THE GROUNDWATER FLOW VELOCITY DISTRIBUTION IN THE URBAN AREAS: A CASE STUDY

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EXTENDED ABSTRACT

Questo lavoro descrive i risultati dell'applicazione dei modelli di flusso allo studio del campo delle velocità delle acque sotterranee nell'area urbana di Milano (Italia settentrionale), la cui falda è stressata dai prelievi, al fine di mettere in evidenza le relazioni fra la distribuzione della velocità di flusso e delle caratteristiche idro-chimiche.

Tale rapporto è stato posto in evidenza da alcuni studi che hanno tracciato il quadro generale del fenomeno dal punto di vista idraulico (ANDERSON & MUNTER, 1981; WINTER, 1999) e da alcuni lavori che hanno trattato aspetti idro-geochimici (JIANG *et alii*, 2011) esaminando ad esempio la relazione fra riduzione della velocità e aumento del ferro e manganese in falda in porzioni dell'acquifero in cui il rinnovamento delle acque sotterranee risultava molto limitato.

Si ricorda infatti che ANDERSON & MUNTER (1981) e WINTER (1999) hanno descritto ampiamente la presenza di aree a bassa velocità in cui il flusso naturale della falda è rallentato di parecchi ordini di grandezza: questi campi a ridotto flusso si vengono a creare solitamente in presenza di barriere idrauliche (CHRIST *et alii*, 2004; COLOMBO *et alii*, 2012; SHAN, 1999; JAVANDEL & TSANG, 1984) che funzionano con buone portate e le particelle di acqua o di inquinante che si vengono a trovare all'interno di queste zone possiedono velocità dell'ordine di poche decine di metri annui, permanendo e persistendo quindi all'interno della zona stagnante.

JIANG *et alii* (2012) invece hanno utilizzato la conoscenza della localizzazione dei punti di stagnazione per datare le acque per scopi dell'Ingegneria petrolifera e della gestione degli inquinanti nelle acque sotterranee.

Tali riscontri sono stati osservati soprattutto in porzioni profonde dell'acquifero, e nel presente lavoro si desidera evidenziare che un impoverimento delle proprietà chimiche delle acque si può registrare anche nelle parti più superficiali degli acquiferi e si è cercato quindi di individuarne le possibili cause mediante un'analisi del campo delle velocità delle acque sotterranee.

A tal fine, si sono utilizzati i numerosi dati piezometrici, idro-chimici e di portata dei pozzi che sono stati raccolti negli anni dai tecnici comunali di Milano e dagli Enti preposti al controllo della qualità delle acque, e si è potuto concludere che esiste l'evidenza di un aumento del residuo salino e della conducibilità elettrica in ampie zone in cui il moto della falda è molto rallentato dalla particolare conformazione piezometrica che favorisce la creazione di zone di ristagno.

Al fine di pervenire a tali conclusioni, si è provveduto ad analizzare il comportamento della falda in seguito al prelievo esercitato dai gruppi di pozzi (centrali di pompaggio) del Comune. L'ampia zona di cattura di questi gruppi di pozzi, che prelevano ciascuno diverse centinaia di litri/s, si estende su aree superiori al km², e al loro interno la depressione piezometrica è di alcuni metri. Per tali motivi il prelievo delle centrali di pompaggio genera il richiamo di inquinanti dalla periferia della città verso il centro cittadino, e l'interferenza fra centrali di pompaggio vicine genera una piezometria molto complessa. Con l'aiuto di un modello matematico si sono stabilite sia la piezometria di dettaglio, appoggiandosi ai riscontri sul campo derivanti dalle rilevazioni compiute dal Comune in molti decenni di accurata attività operativa, sia il modulo e il verso del vettore velocità dell'acquifero superiore. In tal modo si è evidenziata l'esistenza delle aree di bassa velocità sulle quali la letteratura idrogeologica citata pone l'attenzione. Tali aree sono state distinte in base alla morfologia piezometrica e all'estensione. Alcune di esse si sono rivelate particolarmente ampie, come quella generata dalla centrale Padova, e tali da esercitare la propria influenza sulla propagazione degli inquinanti che affluiscono da nord. Gli inquinamenti vengono rallentati e contenuti tanto che, nella porzione meridionale della città, solo perifericamente al centro cittadino si riscontrano consistenti fuoriuscite di inquinanti verso valle. Contemporaneamente il ristagno delle acque ne impedisce il ricambio, e si sono segnalate le aree, situate soprattutto nel centro e nella porzione meridionale della città, in cui si verifica un aumento della concentrazione di alcuni inquinanti rivelata ad esempio dall'aumento del residuo e della conducibilità elettrica. L'interesse della rilevazione dettagliata delle velocità della falda è sottolineato anche dal fatto che, tramite questa analisi, si sono ricostruite le principali direzioni seguite dalle contaminazioni che affluiscono dalla periferia al centro cittadino.

ABSTRACT

This work involves the effects of the piezometric lowering due to the withdrawal of wells in urban areas, by examining in particular the case of Milan (Italy), whose drinking water wells are endowed with several hundred wells, pumping about 30 million cubic meters per year. An analysis performed by means of an hydrogeological model of the velocity field, showed that within the domain of the wide piezometric depression created by pumping wells, there are large areas of low flow velocity. These areas have been found both near the capture zone of the wells and where the capture zone of wells is very close, and it has been demonstrated that they have the effect of slowing the pollutants plume spreading downstream. A delimitation of the areas where the flow velocity drops below 50 m per year has been done. Moreover, a further study has dealt with the hydrochemistry of the city, demonstrating that the stagnation areas cause a renewal time increase, and they are often affected by a deterioration of the quality of water.

Key words: groundwater urban management, stagnation area, velocity vectors, wells capture zone

INTRODUCTION

In order to prevent the groundwater pollution, that affects the aquifers of many industrial areas where the water demand is particularly high a numerical model of aquifer was needed, and as soon as calibrated to a particular area, it becomes a very strongly resource management tool. For this reason, in 2001, a mathematical model is applied to manage the water resources of Milan, allowing the detailed knowledge of piezometric evolution and its behavior. Moreover, by means of mathematical model and by the piezometric survey, it has been established that the distribution of groundwater velocity in the city is extremely heterogeneous.

Moreover, some large stagnant flow zones with very low velocity have been detected due to a divergence or convergence of groundwater flow system. These zones, mathematically, are associated to the stagnation points which have been studied numerically by ANDERSON & MUNTER, (1981), WINTER (1976,1999) and analytically by JIANG *et alii* (2011), SHAN (1999), CHRIST & GOLTZ (2004) and COLOMBO *et alii* (2012). The low velocity zones can be a reservoir for the contaminant in urban areas, as studied for metallic ions and hydrocarbons accumulation by TOTH (1980,1999). Several researchers have reported the importance of a practical utilization of stagnation points and stagnant zones localization in many earth problem such as groundwater age dating (GOODE, 1996; JIANG *et alii*, 2012) prospecting for petroleum and geothermal energy and remediation of polluted water. In this paper, in order to know how the polluted plumes in a urbanized area are affected by stagnation zones, a reconstruction of their position becomes very important in order to know where the diffusion of pollution in a industrialized area could converge. The model has been done for the city of Milan where a number of hydrogeological data supports the model in a local scale. In fact, this city is an interesting case, because groundwater management has been reviewed carefully since the beginning of the 20th century by the technicians of the town hall and by many studies (NORDIO, 1947; DESIO, 1953; POZZI & FRANCANI, 1981; BINI *et alii*, 2004) who provided the accurate detection of the flow rates and piezometric levels.

Moreover, the groundwater pollution in the city of Milan has been well known since the '60s and, being in one of the most industrialized city in Italy, it is quite persistent and diffusive. The inflow of contaminants to the city was favoured by the evolution of the piezometric surface, which led to a creation of a wide depression whose center lies into the city. The piezometric head evolution through the years has been highly influenced by the so-
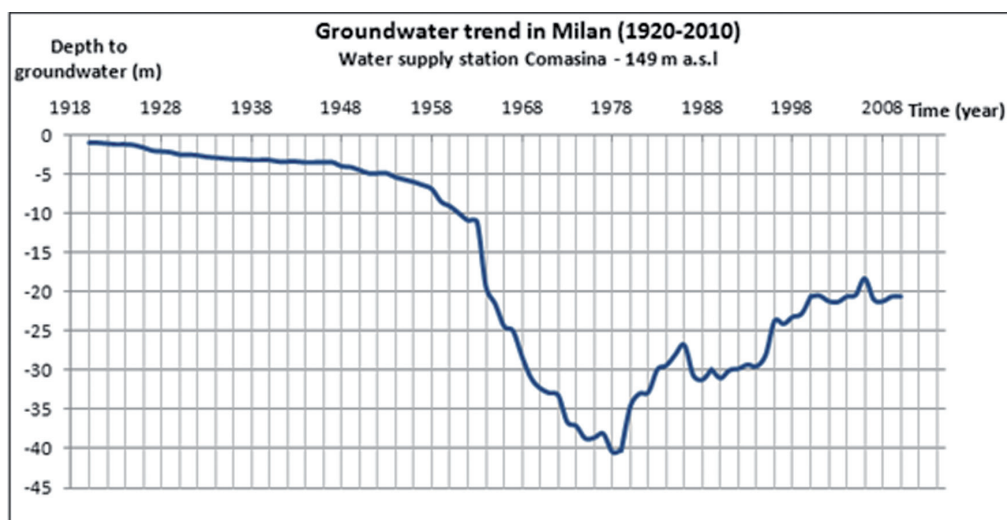

Fig. 1 - Annual average water table depth in the water supply Comasina-North Milan. (1920-2010) MM Data
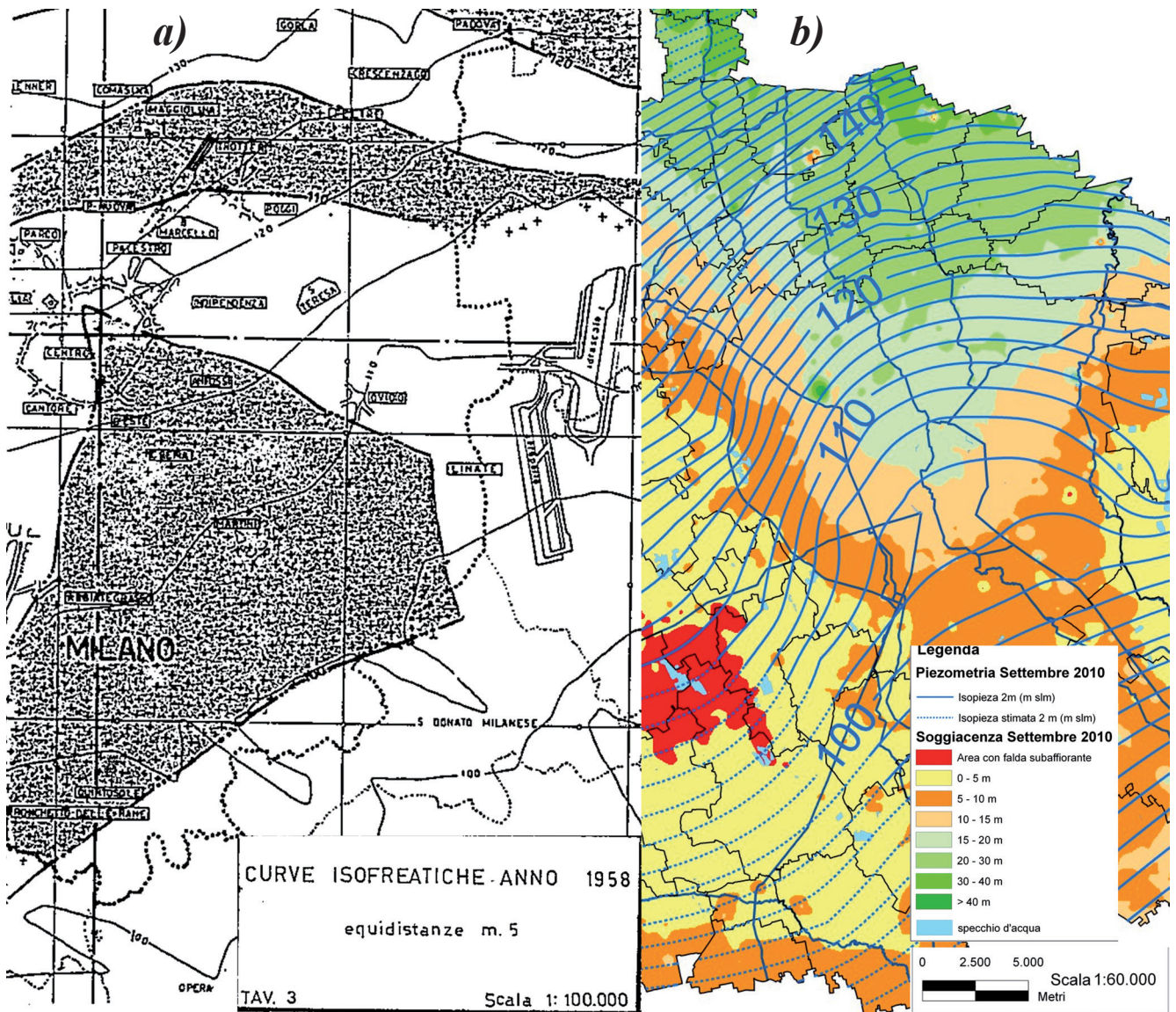
Fig. 2 - Piezometric map of the province of Milano in a) 1958 and in b) September 2011 (Province of Milan, Data)

cio-economical variation and by industrial production in the studied area as shown in the Figure 1 and the piezometric distribution in the city changes from 1958 to 2011 as shown in Figure 2.

By observing Figure 2 (b), in 2011 the isopiezometric contour lines are very distant in the city of Milan more than in the rest of the Region. This is due to the presence of a huge number of water supply wells in the center of the city (see Fig. 7). The natural gradient observed in the vicinity of the city is distorted and it becomes very low, diminishing within one order of magnitude. In fact, the wells for the drinking water in Milan (whose area is about 270 km²) are about 800 (Fig. 7). The water wells are grouped in 38 municipal water supply stations (named "centrali

di pompaggio"), and each station is composed of 4 to 25 pumping wells which draw water on average up to 100 m deep in order to supply an average yearly consumption of the city within $3 \cdot 10^8$ m³. The water supply contained in the aquifers is very important, as the fact that the values of the transmissivity of the layers traditionally exploited are between 10^{-3} and 10^{-1} m²/s.

The piezometric depression created by water wells withdrawal is so pronounced that it has changed the speed of the groundwater, which is increased in the vicinity of the city but has been reduced in Milan.

Because the changes of direction and strength of velocity vector can cause a significant environmental impact, the areas outlined are where speed reduction is most remarkable. In particular, it has

been assessed whether speed reduction has produced the groundwater deterioration, by using a mathematical model extended to the whole province of Milan. The model allows to simulate the piezometric depressions induced by the withdrawal of the wells and calculate the water flow in detail; for this reason a mathematical model has been developed by ALBERTI & FRANCANI (2001), simulating the effects of wells withdrawal and of the irrigation recharge.

PREVIOUS STUDIES ABOUT LOW VELOCITY ZONES: ANALYTICAL AND NUMERICAL MODELING

The effects of water extraction from the wells on the distribu-

tion of speed have been calculated on the basis of many studies found in literature on this topic. The simplest model has been done by SCHOELLER (1962) showing that the piezometric depression created by a single well has a point of stagnation along the groundwater divide and around it a low speed area characterized by the fact that the isopiezometric lines are very spaced out compared to the surrounding area.

Two wells can produce a more complex distribution of the groundwater velocity both downstream the capture zone of single well and on the co-linear disposition of wells (COLOMBO & FRANCANI, 2014).
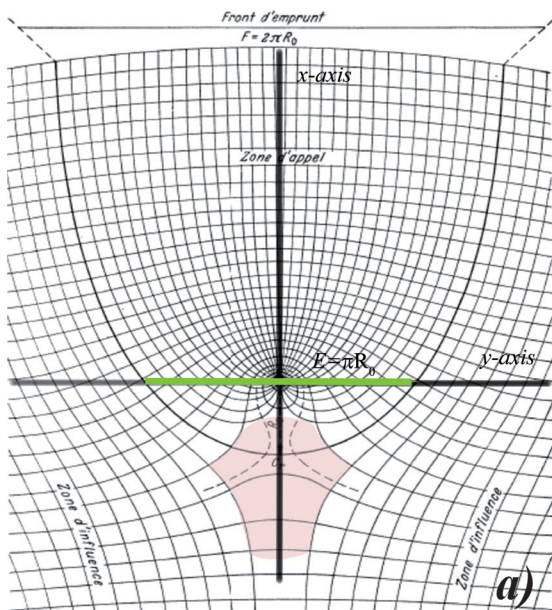

Fig. 3 - a) Stagnation point due to single pumping wells and low velocity area according to Schoeller. Example of stagnation point due to three areas with symmetric depression of groundwater head. b) Stagnation point due to two pumping wells and low velocity area according to COLOMBO et alii (2014)
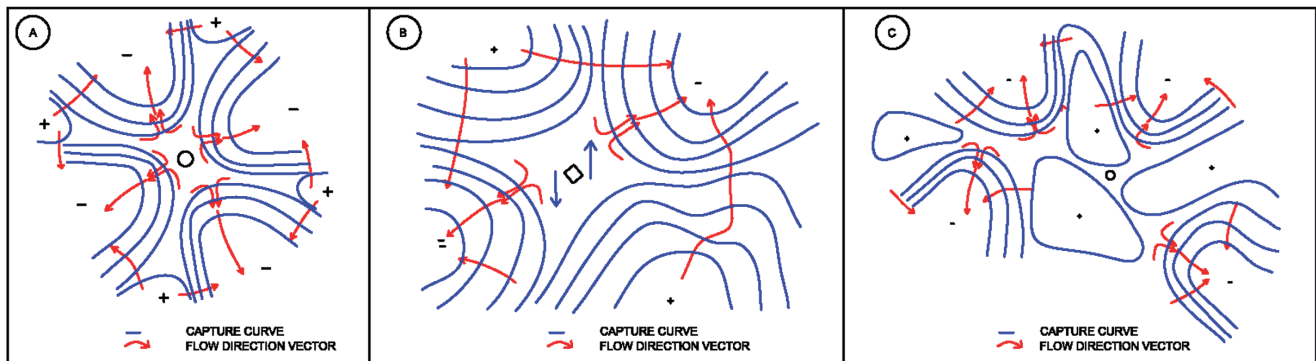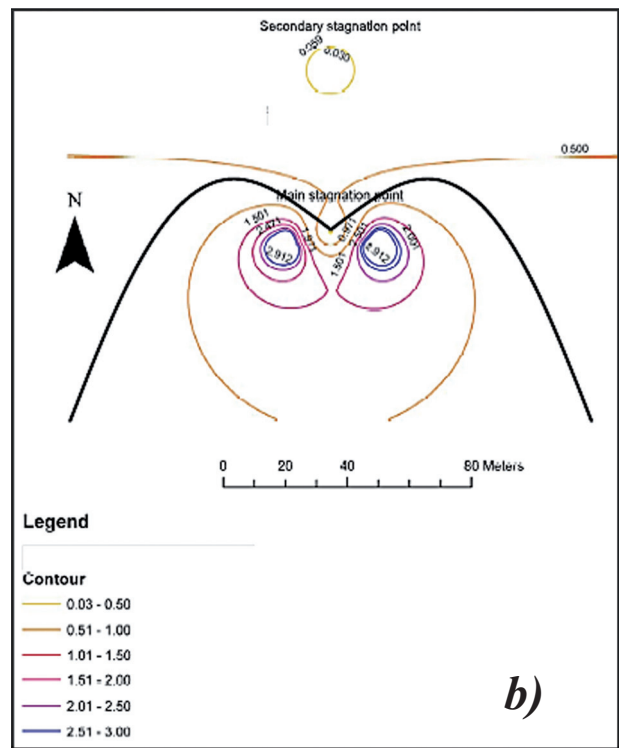

Fig. 4 - Theoretical stagnation zones: a) Four piezometric depressions and a high water table; b) two piezometric depressions (saddle); c) A huge number of depressions with a random flow

To solve the case of many pumping wells, Colombo *et alii*, 2012, have developed a model from the solutions presented by SHAN (1999), CHRIST & GOLTZ (2004). This model takes into account both a number of wells N ≥ 3 and a location in some points of complex plane (x, y) in a homogeneous isotropic confined aquifer, with uniform thickness B [m] and constant Darcy velocity U [m/s]. Also a steady state groundwater flow must be considered. The complex potential w (JAVANDEL & TSANG, 1984), due to the linearity of Laplace's formula, can be expressed as a superposition of piezometric effects of pumping in several wells (injecting or extracting) and of the uniform flow. The following (1.1) shows that

$$w = \phi + i\psi = -Uze^{-i\alpha} + \sum_{j=1}^{N} \frac{Q_j}{2\pi B} ln(z - z_j) + C \qquad (1)$$

where w is the complex potential of the overall system, U [m/s] is the Darcian velocity of uniform regional flow, α [-] is the angle between the regional flow direction and the x-axis, B [m] is the aquifer thickness, Q [m³/s] is the extraction rate of well, N is the number of wells, z (z = x + iy) is the coordinate in the complex plane where the potential w is evaluated, the well coordinate j in the complex plane (x, y), C is a constant of integration that depends on boundary conditions.

The stagnation point can be computed (CHRIST *et alii*, 2002) with first derivative of w.

$$\frac{dw}{dx} = -Ue^{-i\alpha} + \sum_{j=1}^{N} \frac{Q_j}{2\pi B(z - z_j)} \qquad (2)$$

A very simple relationship, which allows to have a preliminary idea of the central stagnation point position for two wells with the same flow rate, has been presented in COLOMBO & FRANCANI (2014). The dimensions of these areas are very important in order to know the most critical points where the survey of contaminants has to be more accurate. The identification of the velocity around the wells using simple analytical methods can simplify the approximate delimitation of low velocity zones. Otherwise, with a numerical bi-dimensional model, it is possible to obtain the shape and the extension of the areas on the plane x, y.

Taking into account the complexity of the geology and the large number of wells to be examined, it was considered appropriate to use the model previously implemented by ALBERTI & FRANCANI (2001) by introducing the necessary changes to get the velocity field in detail.

FLOW MODEL SETTINGS

The applied code, MODFLOW, is developed by the USGS (United States Geological Survey, Mc Donald MG, Harbaugh AW, 1988), and a 3D geometries, boundary conditions and hydrogeological properties have been defined in the flow model settings. The spatial domain of the studied area has been discretized with a 3D grid composed by 900 lines, 1030 columns and 3 layers with cells of 400 m x 400 m in the boundaries area and 20 m x 20 m in the interested area. Along the vertical direction, the layers want to represent the thickness of the aquifer A+B of the Milan plain. A three layer model has been realized:
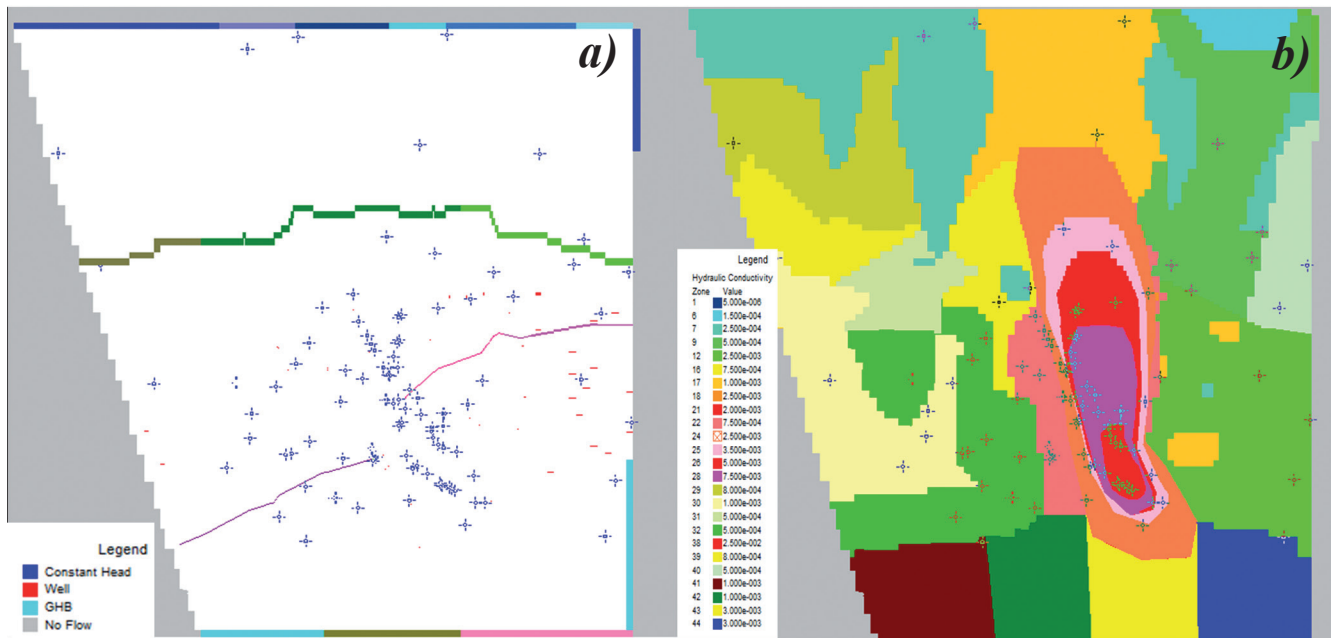

Fig. 5 - a) Boundary conditions used in the model and b) the hydraulic conductivity in the first layer. The crosses are the calibration points in the model

- 1 layer: Aquifer A thickness from 140 to 200 m.
- 2 later: Aquitard which is the clay lens which regulates the water exchange between the two aquifers
- 3 layer: Aquifer B thickness from 15 to 60 m.

Hydraulic conductivity distribution (Fig. 5b) has been defined by lithological maps and hydrogeological properties of the aquifers of the previous work (ALBERTI *et alii*, 2000). The values vary for the layer 1 and 3 from $5 \cdot 10^{-6}$ m/s to $2.5 \cdot 10^{-2}$ m/s. For the aquitard, instead, the range has been $5 \cdot 10^{-6}$ m/s and $2.5 \cdot 10^{-3}$ m/s. Boundary conditions have been set taking into account the real hydrogeological-hydraulic boundaries (Fig. 5a); along the southern area border a GHB condition has been inserted as a Cauchy condition; along the eastern and western a no flow condition has been inserted whereas in the northern border a constant head element has been inserted in order to represent the piezometric values of the 1995. This last condition allows to have a variation of the piezometric head.

The initial condition has been done for layer 1 in order to have a solution not influenced by the boundary condition; the working wells in the model domain, divided by water supply water and private, have been inserted with an imposed flux ("well condition"). The extracting rate has been inserted taking into account the position of filters, which are overall in the third aquifer. The extraction rate imposed is the maximum during the first three months of the year (January-March). The infiltration rate has been constituted by irrigation and rainfall and inserted in the model with a flux imposed taking into account the soil and use properties (due to the fact that city of Milan is highly urbanized and very impermeable, the term of recharge has been within 10^{-8} m/s). The recharge distribution depends also on the presence to streams (Villoresi, Martesana and Pavese) whose inflow contribution the groundwater depends on the different periods in the year. The simulated flow model has been calibrated not only by the measured piezometric head of 1995, but also by means of residual value between measured hydraulic head targets of the 2011 inserted for the superficial aquifer and the simulated hydraulic head (Fig. 6). The calibrated parameters have been then the imposed conditions of the model boundaries (GHB along,
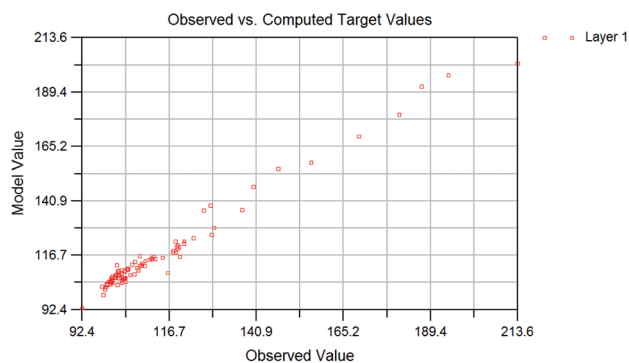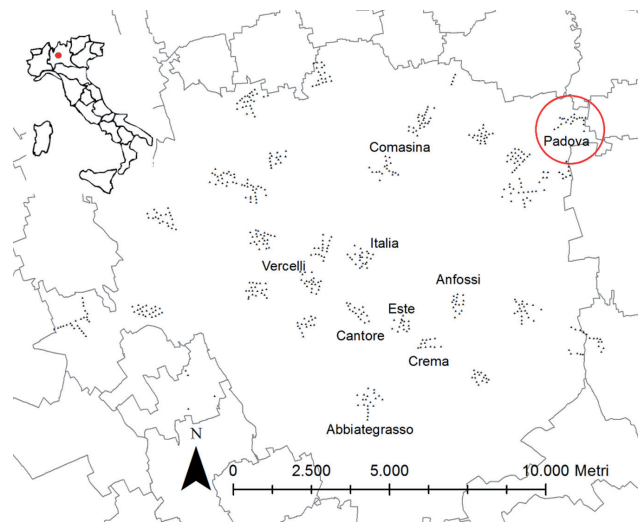

Fig. 7 - *Location map of Drinking water stations in Milan (red point). The Padova water supply station has been analyzed in the present paper in order to know locally the distribution of the stagnation areas*

northern area, constant head along eastern and western areas). The results of the numerical simulation consist first of all in a detailed mapping of piezometric head, of capture zones of individual wells and of pumping stations, and of groundwater velocity field.

The capture zones of pumping wells stations are fairly large: in fact it can be deduced from the piezometric map that they affect a cross flow section within 1000 m. The width of the capture zone is due both to the high transmissivity, exceeding 0,01 m²/s, and to the withdrawal of the wells, which is greater than 200 l/s. The fact that the stations grouping the wells are placed at a short distance between them , means that the zones of influence of the wells of the nearby stations heavily interfere resulting in a significant lowering of the piezometric level. The whole central area of the city is located in the piezometric depression due to the interference of wells withdrawal; this central depression extends over an area that covers the entire surface within the city walls of medieval Milan (about 20 km²), where the number of pumping wells is around 100.

ANALYSIS OF LOW SPEED AREAS DUE TO A SINGLE PUMPING WELLS STATION

The study has been carried out by examining, by means of the numerical simulation, first the lowering velocity produced from the wells of a single station, in order to verify if a single station can generate low speed areas of significant amplitude, and the station in Padova street was chosen, where abundant hydrogeological data are available (Fig. 7).

The Padova water supply station (Fig. 8) consists of 20 wells homogeneously distributed over an area of 0,40 km². The data can be classified as general well data such as location, depth and top level referred to mean sea level. A piezometric surface where all

Fig. 6 - *Observed versus simulated target head values (m a.s.l.) for the layer 1. The RMS error computed is 4.53 and the residual mean is within -3.23*

wells had been discharging about 38 l/s is represented by Fig. 8. The hydrogeological parameters and the screened intervals are shown in the Tab. 1.

The model results highlight that in the Padova water supply station, the velocity is characterized by several slowdown areas, including some stagnation points, caused by a piezometric feature similar to those described theoretically in Fig. 4.

By observing the isopiezometric contour lines, it can be seen that the natural gradient is very low, and that (Fig. 9) immediately downstream the water supply station, a low flow area (Fig. 4a) is located, covering a very large surface. Moreover, near each well a primary stagnation point is observed (COLOMBO & FRANCANI, 2014).

Moreover it can be observed that:

- near each well, a stagnation point is due to the entity of the extraction of each well (the blue points in the Fig. 9)
- downstream the water supply station, a wide stagnation area is formed by the superposition of the depressions created by the individual wells, leaving downstream a large area with higher piezometric level but with lower velocity (the big point in the Fig. 9 as theoretically shown in Fig. 4a).

Figure 9 demonstrates also that the contaminants passing through the capture zones of the single wells are stopped by the piezometric dome containing the lower velocity zone. For this reason, inferring that a detailed flow net may constitute the base for a proper analysis of the evolution of the water quality, an examination of the piezometric map resulting from the simulation of the withdrawal of the wells of the whole city has been done.

Therefore, the effects of each well on the piezometric depression and in direction of velocity vector can be easily examined, and the regional features of the particularity of the flow net of the pumping stations can be detected.

ANALYSIS OF THE GROUNDWATER VELOCITY FIELD IN MILAN

Considering the piezometric map represented in Figure 3a (piezometric head 1958), it can be observed that the piezometric depression of Milan is characterized by higher gradients in the band surrounding the city on the western, northern and eastern sides, while the gradients are slower in the middle of the center of the city and in the southern side. This obviously indicates that the piezometric depression produces an increase in flow velocity around the city, but in Milan the speed is reduced mainly for the decrease in the flow rate caused by the withdrawal of the wells. However, the analysis of the hydraulic gradients in Milan, has revealed that within the city the speed reduction is not uniform , and that the geographical distribution of areas with low speed (Fig. 10) can be summarized as follows:

a) The total area covered is about 50 km², so a little less than half of the municipal area;
b) Two bands can be limited with good approximation in which the

Piezometers	Transmissivities	m³ extracting	Thickness filters (m)
1	1,28E-02	879442	
2	1,28E-02	879442	13,88
3	1,28E-02	879442	18,06
4	1,28E-02	879442	18,06
5	1,28E-02	879442	21,23
6	1,28E-02	879442	19
7	1,28E-02	879442	19,54
8	1,28E-02	879442	10,75
9	1,28E-02	879442	
10	1,28E-02	879442	12,44
11	1,28E-02	879442	
12	1,28E-02	879442	
13	1,28E-02	879442	
14	1,28E-02	879442	
15	1,28E-02	879442	
16	1,28E-02	879442	27,3
17	1,28E-02	879442	24,61
18	1,28E-02	879442	
19	1,28E-02	879442	27,09
20	1,28E-02	879442	27,21

Tab. 1 - Hydrogeological parameters resulting from the interpretation of pumping data. The wells are represented in the next Figure 8
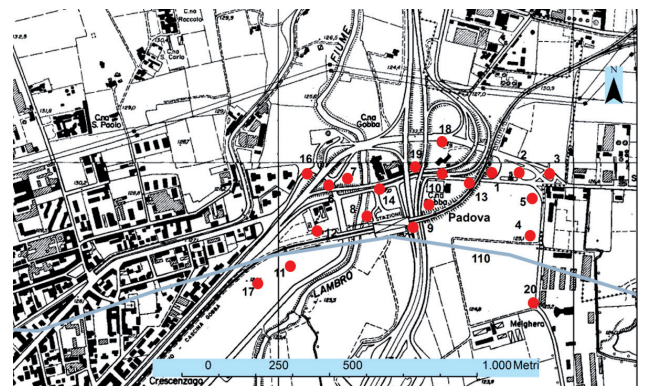

Fig. 8 - Map of the Padova water supply station, when the wells are switched on (the red points are the well positions and the relative number). The piezometric head contour is drawn by blue line

speed of the groundwater is normal. Each of these has a width of about 1500 m , and covers the entire city from North to South;

c) In the western part of the city one of these bands is interrupted by a large patch at low speed.

The details of the piezometric maps around the pumping stations have been resumed in the figure 10b, which highlights the effects of withdrawal of the groups of wells along the direction of velocity vector, that are:

a) the detour northwards or eastwards of normal flow direction (which is NW-SE) near the pumping wells
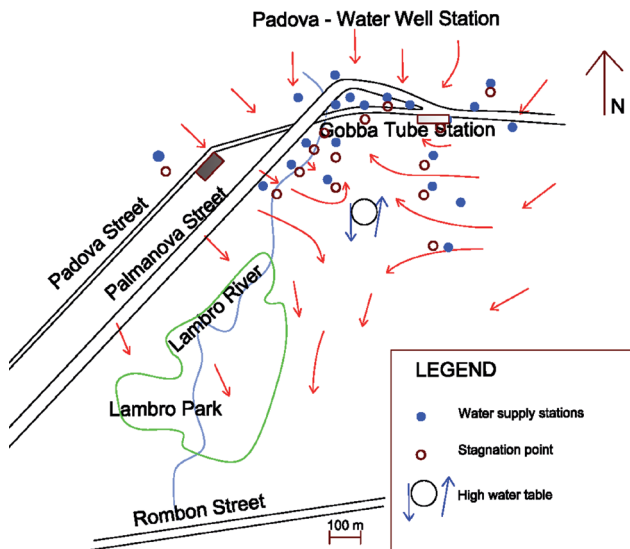b) the occurrence of areas where the direction of velocity vector is random.

Fig. 9 - *Velocity overview generated by the output model for the water supply station of Padova Street*

c) The randomly directed velocity vectors in confined spaces, with the result that, in this area, the sum of the velocity vectors is about zero.

d) In the western part of the city the permeability decreases, favoring the lowering of the groundwater velocity.

The detour of normal flow direction towards the wells causes the decrease of the value of the speed, when the regional flow has an opposite direction: often the areas of flow speed reduction fall in this situation.

DISCUSSIONS

In order to demonstrate that the model can easily describe the origin of the contaminations affecting the central area of Milan, figure 11 represents the main flow direction that highlights the origin of the contaminated areas and the containment effect of the low velocity areas.

It can be observed that the main hydrochemical features are significantly affected by this distribution of groundwater velocity. For example, some maps show that the parameters representing the basic characteristics of the water (i.e.. electric conductivity, hardness) and particularly some contaminants very common in Milan groundwater (es. chromium, organohalogens), have a significant correlation with the areas of low velocity, where the highest concentrations of the pollutants can be measured. Figure 12 for example describes the conducibility of the aquifer (black color), the shape of which is similar to the lower speed areas. It is reasonable to believe that this behavior is related to the fact that a plume of pollutants, to equal mass emitted by the source, has higher concentrations where the flow speed is lower. Moreover, where the water time resides longer, it is acceptable that higher quantities of substances contained in aquifers have been dissolved from the soil matrix, such as carbonates of calcium and magnesium that are present in the gravel and sand of the whole area of Milan.

CONCLUSIONS

One of the main problems in the city of Milan is caused by a heavy contamination of the wells, in particular where the renewal time of the groundwater is higher: this happens in large
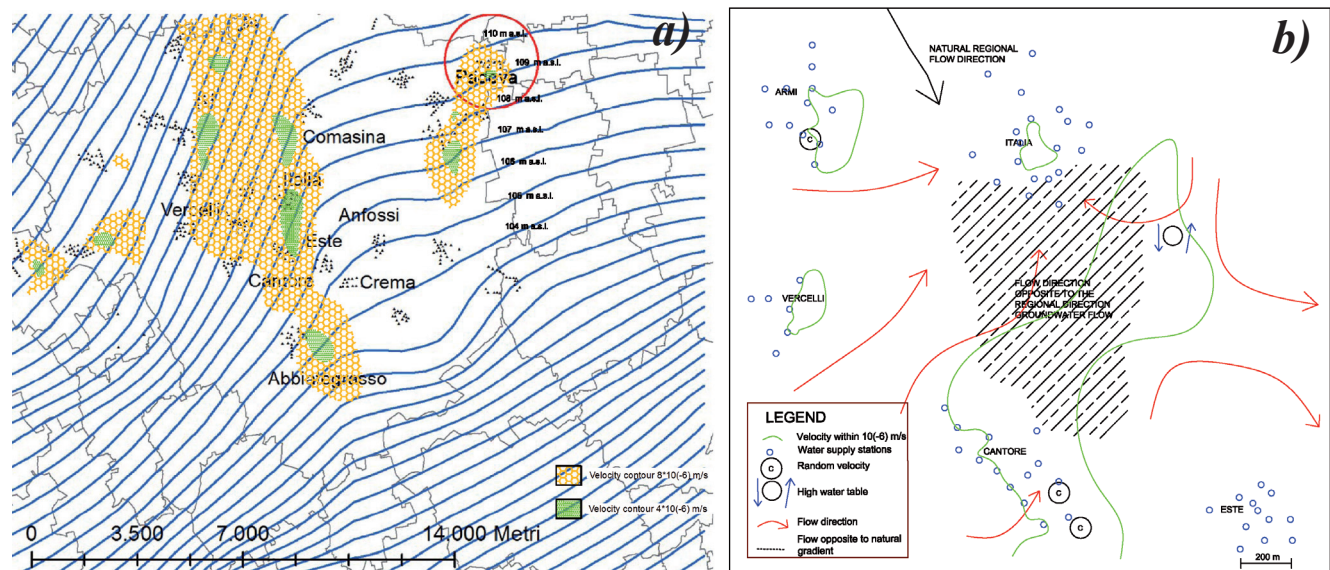

Fig. 10 - *a) There are two different fields velocity in the city of Milan where the velocity is very low (The orange one with 8 10^{-6} m/s and the green with a lower velocity 4 10^{-6} m/s (the red circle represents the area shown in Fig. 9); b) a particular view in the center of Milan where the most low velocity areas are observed*

areas where the velocities are very low and the persistence and the concentration of a given species can be very high.

The study of groundwater velocity in Milan has shown that the water supply wells of the city cause these areas of low flow speed. This fact is due to the superposition between the piezometric depressions created by wells which reduces the hydraulic gradient in areas between one and another group of wells. This behavior has been verified in detail by examining the features of the piezometric surface determined by water supply wells in Padova Street immediately near the city center, and of the other groups of wells. The observed wells generate some stagnation points and several wide low speed areas. The sum of piezometric depressions of wells groups produces two main low velocity areas (about 0,1 m/day) , separated by two bands in which the flow velocity is within the natural one (about 1 m/day).

The central part of the city, and almost all of its northern part, is a wide capture zone which receives several plumes of contaminants from the outer areas of the city. It is possible to verify that in the areas of slow water flow due to the superposition the time of degradation increases, due to recall of plumes of contaminants.
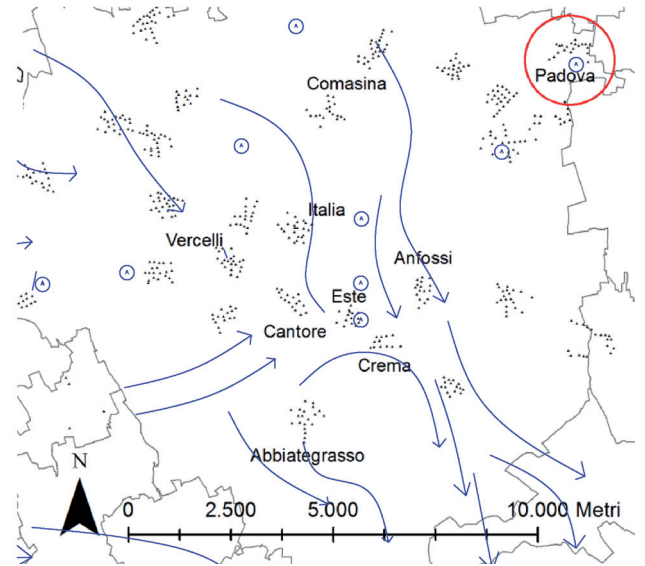

Fig. 11 - *Velocity flow in the city of Milan. There are many stagnation areas (represented with the blue circle)*
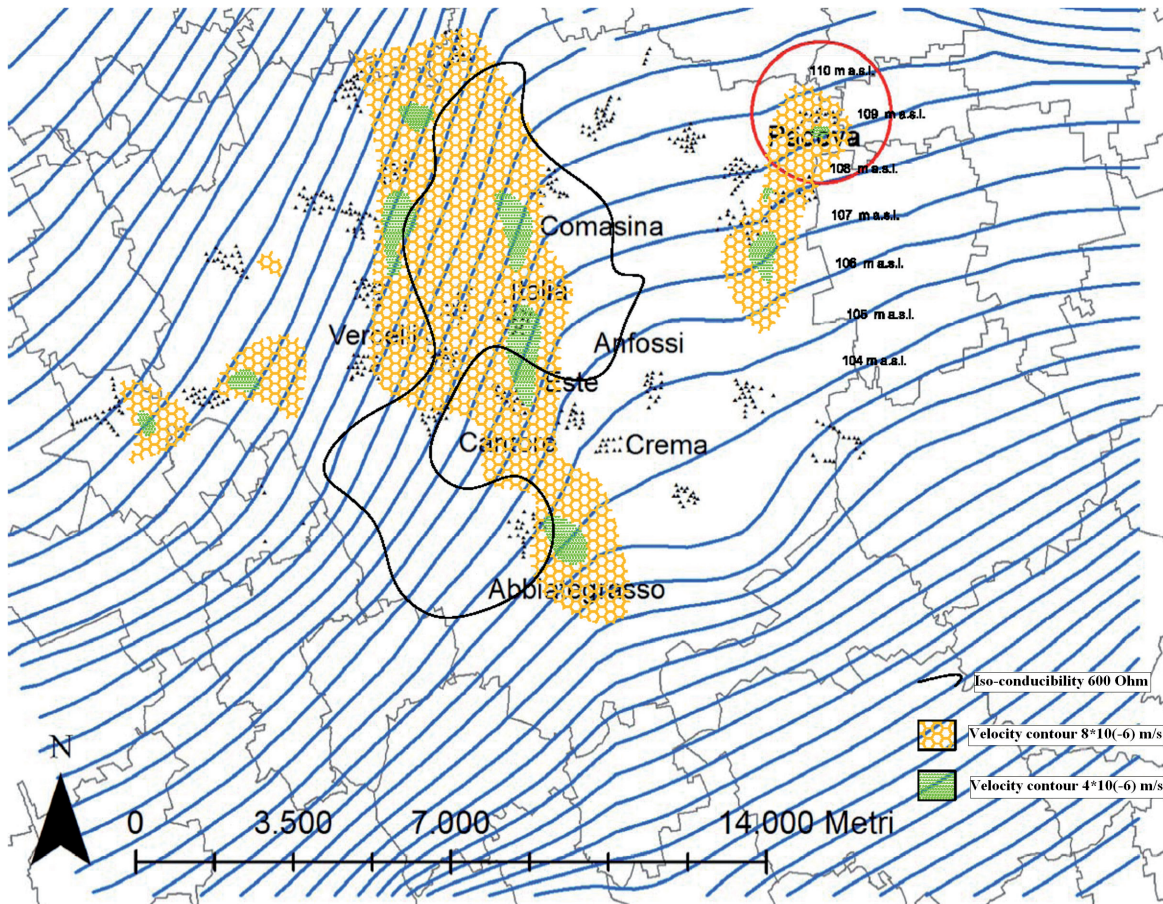

Fig. 12 - *Iso-velocities contours in the city of Milan. The conducibility lines are in black color (600 Ohm m)*

Therefore the hydrogeological setting in the last twenty years , prevented the outflow of the water downstream, favoring the persistence of contamination especially in the northern and central part of the city, and the deterioration of the quality of groundwater.

It is therefore of great interest to analyze in detail the evolution of the areas by slowing down the water flow, to determine whether they will retain their extension, or for the reduction of withdrawal that characterizes the current phase of socio-economic phase, which can be reduced even in the absence of drastic management actions.

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