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A METHOD FOR IDENTIFYING AND PREVENTING THE DIVING PLUMES IN ALLUVIAL AQUIFERS

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EXTENDED ABSTRACT

Le falde profonde dei grandi centri urbani e industriali da tempo hanno visto peggiorare la loro qualità, anche dove spessi e continui livelli poco permeabili ostacolano la filtrazione degli inquinamenti contenuti nella falda superficiale. Il deterioramento delle riserve di acqua potabile più pregiate è determinato in molti casi dall'approfondimento degli inquinamenti che nascono nelle aree prossime ai centri urbani e che si dirigono verso di essi. Esso è prodotto dalla concomitanza di cause diverse, quali ad esempio la densità dei contaminanti (es. tricloroetilene e percloroetilene) e la depressione piezometrica creata dai prelievi dei pozzi profondi, entrambi fattori che agiscono sulla creazione di un gradiente verticale degli inquinanti. Questi fattori fanno in modo che il flusso idrico inquinato entra nelle falde profonde a monte delle aree che sono protette da aquicludes, per dirigersi verso i pozzi fenestrati a maggiore profondità. L'esistenza di questo problema è noto nella letteratura, e su questi particolari inquinamenti (noti come *Diving Plumes*) è stata prodotta una serie di studi di rilevante interesse; essi hanno evidenziato anche altre cause dell'approfondimento, quali la presenza di aree di forte ricarica (Weaver & Wilson, 2000; Lahvis, 2003) e di cambi repentini di litologia in superficie (Amerson & Johnson, 2003; Alvarez, 2003) che provocano la riduzione della velocità di spostamento orizzontale e favoriscono quindi lo spostamento del flusso in direzione verticale. Infine particolari strutture idrogeologiche possono essere determinanti, come indicato da API (2006), nel produrre l'approfondimento dei plumes di contaminanti.

Per far fronte al progressivo degrado qualitativo che si va così delineando in modo sempre più marcato, a causa delle particolari origini e caratteristiche di questi inquinamenti, si deve disporre di una dettagliata ricostruzione delle strutture idrogeologiche, e di un sistema di monitoraggio della falda profonda che risulterebbe molto costoso se eseguito su tutti i pozzi profondi, perché richiede che vengano analizzate le acque sulla verticale dei pozzi finestrati solo in profondità e che vengano prodotte misure non solo con i flowmeters, idonei a evidenziare i gradienti verticali, ma anche con campionamenti e analisi chimiche selettive.

L'articolo vuole dimostrare come sia possibile porre le basi per affrontare in termini economici e temporali accettabili tale problema, circoscrivendo le aree esposte allo sviluppo dei *Diving Plumes* sulla base dello studio idrogeologico e idro-chimico, e concentrando su di esse i punti di monitoraggio. Per evidenziare le caratteristiche delle aree dalle quali possono nascere queste contaminazioni, si sono verificate quali sono le strutture idrogeologiche che determinano un gradiente verticale elevato e una riduzione della portata unitaria (quindi della velocità) della falda, che sono i fattori indice della possibile genesi dei *Diving Plumes*, evidenziandone le caratteristiche fondamentali. Per verificare la fondatezza dei risultati raggiunti, è stato studiato mediante un caso reale un modello numerico i cui risultati dimostrano che queste strutture favoriscono l'approfondimento dei *plumes*. Nell'Area Funzionale di Milano è disponibile una gran mole di dati idrogeologici e chimici, che permettono la ricostruzione delle strutture idrogeologiche con sufficiente dettaglio, la corretta rappresentazione della rete di flusso anche sulla verticale, e la cartografia diversificata nel tempo dei *plumes* storici; si può quindi ritenere possibile la concreta attuazione di una rete di monitoraggio che consenta la prevenzione di queste forme di inquinamento e l'attuazione di provvedimenti non costosi, come ad esempio una migliore gestione delle portate estratte nelle aree di richiamo delle contaminazioni.

ABSTRACT

The phenomenon of "diving plumes" frequently occurs in some particular hydrogeological settings where the groundwater recharge flows into the top of a shallow water table aquifer and, once inside the aquifer, this water begins to move downwards. Due to the preferred horizontal flow path, it can push contaminant plumes downwards up to the deepest aquifers. Therefore, especially in urban areas, where the water table depression is more pronounced, the pollutants are conveyed to the most important groundwater resources for human consumption, often causing a severe decay of the drinking water. This paper thus deals with the most reliable criteria to delimit the areas in which the hydrogeological settings expose the aquifers to the deepening of the contaminants.

To this end, this paper considers several contaminations of alluvial deposits in the Functional Urban Area of Milan. It analyses the hydrogeological setting and uses a mathematical model to highlight the deformations of the flow net produced by each of them. In this way, it was possible to identify the structures that facilitate the deepening of pollution and to set up an appropriate monitoring network that highlights the location of the plumes and allows their attenuation.

KEYWORDS: *diving plumes, heterogeneous aquifer, vertical hydraulic gradient*

INTRODUCTION

The major hydraulic process controlling plume dive is the existence of naturally occurring or induced vertical hydraulic gradients; therefore, the most obvious marker of vulnerability marker for diving plumes is a significant vertical component of the groundwater flow direction. For this reason, in order to delimit the areas exposed to diving plumes, the simplest approach consists of a downward vertical gradient survey in the deeper screened wells, which can reveal the potential for plume dive. The monitoring of the water quality of deep aquifers and use of a flowmeter can also observe the diving plumes (Weaver & Wilson, 2000). However, these methods have several limitations, since the development of diving plumes is very complex; for example some plumes may dive because of a gradual build-up of recharge (Weaver & Wilson, 2000; Weaver *et alii*. 1999; Landmeyer *et alii*, 1998; Lahvis, 2003) but also because of stratigraphy (Amerson & Johnson, 2003) and changes in the lithology of the water table (Alvarez, 2003). Figure 1b shows some different examples of diving plumes due to accretion of clean recharge: diving plumes along leaking water main and supply wells, diving plumes due to stratigraphic controls and diving plumes near a gaining stream.

The vertical hydraulic gradient of an aquifer affects the amount of vertical spread of a plume. According to the researches mentioned above, several hydrogeological factors affect the extent of the vertical gradient (Fig. 1a), that is the distribution in the subsoil of the vertical permeability of the contaminated hydrostratigraphic unit and the shape and thickness of less permeable layers. For these reasons, the geological factors appear to have the greatest impact on the genesis of diving plumes.

Therefore, this study aims to explain the geological features that ease the occurrence of strong vertical gradients. This is achieved through the numerical simulations of the hydrogeological settings' field of hydraulic potential in the Milan plain.

The analysis aims to create a monitoring network of deep wells suitable for forecasting and remedial actions for diving plumes.

It is well known that the 3D representation of the equipotential surfaces provides the hydraulic gradient of the groundwater flow, and that it allows to calculate both J (horizontal) and Jv (vertical) piezometric gradient.

Jv represents the ratio between the piezometric head between two points that are on the vertical and their distance (Fig. 1c):

$$(h_2-h_1)/((z_2-z_1) \qquad (1)$$

According to API (2006), an unrecognised diving plume could result in an inadequate evaluation of risk to receptors, erroneous interpretation of the significance of natural attenuation, under-design of a remediation system or inadequate assessment of remedial performance.

In fact, API (2006) has examined the problem of the deepening of contaminant plumes and has highlighted the importance of both the hydrologic and of the geologic control of the plumes. Above all, it highlighted the layering of different lithology that results in changes in hydraulic conductivity, and described several cases demonstrating the influence of the hydrogeological framework. Therefore the importance of the forecasting the evolution of the diving plumes, requires a more detailed analysis of the geological factors influencing the deepening of the contaminants, acting on several hydraulic parameters as the slope *J'* of the diving plume.

In fact, API (2006) demonstrated that the slope *J'* of the deepening plumes is derived from (2):

$$J' = \frac{I}{V} = \frac{i}{q} \qquad (2)$$

where *I* is the accretion rate (m/year), recharge rate divided by porosity, where the recharge rate *i* is the real infiltration reaching the saturated portion of the aquifer (m/year) and *q* is the Darcy velocity (m/year); *V* is the horizontal seepage velocity.

In this paper, geological heterogeneities are divided into the following categories in order to simplify the achievement of the results:

- changes of transmissivity in a horizontal or low inclined hydrostratigraphic unit;
- deepening of the pollutants due to some interesting geological setting (aquifer thickness, inclination and the continuity of the impermeable or semipermeable layers).

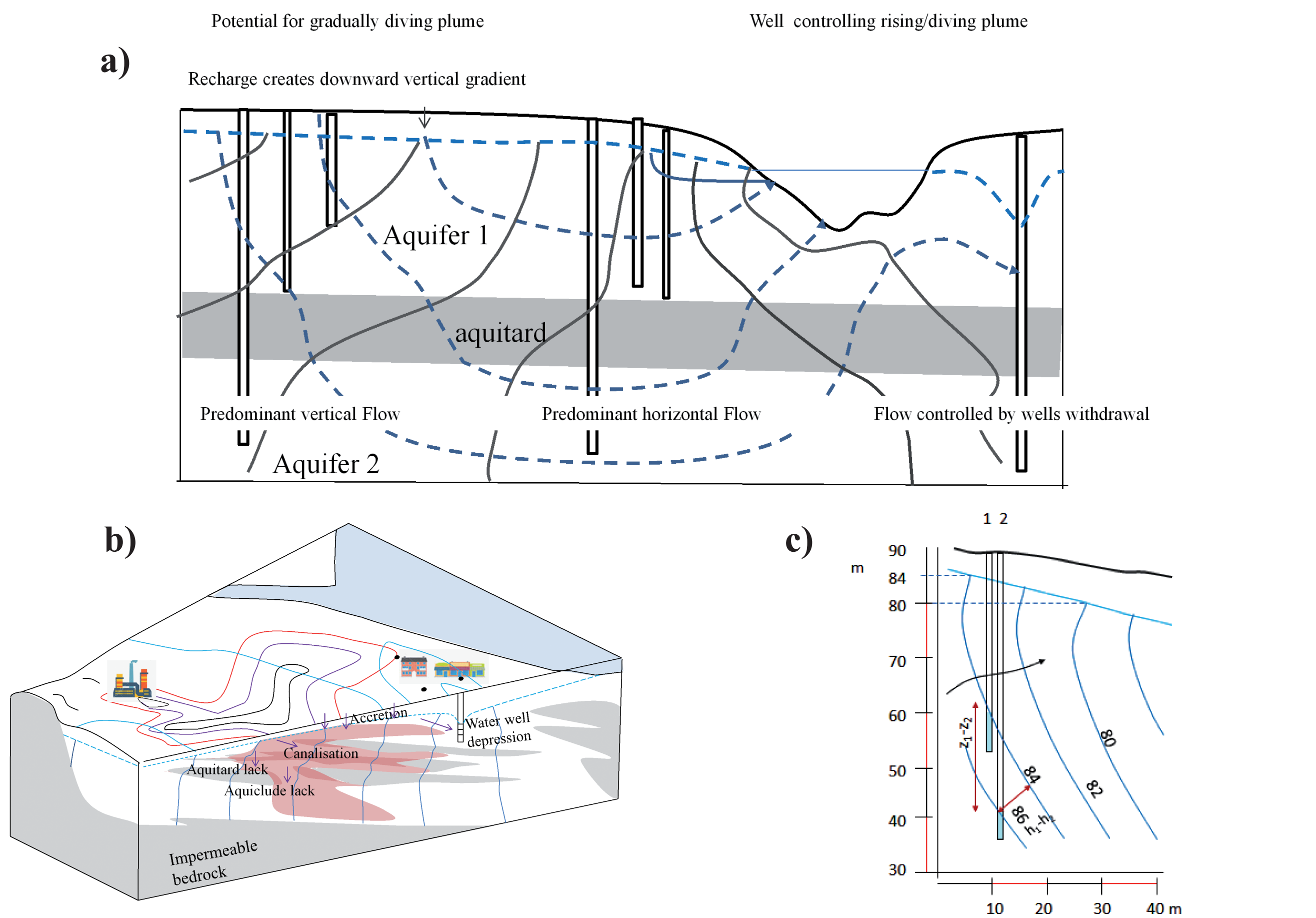

Fig. 1 - a) Hydrologic conditions promoting the diving plumes and their controlling factors after API 2006 (modified); b) Main types of hydrogeological heterogeneity promoting the deepening of the plumes (according to API, 2006); c) Vertical gradient computed as the relation (1) is (86-84)/(60-40)-10%

CHANGES OF AQUIFER TRANSMISSIVITY IN A HORIZONTAL OR GENTLY INCLINED HYDROSTRATIGRAPHIC UNIT

In the alluvial heterogeneous aquifers of the Milan area, the groundwater flow sections often changes in both shape and in width, when the layering is horizontal. The piezometric maps and the modelling results demonstrate that these changes lead to a significant reduction of the aquifer's specific flow rate.

In effect, variations of equipotential and flow lines, where impermeable or semipermeable layers or lenses reduce the aquifer section (Fig. 2), cause the lengthening of flow lines, which produces a reduction of the hydraulic gradient, of the specific flow rate and of the seepage velocity. Conversely, the vertical component of the velocity vector and the ratio of the vertical/horizontal gradients increase. These effects can have a remarkable impact on the contaminants spreading of contaminants.

Taking a section of the aquifer of a length *L (m)* into consideration, where the grid thickness of the flownet of an

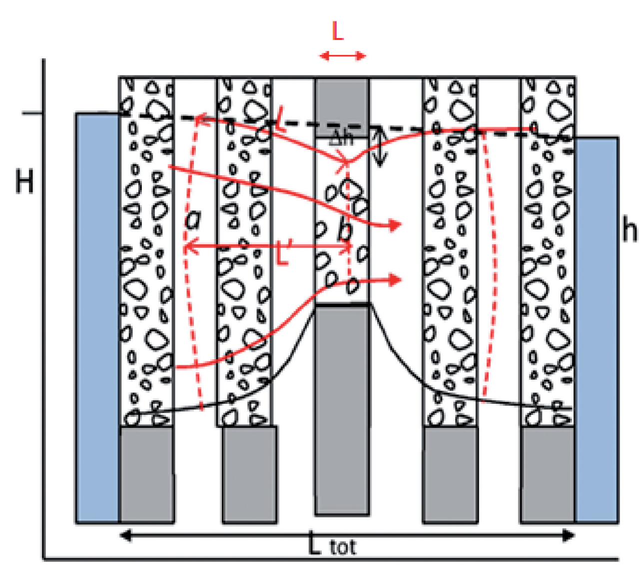

Fig. 2 - Schematic geologic cross-section describing the flownet deformations due to horizontal change of the transmissivity

aquifer of constant width passes from *a* to *b*, the relation between the change of section and the others hydrogeological parameters can be obtained from (3):

$$H - h = \frac{Q\ln\left(\frac{a}{b}\right)}{TL(a-b)} \qquad (3)$$

By identifying the boundary length of the trapezoidal grid of radial flownet generated by the piezometric deformation with *L' (m)* (Fig. 2), the lengthening of the flow line for each grid is *L'-L*.

Since the gradient loss is proportional to the decay of the seepage velocity and of the specific flow rate, the reduction of the flow section involves the increase of the gradient *J'*. For the same reasons, it can be inferred that the higher the ratio *L/Ltot*, where *Ltot* (Fig. 2) is the length of the total aquifer between the supply area and the outflow zone, the higher is the value of ΔJ.

The piezometric loss due to the change of the aquifer's flow section is mostly predominant when groundwater flows from a hydrostratigraphic unit or from a permeable aquifer towards a unit with lower transmissivity, that is, in the Milan area from the units A to B. This phenomenon is particularly evident at the boundaries of these units. Since the higher the ΔJ, the higher the vertical component of the gradient (according to eq. 1 of API, 2006), the downward component of the velocity vector is predominant on the upward one in these hydrogeological frameworks.

Therefore, the development of the diving plumes affects the areas where the vertical gradients are enhanced by a reduction of the flow section.

Several examples were examined on the alluvial plain by means of cross-sections and aquifer tests which include some gravelly-sandy aquifers separated by clayey aquicludes.

Vertical gradient data were obtained by means of a numerical model and confirmed by direct measures using a vertical flowmeter.

The aquifers' piezometric cross sections resulting from these calculations show that the vertical gradient undergoes several strong changes in correspondence with the variations in the permeability of levels crossed; the values of the vertical gradient can be a magnitude higher than the horizontal ones. The direction in which the contaminants are conveyed is thereby substantially altered and deviated downwards.

In these cases, calculations demonstrate that the lower values of the seepage velocity coincide with cases that are higher than the transmissivity difference between the aquitards and the aquicludes. Figure 3 illustrates the results of these calculations, showing the relation between the seepage velocity and the variance σ^2 of the transmissivity of the lithological levels along the vertical gradient.

Therefore, the greater the degree of heterogeneity in the subsurface, for example where the aquifers include clay or silt lenses (Fig. 4a), the greater is the potential for preferential downward migration of the plumes.

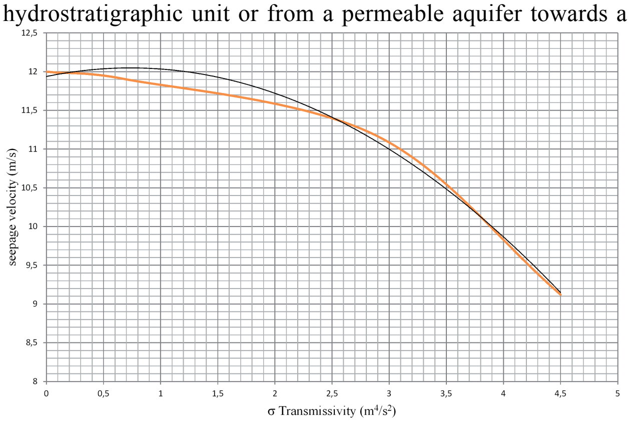

Fig. 3 - Relations between the variance of T along the vertical gradient and the reduction of seepage velocity (and unitary discharge rate), in the case in which the anomalous sector occupies a third of the total length of the aquifer. The black line represents the values of the polynomial interpolating line of the function $y = -0.2047x^2 + 0.3011x + 11.938$

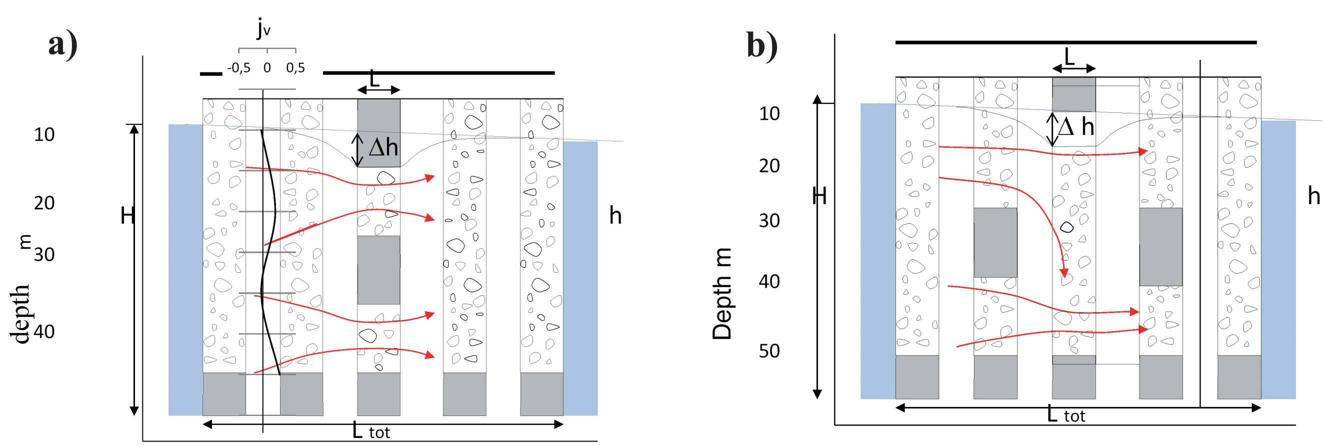

Fig. 4 - a) Cross section including a heterogeneous sector with two aquitards and two aquifers Jv is the vertical gradient profile. b) Schematic cross-section describing a local increase of permeability of the aquitard. The total length Ltot of the aquifer is 4 km

The magnitude of heterogeneity-induced dive may be more easily observed with time or with increasing seepage velocity, since longer plumes occur under these conditions.

Frequently, a lateral (Fig. 4b) increase in the permeability of the layers could be observed. The figure shows that the pollution passes easily from the contaminated section towards the protected portions of the aquifer. It also illustrates the changes in the vertical piezometric gradient as a consequence of the piezometric deformation.

Figure 5 is obtained by monitoring a heterogeneous aquifer including a semipermeable layer (k about 10^{-5} m/s), by means of two piezometers, with the first screen located in the upper part of the aquifer and the second in the lower. The measures revealed that the deeper drain (PzMI1) maintains higher values of the piezometric head over time when compared to the lower one (PzMB1).

EFFECTS OF THE AQUIFER THICKNESS AND FLOW SECTION WIDTH CHANGES

The case where transmissivity remains constant was examined, resulting in a thickness of the aquifer variables (if the permeability varies inversely) (Fig. 6). The most important reason for the decrease in the discharge rate is the reduction of the velocity in some areas of the aquifer, especially where an increase in the thickness is followed by a sudden decrease.

Across the examined area, the hydrogeological settings show a horizontal change of flow sections. Therefore, the horizontal arrangement of the semipermeable or impermeable layers' permeability was examined together with the calculation of the values of piezometric heads at different depths. The results of these calculations indicate that the changes of the flow section width leads to remarkable changes both in the piezometric head and in the vertical gradient. In particular, it should be highlighted that the occurrence of a semipermeable bed or lense causes a loss of piezometric head along the flow direction, and an increase of the vertical gradient.

Ultimately, the calculations demonstrate that the heterogeneity of geological settings influences the specific discharge and increases the vertical gradient. The deepening of the plumes is more significant the greater the deformation of the flow network. For this reason, the lithozones of low permeability embedded in the aquifer are more numerous, extended and thicker.

A REAL FORECASTING CASE OF A CONTAMINANT PLUME IN THE FUNCTIONAL URBAN AREA OF MILAN

In urban areas, where the water table depression is more pronounced, the diving plumes often cause a severe decay of drinking water. The analysis of the effects of the piezometric depression and of the heterogeneities of the alluvial deposits, leads to an indication of the geological causes for the deepening of the contaminants; these frameworks have been synthetised in Fig. 7.

The hydrogeological framework of the Milano area was examined based on the identification of the previous causes for the deepening of contaminants. In particular, it was verified that the distribution of horizontal velocity and specific flow rate, and the increase of groundwater, are significantly influenced by these parameters in the north-east of the city where a real-life case was

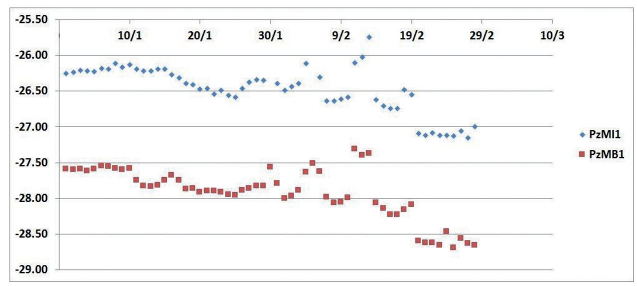

Fig. 5 - A real case of the vertical gradient's increase at deeper levels

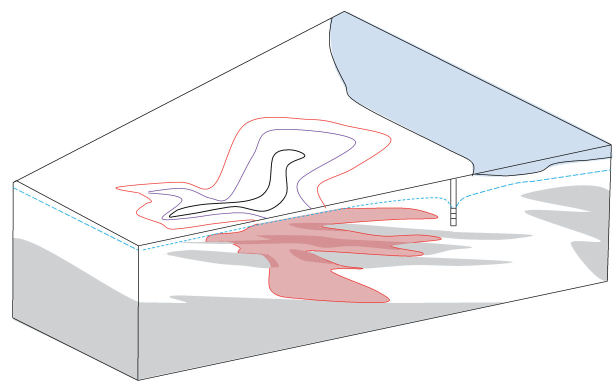

Fig. 6 - The increase in thickness produces a reduction of the hydraulic gradient that is accompanied by a decrease in the unitary discharge rate. These conditions allow the deepening of the plumes (API, 2006)

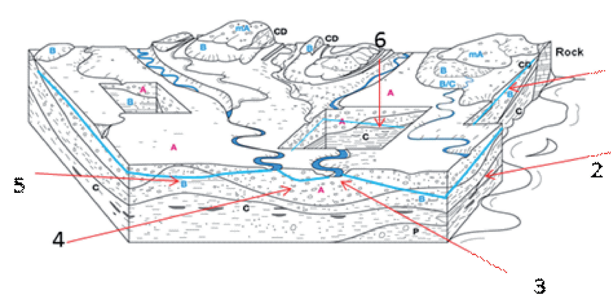

Fig. 7 - Main types of hydrogeological setting that can promote the deepening of the contaminant plumes in alluvial plains: 1) Dipping impermeable layers 2) Aquifer embedded into impermeable or semipermeable dipping layers 3) Mass due to groundwater supply by watercourses 4) Thickness change of the aquifer 5) Vertical changes of permeability 6) Lateral change of transmissivity. In the figure, A, B, C, CD and P indicate the name of the main hydrostratigraphic units of the studied area

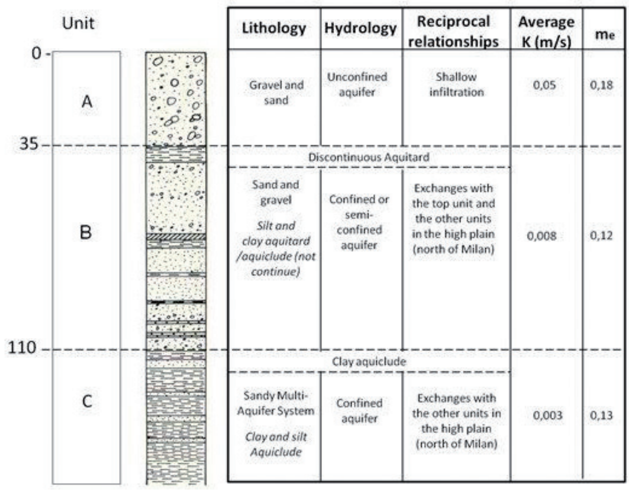

Fig. 8 - Hydrogeological bodies of Milan and its synthetic representation of the characteristics of the hydrostratigraphic units

studied.

The hydrogeological context of the area was examined by using the well-known principles given in the literature (Castany, 1982), for the rebuilding of the hydrostratigraphic units. In the studied area, the typical values of the hydrostratigraphic units' transmissivity (Regione Lombardia, 2002) are outlined in Table 1.

From Table 1 it can be inferred that the values of the transmissivity on the vertical (A, B and C) show a discrepancy. However, the average T of the different units (Southern, Central and Northern) is very uniformly maintained locally.

The discontinuity between A (shallow free aquifer having high transmissivity) and C (confined aquifer having low transmissivity) causes a sharp shrinkage of the flow section; Figure 8 shows a similar behaviour in the groundwater flow at the boundary of units A with B and B with C.

The geological cross-sections show that within each hydrostratigraphic units, several gently inclined aquifers are embedded. These are, partially or totally separated by lenses or layers having low permeability.

IMPLEMENTATION OF NUMERICAL MODEL: FLOW AND TRANSPORT SIMULATION

The applied code, MODFLOW, was developed by the USGS (McDonald & Harbaugh, 1988), and a 3D geometries, boundary conditions and hydrogeological properties were defined in the flow model settings. The spatial domain of the studied area was discretized with a 3D grid composed of 50 lines, 50 columns and 4 layers with cells of 50 m x 50 m in the area concerned near an industrialised zone close to the city of Milan. Along the vertical direction, the layers want to represent the thickness of the aquifer A+B of the Milan plain. A four layer model was developed (Fig. 9):

- Layer 1-2: Hydrostratigraphic unit A average 30 m thickness.
- Layer 3: Aquitard which is the silty clayey lens that regulates the water exchange between the two aquifers
- Layer 4: Hydrostratigraphic unit B, average 25 m thickness.

Lithological maps and hydrogeological properties of the aquifers with a huge number of stratigraphic log-values have defined hydraulic conductivity distribution. Hydrogeological section 2 is represented in the Fig. 10, showing the geological uncertainties representing the layer (aquitard) which separates the Aquifer A and Aquifer B.

The values vary for the layer 1 and 2 from $3.36*10^2$ to $3.5*10^1$ m/day. For the aquitard, instead, the range was $1.42*10^0$

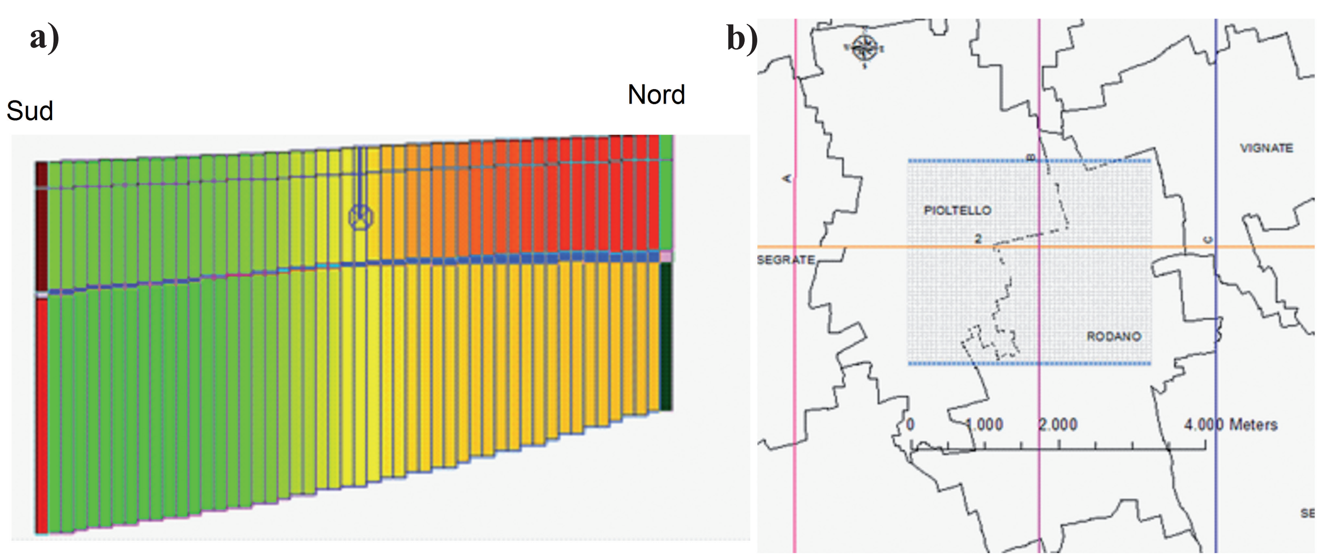

Fig. 9 - a) Model domain with a vertical exaggeration 1:50. b) The boundaries condition used in the model and the hydrogeological cross-section

and 9.3*10^{-3} m/day. Aquifer B has a different hydraulic conductivity. The hydrogeological section shows a more conductive area in the aquitard representing a sort of linking with the Aquifer B, as shown in Fig. 11. Boundary conditions have been set taking into account the real hydrogeological-hydraulic boundaries due to a piezometric survey during May-April 2014; along the eastern and western border, a no flow condition was inserted whereas, in the northern and southern border, a constant head element was inserted in order to represent the measured piezometric values.

The working wells (aqueducts and private) in the model domain were included with the analytical elements. The extracting rate was inserted taking into account the screened position that

Zone	Hydrostratigraphic unit	T (m^2/s)
Northern	A+B	10^{-2}
Central	A+B	2*10^{-2}
Southern	A+B	8*10^{-3}
Northern	C	8*10^{-3}
Central	C	6*10^{-3}
Southern	C	5*10^{-3}

Tab. 1 - Distribution of T of the hydrostratigraphic units of the FUA area. A-B are the shallow aquifers, C is the confined aquifer

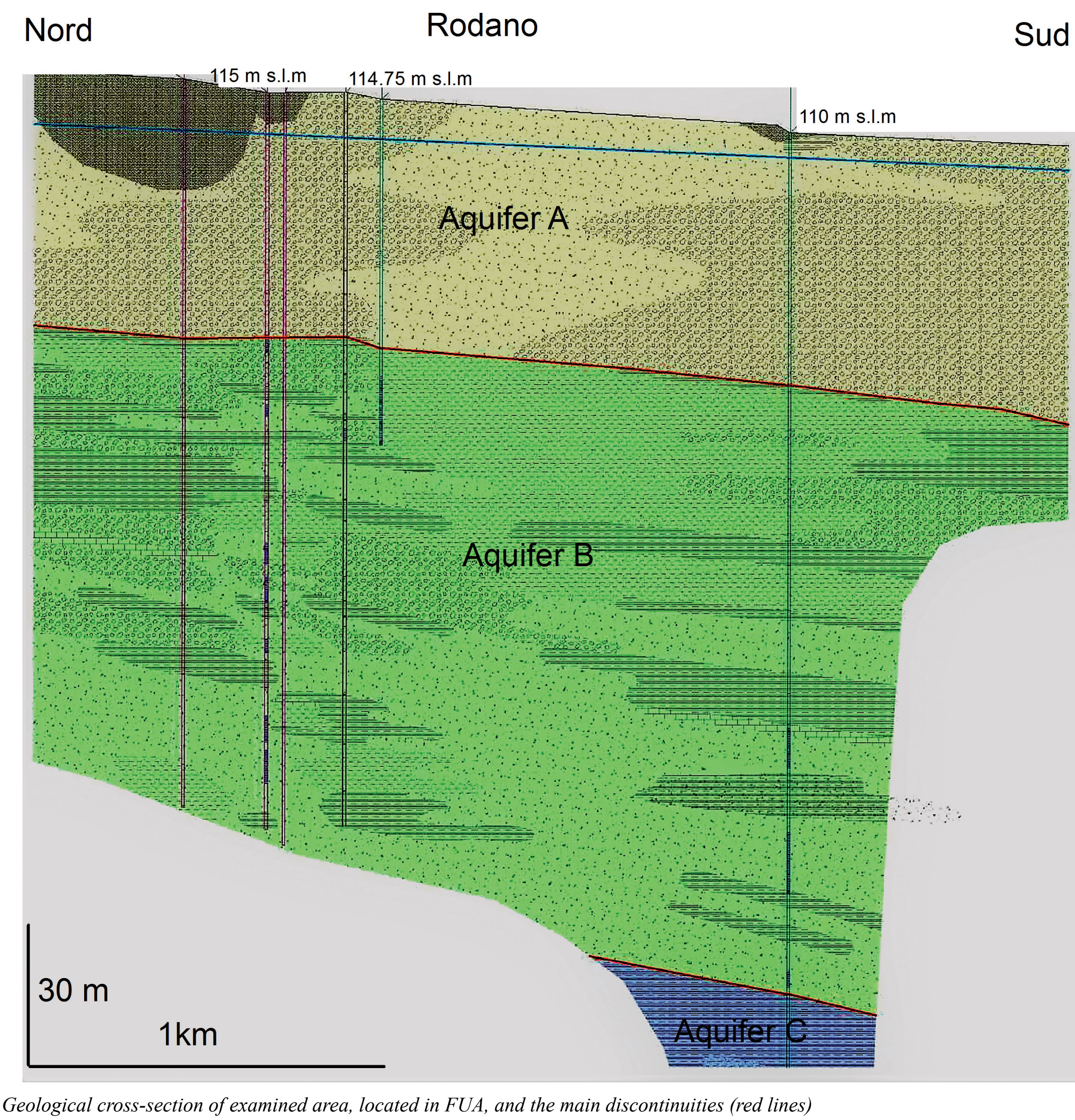

Fig. 10 - Geological cross-section of examined area, located in FUA, and the main discontinuities (red lines)

are generally to be found in the second aquifer. The infiltration rate was established by irrigation and rainfall and inserted in the model with imposed-flux, taking the soil and properties of use into account. PEST calibrated the simulated flow model. The calibrated parameters, such as hydraulic conductivities, were used as the model's properties. The numerical simulation results consist first in a detailed mapping of the piezometric head, the capture zones of individual wells and the pumping stations, representing the piezometric head.

Groundwater solute transport was simulated by using an MT3D-MT3DMS numerical code (Zheng & Wang, 1999). The partial differential equation describing the fate and transport contaminants in 3-D, transient groundwater flow systems is

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{\theta}C_s + \sum_{k=1}^{N} R_k \qquad i.j = 1.2.3 \qquad (4)$$

The governing equation is divided into the different transport processes: dispersion (a), advection (b), pollutant sources (c) and, chemical reaction including "sorption" (d). The calibration phase was undertaken in order to obtain the correct value to insert in the model transport PCE. A comparison between the calibrated value and the literature, was carried out in Table 2.

Based on the conceptual model and the knowledge on the studied area, a direct infiltration in the saturated portion of the aquifer was considered. This condition was inserted with a constant concentration in the model domain where the sources were found.

The PCE sources were located near the model domain as shown in the figure below. The results of the modelled contaminants differentiated according to two different interpretations (average and heterogeneities) are shown in the Figures 12a and 12b.

Figure 13 shows different results for different configurations: in heterogeneous aquitard the contribution into the deeper aquifer is higher than in the homogeneous one.

DISCUSSION OF RESULTS AND CONCLUSION

Some authors (Weaver & Wilson, 2000) show that the areas where deep contaminations develop can be highlighted and monitored by means of piezometric control along the vertical of the deep-screened well, coupled with flow meter measurements,

	PCE modeled	References [Gelhar *et alii*, 1992; Hill & Tiedeman, 2007]
α_l (m)	20	30.5
α_t (m)	3	$\frac{1}{10}\alpha_l \div \frac{1}{3}\alpha_l$
α_v (m)	0.03	$\frac{\alpha_l}{100} \div \frac{\alpha_l}{1000_l}$

	K_d (m^3/kg)		$t_{1/2}$	
	modelled	Reference [Gelhar *et alii*, 1992; Hill & Tiedeman, 2007]	modelled	Reference [Spitz *et alii*, 1997]
PCE	0.000426	0.0027-0.0059	6 years	0.7 days-2 years

Tab. 2 - left) Dispersivity coefficients inserted in the model and suggested by literature for PCE, right) Values of distribution coefficient K_d and half time inserted in the model for PCE

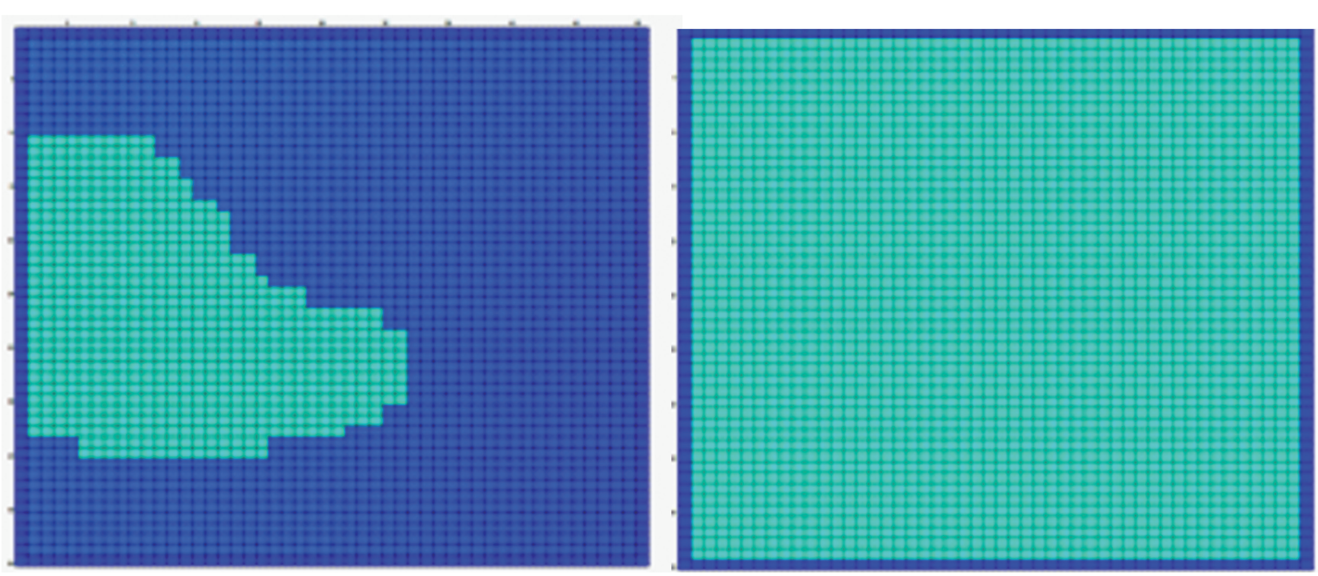

Fig. 11 - left) Heterogeneities of log-permeability fields ($1.42*10^0$ and $9.3*10^{-3}$ m/day); right) Homogeneous fields ($1.42*10^0$ m/day) due to an average value of log-stratigraphy. The porosity values is similar and within 0.2

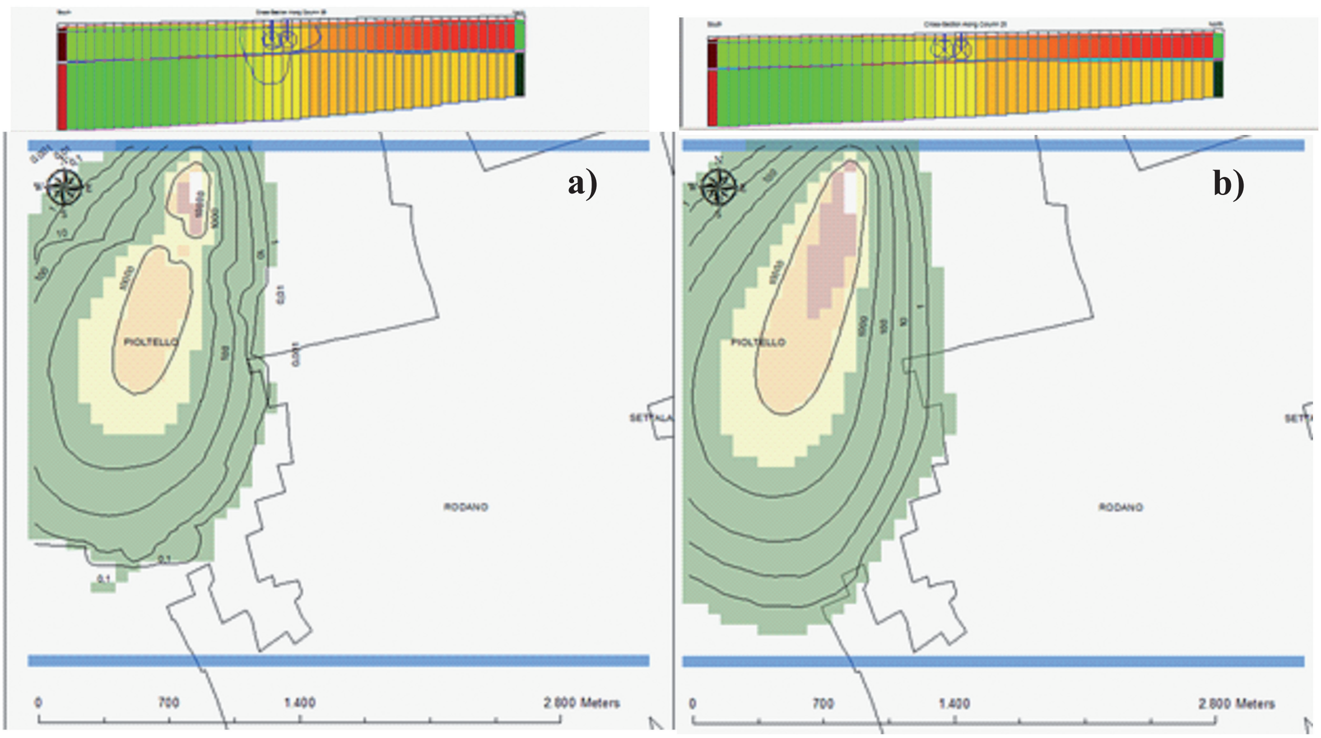

Fig. 12 - Plumes configuration at a) Heterogeneities of log-permeability fields ($1.42*10^0$ and $9.3*10^{-3}$ m/day) b) Homogeneous fields ($1.42*10^0$ m/day) due to an average value inserted in the model of log-stratigraphy. The porosity values is similar and within 0.2

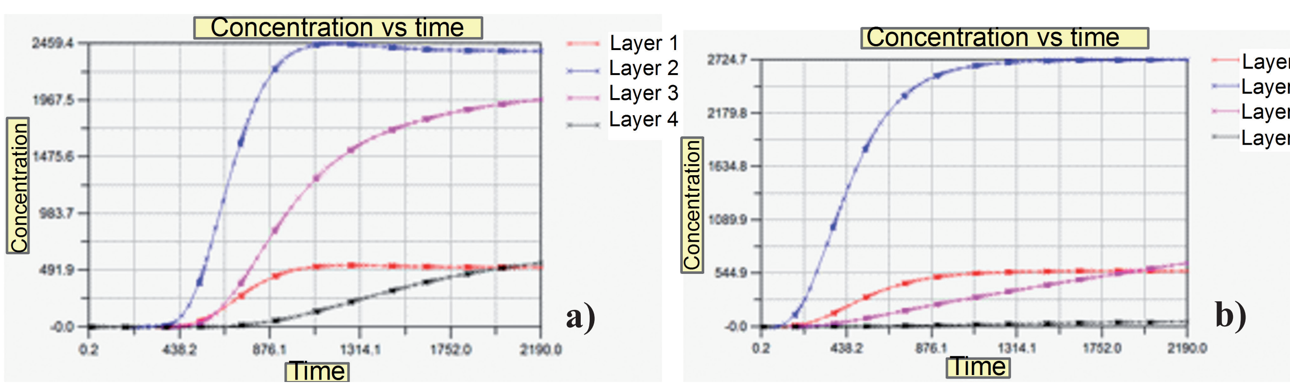

Fig. 13 - a) Comparison of the calculated breakthrough curves based on monitoring wells. The concentration in layer 3 increases with heterogeneities more than in the homogeneous domain

and chemical analyses. The cost of this approach is very high if the area that has to be controlled covers many square kilometers; for this reason, it is necessary to determine the areas where the geological and geochemical conditions facilitate the development of deepening plumes, and focus the survey on their deep wells. This paper demonstrates that the alluvial plains are also affected by diving plumes. Their hydrogeological framework favours the genesis of strong vertical hydraulic gradients due to their geological heterogeneity. Furthermore, the study has identified several hydrogeological settings characterised by the coupling of inclinations of semipermeable and impermeable lenses with horizontal and vertical changes of permeability. These can exert a strong influence on the contaminant plumes, promoting their deepening.

In order to select the areas to be monitored, the hydrogeological setting boundaries favouring the development of diving plumes were outlined, and the behaviour of the groundwater examined by means of a numerical model, thus highlighting the changes of the flownet features depending on each geological setting.

These calculations enabled the identification of those areas that are most exposed to deepening plumes, and a real-life case of a contaminant plume near Milan was examined by means of a numerical simulation. The results of the simulation confirm that the diving plumes develop where the hydraulic vertical gradient is increased by the vertical and horizontal changes of permeability.

The study allows the identification of areas that are potentially exposed to diving plumes, and the delimitation of their boundaries based on the approach that can be summarised as follows:

1) the measures of a vertical hydraulic gradient, by means of a flow meter, reveals the downward flow direction;
2) presence of inclined aquicludes and aquitards channelling down the groundwater flows;
3) geochemical indicators, showing hydrochemical facies characteristic of the beginning of contamination;
4) important groundwater accretion due to irrigating channels or rains on permeable shallow aquifers;
5) noticeable withdrawal of groundwater wells, causing marked piezometric depression;
6) local permeability increase of aquitards or aquicludes;
7) local transmissivity increase due to the deepening of the impermeable substratum of the aquifer.

Therefore, by monitoring the deep-screened wells, the areas where diving plumes occur can be delimited, and preventive measures planned. This includes the selection of deep wells in which to reduce withdrawals by means of suitable hydrogeological models.

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