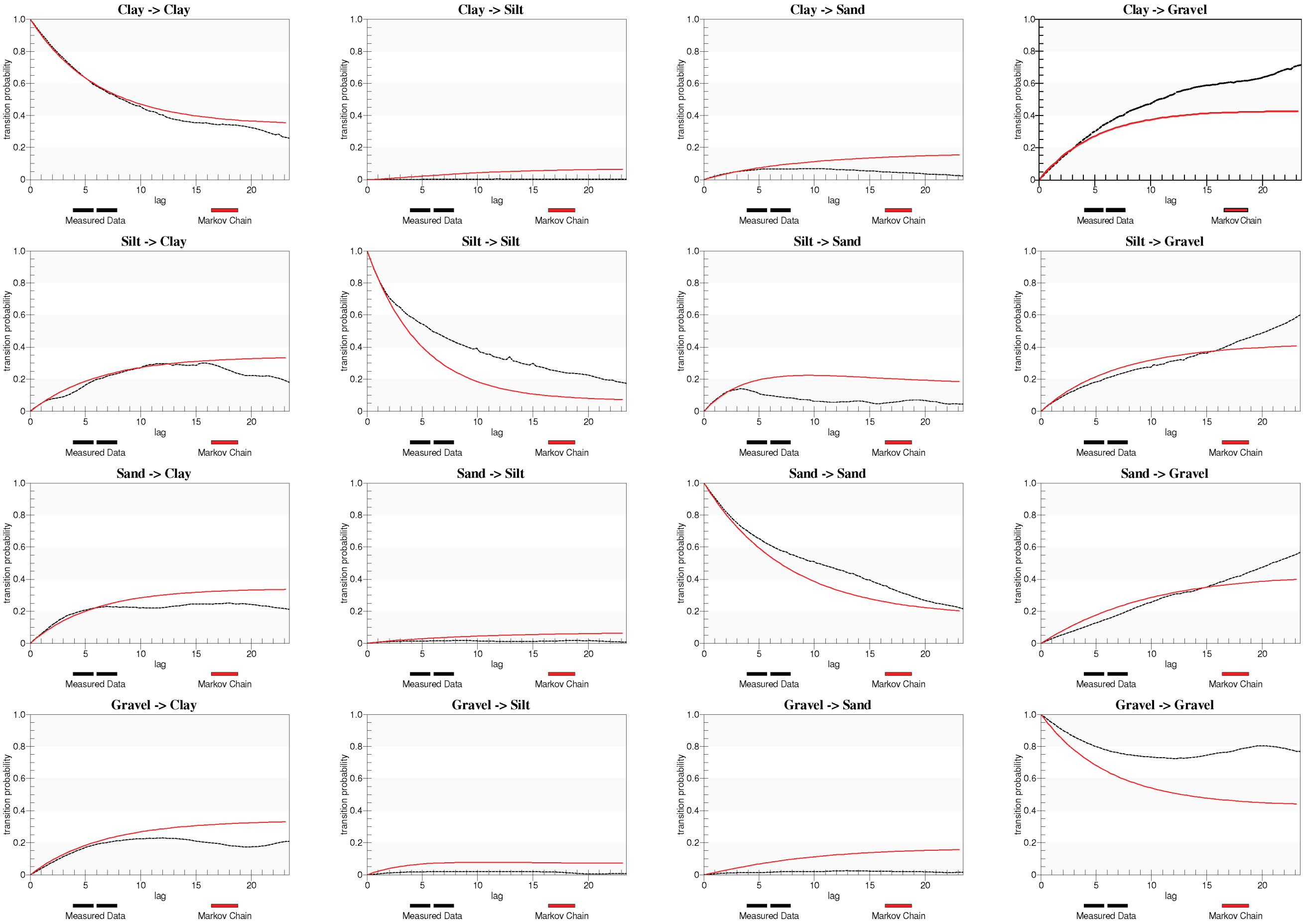

Fig. 7 - Transition probability matrix along the vertical direction; the experimental transition probabilities based on the lithologic data (dashed black line) and the fitted theoretical transition probabilities (i.e., MCM; red solid line) are reported

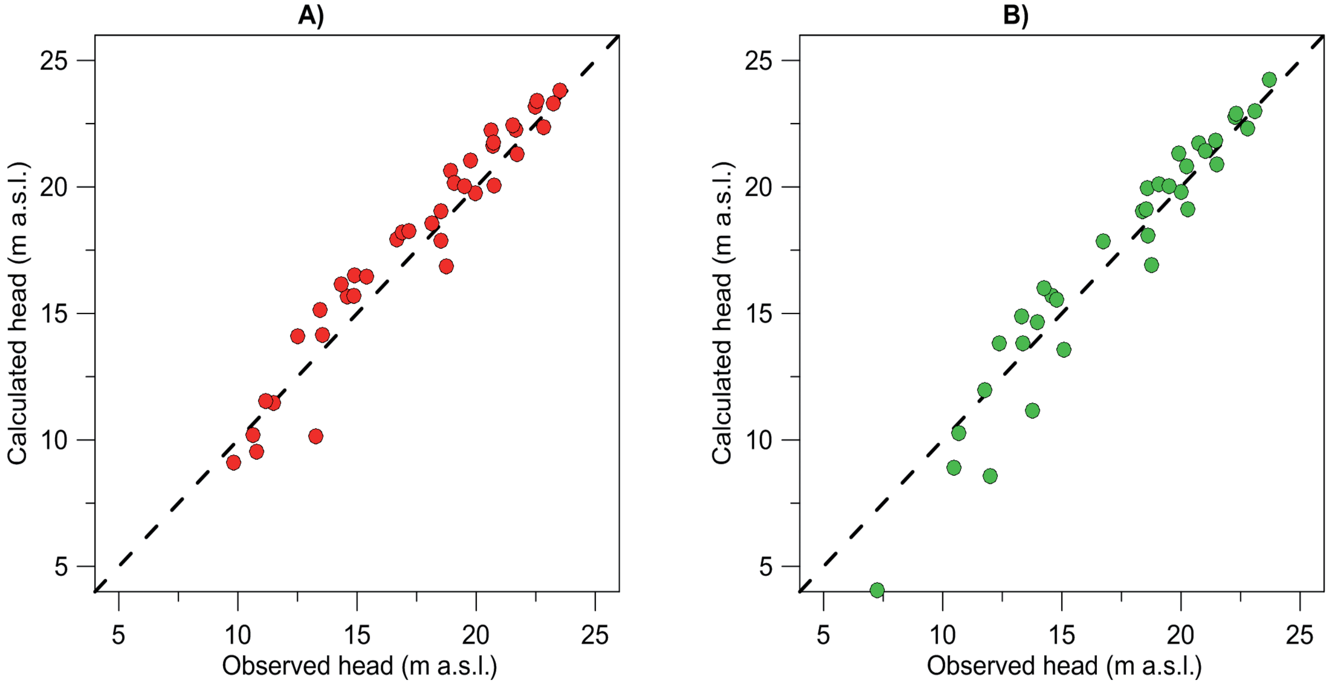

Fig. 8 - Observed vs. calculated hydraulic head for the: (A) calibration simulation (May 2013) and (B) verification simulation (November 2013)

steady-state because there are no important differences between inflow and outflow. The discrepancy percentage is always below the acceptability limit of ± 2% (Tab. 6). In addition, the model highlights that the discharge from public and private wells only represents 20% of the total flow of the first confined aquifer, confirming the potential of this aquifer.

The results of the steady-state simulations were used to perform a backward particle analysis from pumping wells and to calculate both the isochrone of 60 days and its associated ZOT area. The total area of 60-day ZOTs for 11 wells is approximately 16.12 km^2, while the single ZOT ranges from 9.62 to 3.63 km^2 (Tab. 7 and Fig. 10). The extension of each ZOT depends on (i) the pumping rate; (ii) the well position with respect to the groundwater flow direction; and (iii) the geostatistical simulated aquifer heterogeneity, as shown by a comparison between pumping rate and ZOT extension (Fig. 11). From a theoretical point of view, the non-overlapping ZOTs, derived from a simulation with constant K (or lithology) and constant thickness, will mainly depend on the pumping rate, and the relative point will fall on the line of perfect agreement, which in the scatter-plot is approximated by a linear regression of the points P-1, P-2, P-17 and P-29. In Figure 11, the private wells fall above this line due to their location downstream of the public wells and to local heterogeneity. This means that proportionally to the extracted flow rate, the 60-day ZOTs calculated for the private wells are larger than those of the public wells due to hydraulic barrier effects operated by the latter. On the other hand, the public well P-28, despite a large pumping rate

Simulation	*Calibration*	*Verification*
Number of points	38	35
Max residual (m)	1.81	1.74
Min residual (m)	-3.13	-3.42
Mean residual (m)	0.44	0.02
Absolute mean residual (m)	0.97	1.04
RMS (m)	1.14	1.30
NRMS (%)	8.35	7.90

Tab. 4 - Statistical parameters of the quantitative calibrations; RMS is the Root Mean Squared residual; NRMS is the Normalized Root Mean Square residual

Material	*K_x* *(m/s)*	*VA* *( )*
Clay	1.0×10^{-7}	1
Silt	1.0×10^{-5}	1
Sand	1.0×10^{-3}	1
Gravel	8.7×10^{-2}	29.3

Tab. 5 - Final values of horizontal hydraulic conductivity (Kx) and vertical anisotropy (VA) derived from the automatic calibration

A)

BCs	*Flow IN* *(m^3/d)*	*Flow OUT* *(m^3/d)*
Specify Head	531390.4	426137.9
Well	0	105252.5
TOTAL	531390.4	531390.4

B)

In-Out (m^3/d)	0.00098
% Difference	0.000018

Tab. 6 - Flow budget in the steady-state groundwater calibration simulation (A) and discrepancy percentage between inflow and outflow (B)

Well	***Type***	***ZOT area*** *(km^2)*
SB-5	private	3.65
SB-6	private	3.76
SB-7	private	8.36
SB-12	private	9.62
PPS-1	private	3.63
P-1	public	4.36
P-2	public	4.85
P-17	public	5.33
P-27	public	7.46
P-28	public	4.90
P-29	public	5.61

Tab. 7 - Extension of the 60-day ZOTs obtained from steady-state backward particle tracking analysis

(Tab. 2), presents a smaller ZOT, probably arising from favorable heterogeneity conditions. In contrast, P-27 is influenced by an unfavorable heterogeneity condition. The role of the heterogeneity in the delineation of the P-27 and P-28 ZOT is also confirmed by comparing the overlapped and non-overlapped area of each well in terms of absolute value (Fig. 12A) or percentage (Fig. 12B). In fact, these wells show opposite behaviors, despite a higher non–overlapped area due to their lateral location with respect to the alignment of the other points.

CONCLUSIONS

Groundwater management requires the definition of the WHPAs for water supply wells. Italian law (D.Lgs. 152/06) uses geometrical, chronological and hydrogeological criteria for WHPA identification. In particular, chronological criterion

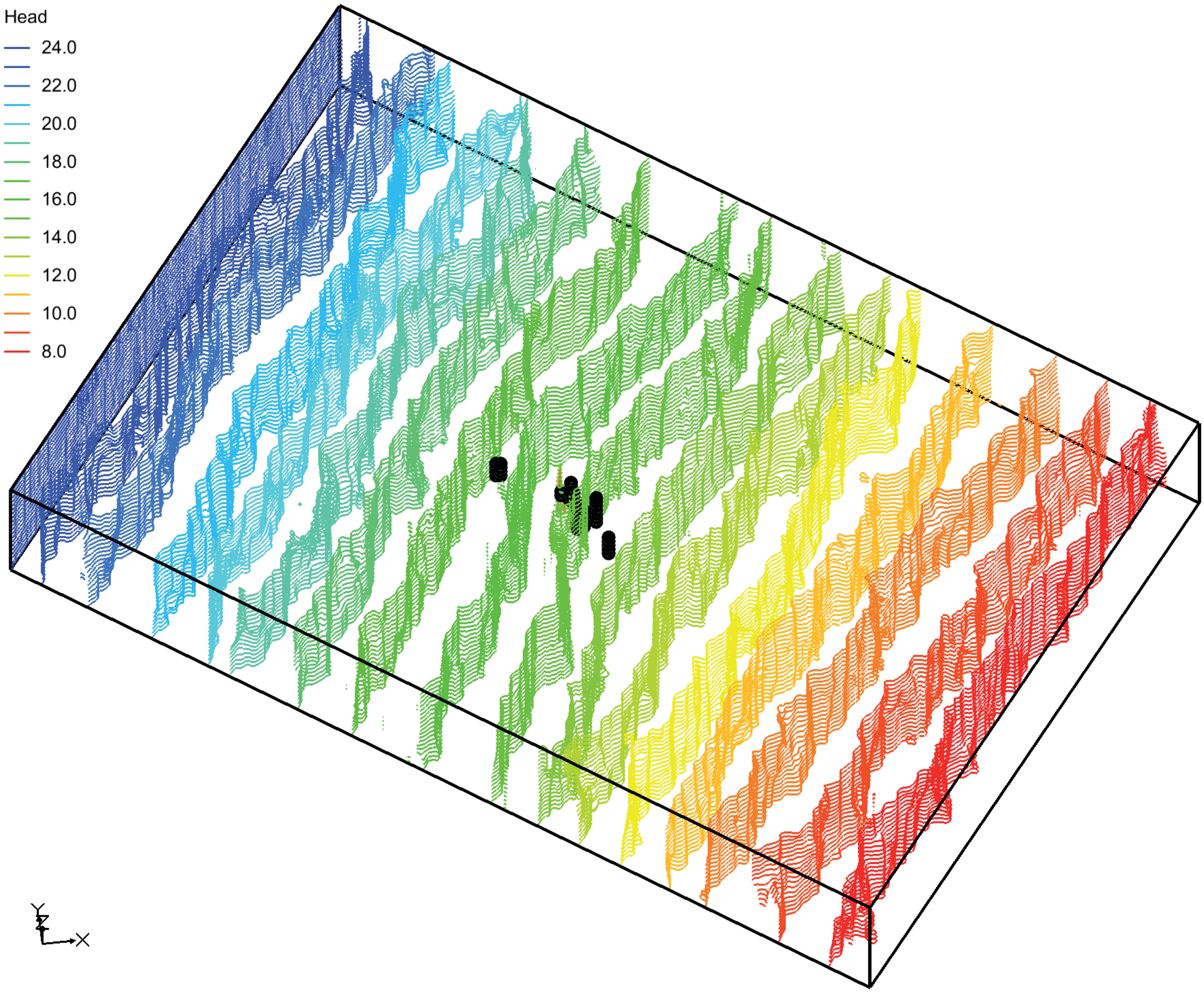

Fig. 9 - Three-dimensional view of the calculated hydraulic head distribution (m a.s.l.) derived from the calibration simulation. Black dots are the simulated pumping wells

provides a travel-time of 60 days toward the wells for the ZOT definition. An exhaustive ZOT delineation must involve both numerical modeling of groundwater flow and simulation of the advective component of the transport process. The assessment of the spatial variability of both hydrodynamic and hydrodispersive parameters, as well as the reconstruction of the subsoil heterogeneity, are critical aspects of such a modeling process. A classical modeling approach consists of using polygonal zones with uniform properties, which are commonly derived from poor coverage for both borehole and pumping test data. This approach leads to great uncertainty at a local scale, where groundwater flow is driven by aquifer heterogeneities (i.e., lithologic and hydraulic conductivity heterogeneities). As suggested by many authors, a more useful approach may involve taking into account both the subsoil heterogeneity and spatial variability of hydrodynamic properties: geostatistical simulation.

This article presents an example of ZOT delineation in the middle Venetian Plain, using an approach of combining numerical groundwater flow modeling and automatic calibration. The geostatistical approach with T-PROGS results particularly suited to reproduce a detailed, geologically plausible distribution of the aquifer heterogeneities. The T-PROGS output is a conditioned stochastic realization of subsurface lithology distribution on a three-dimensional grid in which borehole data are exactly honored when the stratigraphic horizon coincides with the grid cell. This grid is converted into MODFLOW-2005 using the HUF package, which preserves complex heterogeneity using reasonable cell sizes. In addition, the automatic calibration with PEST-ASP represents a suitable tool for assigning realistic hydraulic properties to lithologic distribution. The result of this process is a ZOT delineation for several supply wells for which contribution areas are very different in size and shape. These differences are consistent with the pumping rate and simulated aquifer heterogeneity.

Lithologic geostatistical simulation produces a geologically plausible image of the subsurface lithology distribution. The simulation specifies a series of material sets on a 3D grid, where

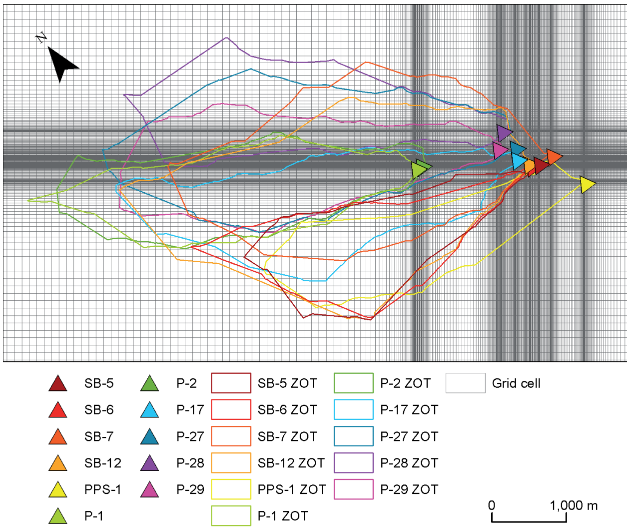

Fig. 10 - Bi-dimensional projection of the calculated 60-day ZOT

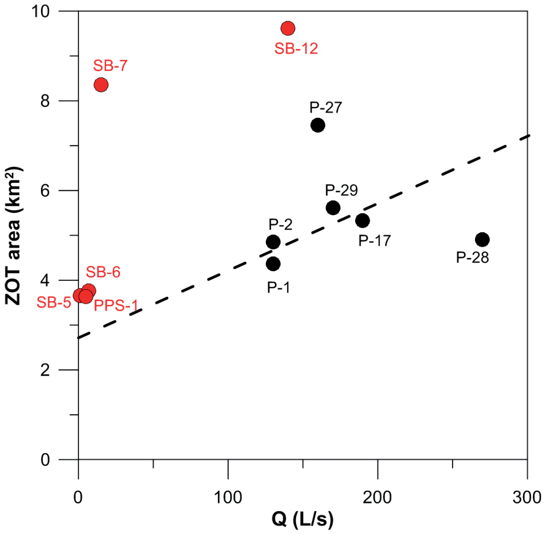

Fig. 11 - Pumping rate (Q) vs. ZOT area, derived from steady-state backward particle tracking analysis. Red dots are the private wells, while black dots are the public wells

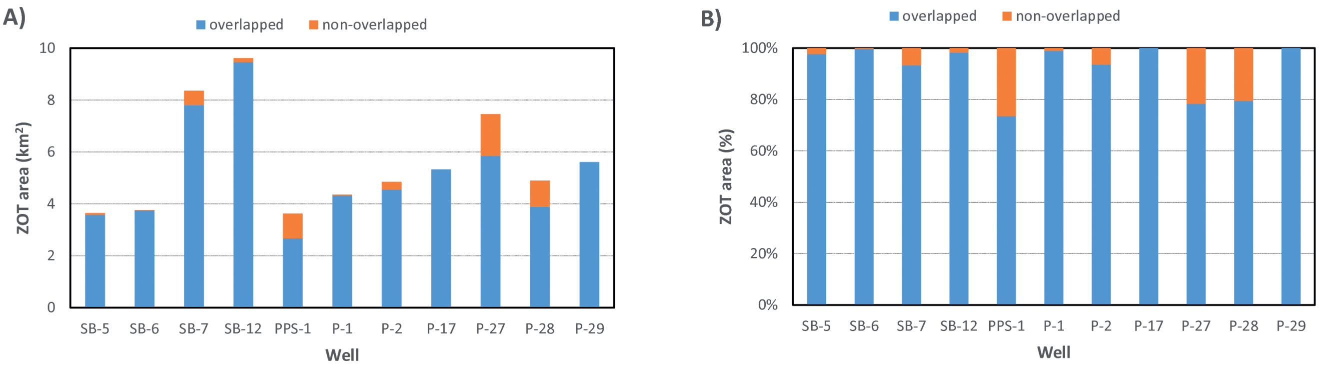

Fig. 12 - Comparison between overlapped and non-overlapped ZOT area in terms of A) absolute value and B) percentage

every simulation represents a different realization of aquifer heterogeneity, yet all come from the same random function. In the present study, only a realization is taken into account, treating it deterministically by an automatic calibration of the hydrodynamic parameters associated to lithologies. The quality of this process is indirectly verified by comparing the calibration results with available hydrogeological data, avoiding the traditional time-consuming approach.

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