Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0725

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Blue-green infrastructures and groundwater flow for future development of Milano (Italy)

Infrastructures bleu-vert et écoulement des eaux souterraines pour le développement futur de Milan (Italie)

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ABSTRACT: Milan has always been considered a city of water due to the presence of a network of natural and man-made canals, lying on one of the most important Italian aquifer system which has been heavily exploited for public and industrial supply, but the future use of this resource still has to be decided. The rate of abstraction decreased of more than 30% since the 1970 (3.5x10^8 m^3/year on 1975 to about 2.3x10^8 m^3/year on 2016), with the number of inhabitants, the diminished per capita consumption and the decommissioning of industrial activities. This resulted in a groundwater rebound causing flooding of underground structures. Climate change scenarios project that urban regions will be exposed to extremes of precipitation and temperature, increased storm frequency and intensity. In recent thinking, portfolios of “blue-green” technologies and infrastructure (connected network of multifunctional, predominately unbuilt, space that supports both ecological and social activities and processes) combined with conventional “grey” infrastructure have been identified as best practices for achieving greater urban sustainability and resilience. In this context, a steady-state groundwater flow model was calibrated on a monitoring dataset and used to evaluate the impact of a blue-green infrastructure at the urban scale. The development of a continuous network of wells withdrawing water from the unconfined aquifer are placed along a ring linking the dismissed rail yard areas which will undergo significant urban developments in the next years. Various scenarios were simulated in order to evaluate the multiple functions of such system: (i) blue-green infrastructure irrigation, (ii) geothermal energy production, (iii) water table lowering and (iv) CO2 emission avoided and pollution reduction.

RÉSUMÉ:

Milan a toujours été considérée comme une « ville d’eau » à cause de la présence d’un important réseau de canaux naturels et artificiels. Pour cette raison, la nappe phréatique de Milan a toujours été l’une des plus fortement exploitées en Italie, mais sa future utilisation est aujourd’hui fortement débattue. Le taux de rabattement de la nappe a diminué de plus de 30% depuis 1970 (de 3,5 x 108 m3/an en 1975 à environ 2,3 x 108 m3/an en 2016), en raison du nombre d'habitants, de la diminution de la consommation par habitant et de la disparition de certaines activités industrielles. Cela a entraîné une remontée de la surface de la nappe, déclenchant l’inondation de structures souterraines. De plus, les scénarios de changement climatique sont plutôt pessimistes : on prévoie que les zones urbaines seront exposées à des situations extrêmes en terme de températures et de précipitations, avec une augmentation de la fréquence et de l’intensité d’orages.

Récemment, une manière optimale de parvenir à une meilleure résilience et un développement durable de zones urbaines a été identifiée. Il s'agit de combiner une infrastructure «grise» conventionnelle avec des technologies et infrastructures «bleu-vert», définis comme un réseau connecté d'espaces multifonctionnels, peu urbanisés et facilitant des activités à caractère écologique et social. Dans ce contexte, un modèle d'écoulement des eaux souterraines en régime permanent a été calibré grâce à un ensemble de données d'auscultation, et utilisé pour vérifier l'impact d'une infrastructure « bleu-vert ». Un réseau continu de puits en nappe libre sera développé sur une couronne reliant des zones ferroviaires abandonnées destinées à un important redéveloppement. Plusieurs scénarios ont été simulés pour évaluer les différents fonctions faisant partie de ce système complexe: (i) l'irrigation d'infrastructures bleu-vert, (ii) la production d'énergie géothermique, (iii) le rabattement de la nappe phréatique, et (iv) la réduction de la pollution et la limitation d'émissions de CO2.

Keywords: modelling; geothermal; groundwater; CO2; energy.

1 INTRODUCTION

The availability and the quality of the groundwater resources in densely populated areas are strongly affected by the socio-economic development and the urbanization. In the Milan Metropolitan area the groundwater has been heavily exploited for public and industrial supply but the rate of abstraction decreased during the last century (from about 350×10^6 m^3/year in the '70s to about 230×10^6 m^3/year at present days, Fig. 1c), with the number of inhabitants, the diminished per capita consumption and the decommissioning of industrial activities. This could result in a groundwater rebound (Crosta and De Caro, 2018) inducing damage to underground engineering structures as a result of inundation of subsurface facilities, hydrostatic uplift or reduced bearing capacity, excessive ingress of groundwater in sewers, chemical attack on concrete foundations, and the mobilization of contaminants (Foster, 2001).
Moreover, it is widely recognised that global changes can significantly affect water resources. These changes are expected to affect the hydrological cycle, altering groundwater levels and recharge with various associated impacts on natural ecosystem and human activities (Taylor et al., 2013). In this context, new solutions such as blue green infrastructures are required to manage water resources. Blue green infrastructures use natural or semi-natural systems such as nature based solutions (*NBS*) to provide water resource management options with benefits that are equivalent or similar to conventional grey water infrastructures. These infrastructures allow to maximize nature's potential to achieve the three main water management objectives: (i) enhancing water availability, (ii) improving water quality and (iii) reducing water-related risks. In this context, a finite element groundwater flow model was developed to study the effectiveness of a blue-green infrastructure for mitigating possible future groundwater level rise in the Milan metropolitan area. This includes steady state calibration, processes identification, and the simulation of future scenarios, considering also the potential in term of clean energy harvested via water-to-water heat pump, both for heating and cooling purposes.

2 STUDY AREA

The Milan area (Fig. 1a) covers a portion of 535 km^2 in the Po Plain (Lombardy region, Northern Italy) and is characterized by a relatively flat topography between 170 m and 95 m a.s.l. Mean annual precipitation (P) is about 900 mm mostly falling during spring and autumn. The mean annual temperature is about 13 °C, with maximum mean temperature of about 24 °C during summer.

Within the city, the natural hydrographic network (i.e. the Olona and the Seveso rivers) is completely culverted, except for the Lambro River (Fig. 1a). The area is characterised by a system of man-made canals, called Navigli, built since the 12th century for connecting Milan to the nearby Adda and Ticino rivers, and for meeting irrigation needs of this portion of the plain.

The geology of the area (Fig. 1b) is mainly composed of Pliocene - Pleistocene continental sediments forming three main aquifers (Regione Lombardia and Eni Division 2002). From bottom to top, the aquifer system includes: (i) a deep multi-layered aquifer consisting of interlayered sand and silt/clay layers, (ii) an intermediate aquifer consisting of a homogenous sandy-gravel and (iii) an upper unconfined aquifer with a discontinuous impermeable basal aquitard that progressively disappears northward.

Recently, the compositional variations of the Po-plain deposits have been related to the LGM (Last Glacial Maximum between 22,000 and 16,000 year BP) and post LGM evolution of alluvial megafans and fans (Fontana et al., 2014). Accordingly, several fan systems have been distinguished in area (Fig. 2, Lambro megafan, Seveso fan, Olona megafan, Lura fan, and Molgora megafan).

Milan urban area has also persistent issues in term of very poor air quality: air pollution due to population and industries density, heavy traffic and local climate creates critical conditions for people’s health.

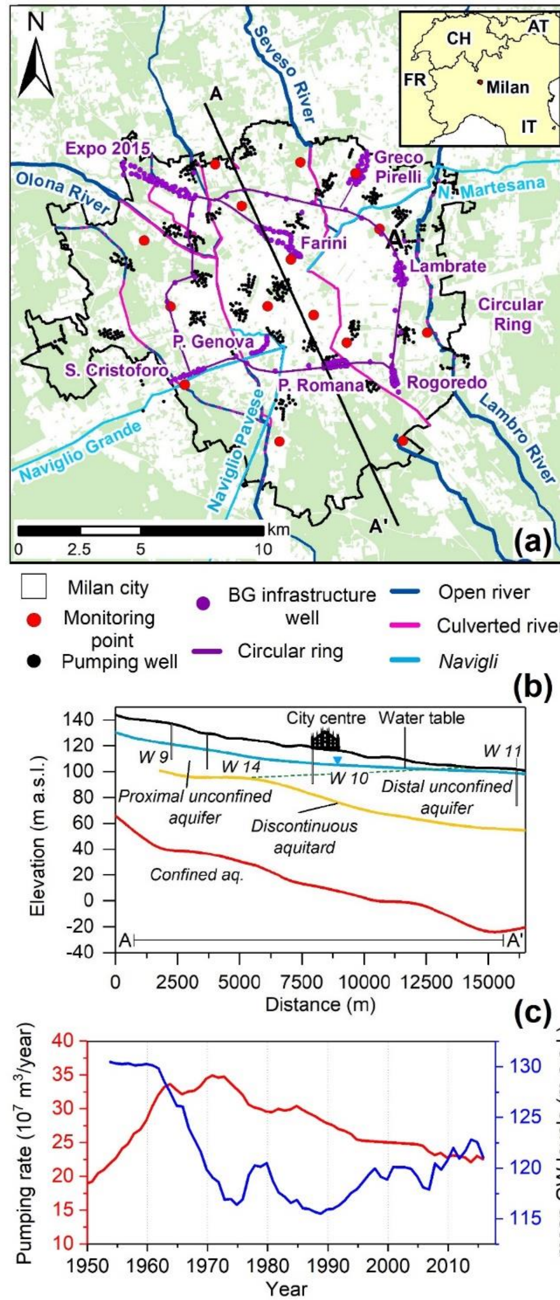

Figure 1 – (a) Map of the Milan area showing the location of monitoring and pumping wells, and the superficial water network together with the designed Blue-Green infrastructures (BG) ; (b) simplified geological cross-section of the hydrogeological system (see panel a for section location); (c) total groundwater abstraction rate and levels.

3 GROUNDWATER FLOW MODELING

The hydrostratigraphic model available for the area (182 km^2), its hydrographic and subway networks, and the conterminous suburban areas (for a total area of 535 km^2) were implemented into a 3D finite element model (FeFlow; Diersch, 2013). The model domain is discretised with a 3D mesh including 12,878,484 triangular prismatic elements divided in 12 layers (Fig. 2a). The distance between nodes ranges from 200 m to 2 m in proximity of pumping wells, and hydrographic and subway networks. The thickness of the layers depends on the thickness of the hydrogeological units, the well screen position, the subway tunnel dimensions and the hydrographic network depth. The vertical discretisation of the model can be summarised as follow (Fig. 2a). Layers 1 to 7: represent the unconfined aquifer. These layers were subdivided according to the distribution of fan deposits and their internal transition from proximal to distal fringes (gravelly to sandy aquifer). The first two layers (each layer 1.5 m thick) include the Naviglio Grande, the Naviglio Pavese, and the Naviglio Martesana canals. Layer 8: represents the discontinuous aquitard (3m mean thickness) between the unconfined and the semi-confined aquifers. Layers 9 to 11: include the semi-confined aquifer. Most of the pumping wells are screened in this aquifer. Layer 12: represents the lower aquiclude.

4 WATER BUDGET

Main water inputs and outputs to the hydrogeological system are the recharge at the ground surface, the abstraction of public and private supply wells and, the outflow from the lowland springs and rivers (Fig. 2b). Average monthly recharge rates for the study area were derived from water table fluctuation method carried out on daily groundwater levels (De Caro, 2018).

Accordingly two patterns of recharge have been applied on the model surface by distinguishing

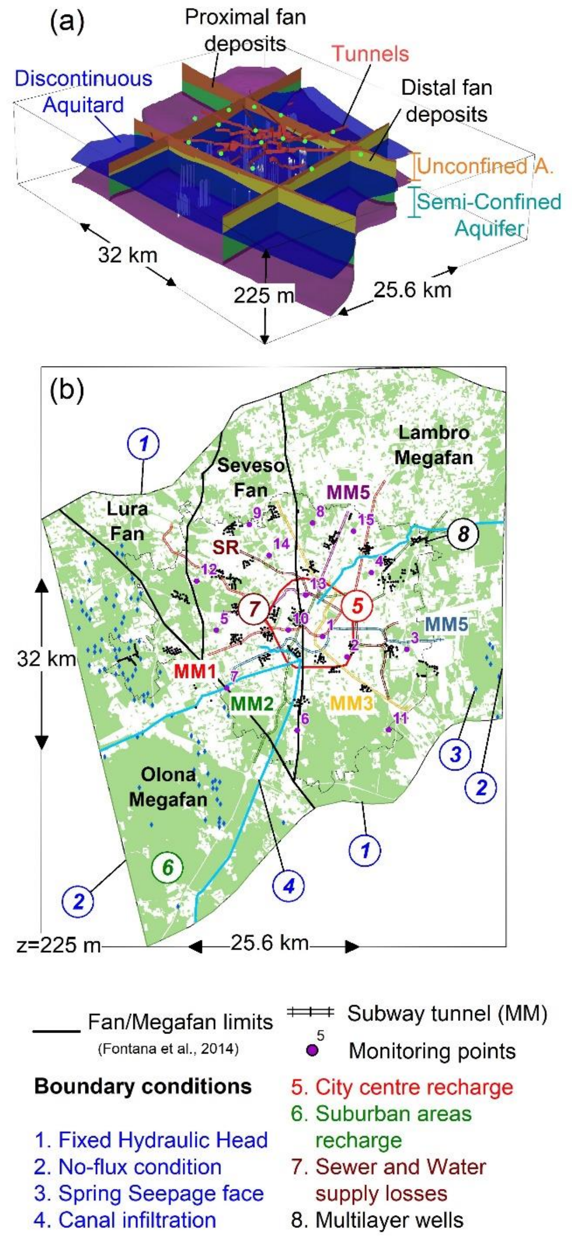

Figure 2 - (a) Fence diagram showing the body, vertical discretization of the model, and the underground structures; (b) plan view showing the horizontal discretization according to the fan/megafan distribution (black lines, adapted from Fontana et al., 2014), and the applied boundary conditions (i.e. prescribed hydraulic heads, springs, multilayer wells, and canal infiltration).

city centre (i.e 20% of total rainfall) and suburban areas (i.e. 60% of total rainfall). Water losses from supply network (i.e. 15% of the total water supply) were applied according to estimates from the water suppliers in the metropolitan area (MM SpA).

Infiltration rates of 43 L/s*km, 5 L/s*km, 24.3 L/s*km have been applied to nodes representing the Naviglio Grande, the Naviglio Pavese, and Naviglio Martesana canals, respectively.

Groundwater abstraction from 576 wells was simulated via the Multi-layer wells boundary condition. The northern and the southern boundaries were simulated by a Dirichlet condition based on hydraulic head data surveys.

The eastern and the western limits of the model were simulated as no-flux boundaries. The lowland springs were simulated by assigning a fixed hydraulic head equal to the nodal elevation (i.e. flux-constrained Dirichlet boundary condition).

5 MODEL CALIBRATION

The mean groundwater levels for 2016 were used for the steady-state calibration by means of inverse procedure (PEST; Doherty et al., 1995).

For the unconfined aquifer, grain size distribution data were analysed with different empirical equations. Then, permeability values (K_{eq}) were assigned to each borehole log within the unconfined aquifer, then the equivalent values were interpolated to obtain a map of hydraulic conductivity. For the semi-confined aquifer, aquifer test data were acquired and analysed with proper solutions (Cassan, 1980; Theis, 1935) to obtain transmissivity and conductivity values.

The obtained hydraulic conductivity values for each model sub-units were used as initial parameter value. During the optimization process, the hydraulic conductivity (i.e. zonally constant parameter) values were adjusted within the maximum and minimum values (± one order of magnitude) of estimated hydraulic conductivity.

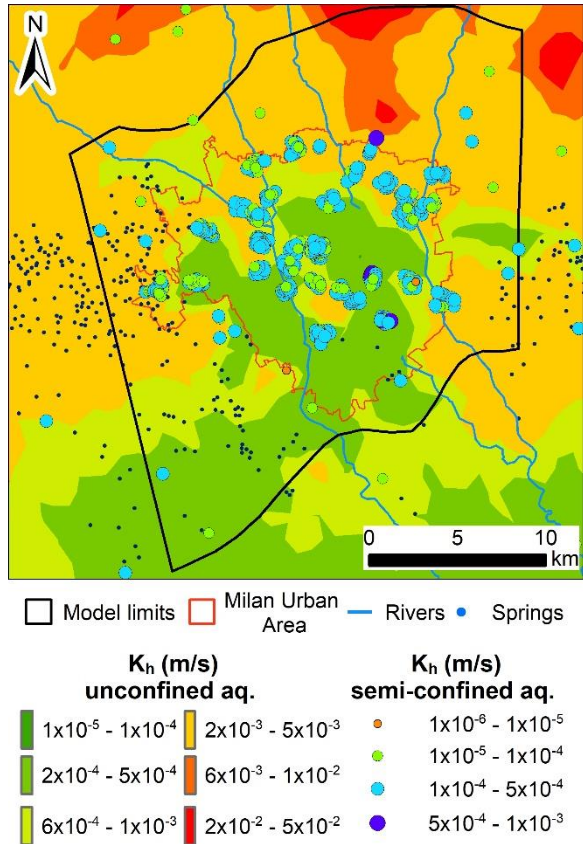

Figure 3 – Map of equivalent hydraulic conductivity for the unconfined aquifer obtained by ordinary Kriging and estimated hydraulic conductivity values by means of well tests analysis (dots).

6 FUTURE SCENARIOS

A blue-green infrastructure can be defined as a connected network of multifunctional, predominately unbuilt space that supports both ecological and social activities and processes. These infrastructures relate to matrices of greenspaces that can be found in and around urban landscapes. These infrastructures include street trees, public gardens, parks, riparian zones along urban drainage lines, undeveloped ridges, and urban agricultural spaces (Mell, 2008).

Starting from the reference scenario (i.e. 2016), the calibrated model was used to simulate the development of a continuous network of vegetated areas in place of decommissioned rail

yards in the Milan city area. In this vision, wells withdrawing water from the unconfined aquifer are placed in unused rail yards and along a ring linking these areas, with multiple functions: (i) Blue-green infrastructure irrigation, (ii) geothermal energy production, and (iii) water table lowering.
This underground Blue ring can work in parallel with existent high temperature district heating, fit for existing building from the 60-70's, creating a neutral-temperature water city network able to power water-to-water heat pump that provide heating, cooling and domestic hot water to newer and retrofitted buildings, characterised by a lower energy demand.
Due to its size and volume the Blue ring can become an integrated heating and cooling city network where heat and coolth exchange can happen at the same time in different part of the city, allowing also for low-grade waste heat application. The Blue ring is intended as an infrastructure that links the dismissed rail yard, but a higher coverage could be reached considering a broader infrastructure, even if additional studies are required to better investigate heating and cooling demand balance.
A first preliminary assessment of the thermal potential of the infrastructure could start considering - with a conservative approach – the pumping rate of 1994 as the historical peak.
After 1994 in fact there is a progressive reduction of the water use in Milan and consequently a progressive increase of the table water level.
The difference in term of yearly water abtraction between today and 1994 is around $55x10^6$ m^3.
If we refer to the daily pumping rate as per Figure 5, the maximum achievable thermal capacity associated to this water volume is closed to 250 MWt, considering $\Delta T=5\pm1°C$ to minimise the risk of thermal pollution, whilst the overall heating and cooling energy output can be estimated in 440 GWht/year.
This number is equivalent to a potential cut of CO2 emission on site for the city of $140x10^3$ tons yearly.
In order to offset the CO2 associated to the power required for operating the water extract pumps and heat pump systems we consider to integrate the Blue ring with a renewable electrical generation. Using power plants supplied by a sustainable biomass supply chain, located in the pre-Alps territories, this solution can also achieve a social benefit in term of green economy, re-population of abandoned areas and hydrogeological risk reduction.
The results of this preliminary analysis can be also read in term of coverage of the city population energy demand. We estimate that 240'000 inhabitants of Milan, equivalent to the 20% of the actual population of the city, can be supplied through the Blue ring.
Note this estimation is based on the difference between today and 1994 water absorption, which is only the 20% of the overall water absorption that is currently happening in the city, close to 250 mln m3/year. This means that the overall yearly water absorption has the potential to cover the whole city population energy demand for heating, cooling and DHW.
We consider the Blue ring a great opportunity to foster the decarbonisation of the city of Milan. It offers a unique opportunity for Milan to become the first city in Europe that can reduce drastically the use of fossil fuels in their energy mix whilst improving the air quality and health conditions for its population.

7 RESULTS

The steady-state model was calibrated on the 2016 average groundwater head monitored at 15 wells (Table 1).
Scatter plots of differences between observed and computed groundwater levels of steady state model show (Fig. 3a) mean residuals of 0.10 m indicating a reasonable agreement between simulated and observed hydraulic heads. Hydraulic heads and flow patterns for the unconfined aquifer are shown in Figure 4. Results suggest that at the metropolitan scale

groundwater levels heavily depend on distance from pumping wells.

Table 1 - Calibrated values of hydraulic conductivity for each unit of the groundwater flow model (for zone location and extent see Fig. 2).

zone id	K_x [m/s]	K_y [m/s]	K_z [m/s]
Lambro mf - Proximal	3.4x10^{-2}	1.08x10^{-3}	7.3x10^{-4}
Lambro mf - Distal	1.5x10^{-4}	9.3x10^{-4}	4.8x10^{-5}
Seveso f - Proximal	1.5x10^{-3}	2.1x10^{-3}	7.7x10^{-4}
Seveso f - Distal	1.2x10^{-4}	5.9x10^{-4}	9.4x10^{-5}
Lura f - Proximal	3.6x10^{-3}	5.1x10^{-3}	1.2x10^{-3}
Lura f - Distal	8.8x10^{-4}	5.9x10^{-4}	3.1x10^{-4}
Olona mf - Proximal	8.6x10^{-2}	9.2x10^{-2}	2.9x10^{-2}
Olona mf - Distal	2x10^{-2}	2.4x10^{-2}	1.3x10^{-2}
Aquitard	8.61x10^{-7}	8.61x10^{-7}	8.61x10^{-8}
Semi-Confined	1.01x10^{-4}	9.3x10^{-5}	4.2x10^{-5}
Aquiclude	1x10^{-7}	1x10^{-7}	1x10^{-8}

7.1 Blue-green infrastructure scenarios

Scenario 1 simulates local heavy withdrawals (i.e. 6,500 m^3/d for each well) in the Greco-Pirelli dismissed area (Fig. 4c). A local groundwater lowering of about 12 m is observed at monitoring point 15, whereas the effects are almost negligible in other sectors. Scenario 2 (Fig. 4) simulates local heavy withdrawals (i.e. 6,500 m^3/d for each well) in four dismissed areas (Greco-Pirelli, Lambrate, Farini, and Expo 2015 areas Fig. 1a). The effects are relevant in the whole Milan area and groundwater lowering range between 20 m to 8 m in the city centre and in the southern sectors, respectively. The simulated pumping rate results in groundwater levels lower than the minimum values reached in 1975 (Fig. 4b). This can cause a decrease in pore water pressure and an increase of effective stress in the ground, leading for example to localised subsidence. Scenario 3 (Fig. 4c) simulates the effects of local heavy withdrawals (i.e. 6,500 m^3/d for each well) in two dismissed areas (Greco-Pirelli and Farini areas). The effects are similar to those observed in scenario 2, and a drawdown of about 12 m is observed in the city centre. Scenarios 4 and 5 simulate (Fig. 4c) the effects of withdrawals (i.e. 750 m^3/d and 670 m^3/d, respectively) in all the seven dismissed areas, and along the connecting ring (scenario 5). The effects on groundwater levels for these scenarios are similar and a water-table lowering in the range between 2 m and 6 m is observed in northern and southern sectors, respectively.

In Figure 5c the water-table lowering with respect to the reference scenario (i.e. 2016) is shown for the simulated scenarios.

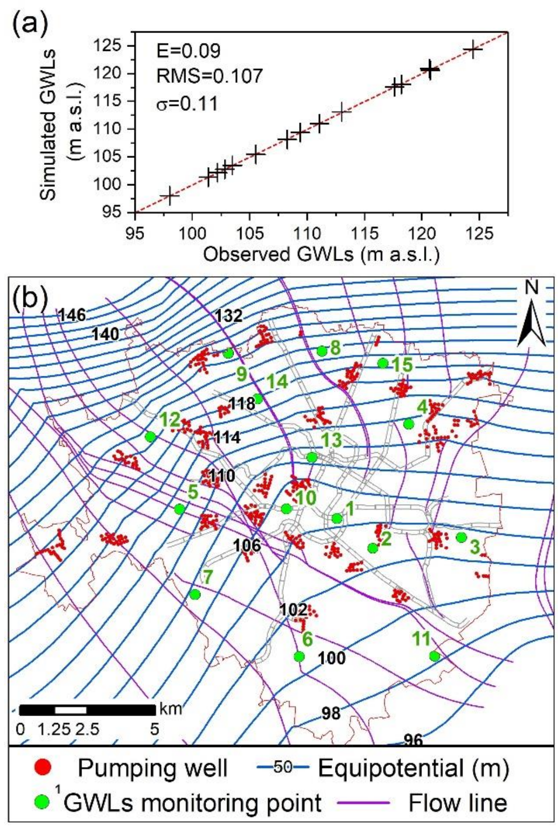

Figure 4 – Results of steady-state calibrated model: (a) scatter plots of observed vs. simulated groundwater levels, E, RMS, and σ are the absolute error (m), the root mean square error (m), and the standard deviation, respectively. (b) Hydraulic heads pattern for the unconfined aquifer.

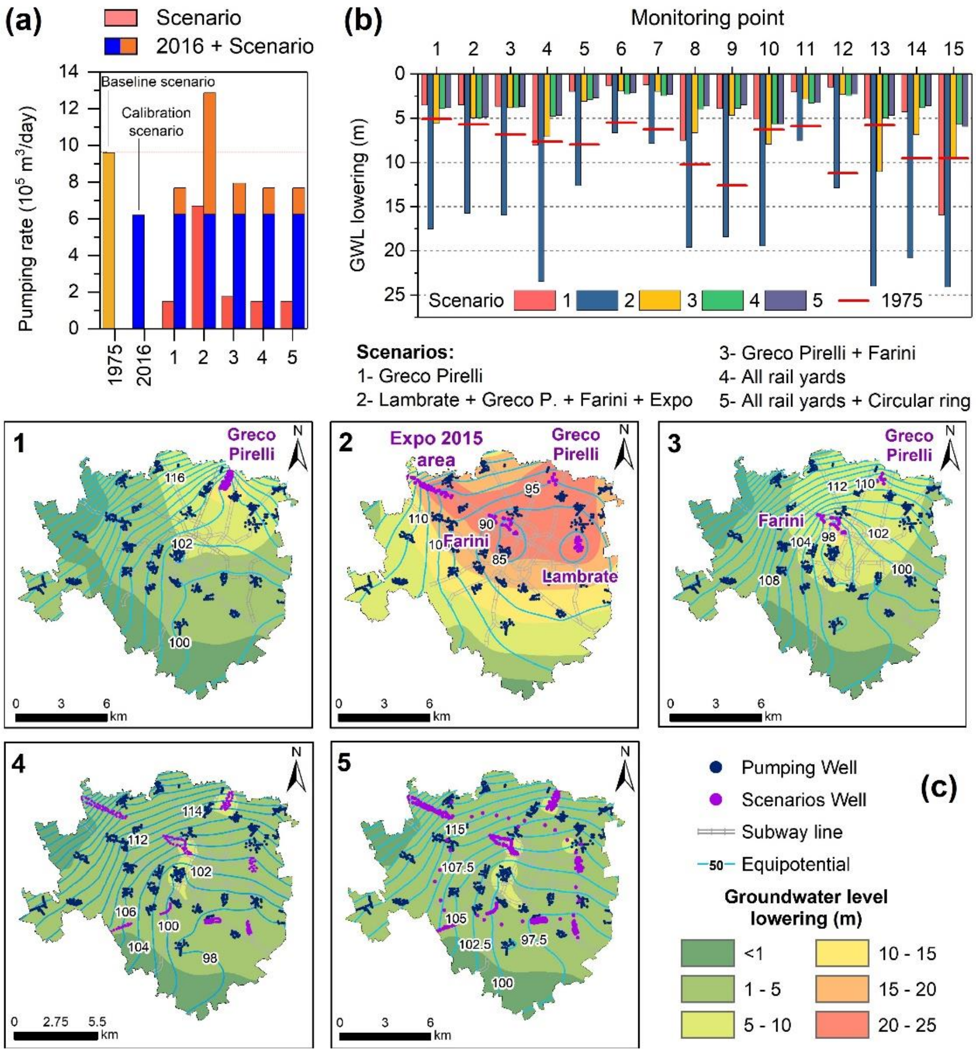

Figure 5 - Results of blue-green infrastructure scenarios: (a) pumping rate according to simulated scenarios; (b) groundwater level lowering at 15 monitoring points (see Fig. 1 for point locations), and (c) hydraulic head and groundwater level lowering distributions for the simulated scenarios.

8 DISCUSSION

Late stages of urban development and the relocation of industrial plants outside urban areas result in a groundwater rebound. In the Milan area, most buildings and underground structures (i.e. subway lines, underground parking and building foundations) were built during the 1960–1990 period, that corresponds with the period of maximum groundwater abstraction. At that time, groundwater levels were not expected to rise and no action was adopted to prevent water inflow and most of the contaminations occurred in the expanded vadose zone. In this framework, quantitative groundwater modeling allow to simulate groundwater levels and the effects of a development of a blue-green infrastucture. Blue-green technologies and infrastructures combined with conventional “grey” infrastructure have been identified as best practices for achieving greater urban sustainability and resilience (Foster et al., 2011).

Results pertaining to the effect of additional pumping wells feeding such infrastructure show that the proposed solution could manage both direct and indirect impacts of climate change on the urban hydrogeological system. Potential benefits include the lowering of the water-table in proximity of subway tunnels, the reduction of storm-water runoff over impervious surfaces, air-filtering by green assets and vegetation, reconnection between humans and nature, geothermal energy production (Kirnbauer and Baetz, 2014), CO2 emission avoided due to use of heat pump, driving also a changing in the local electrical energy mix, due to the demand increase of clean electricity. It is important to observe that any solution needs to be planned immediately, and the construction of such blue-green infrastructure and pumping network must be carefully carried out to avoid dangerous surface settlements. Overall, this is significant because global change is expected to affect multiple interrelated factors which can affect the hydrological cycle (i.e. groundwater levels and recharge), but they can also hamper the adaption capacity of a city by disrupting essential networks including underground transport networks, power, potable water supply, waste water facilities and telecommunication systems (da Silva et al., 2012), affecting also the territory at a regional scale considering the production of clean electricity, together with possible improvemente in term of occupation related to biomass supply chain.

9 ACKNOWLEDGMENTS

This article is an outcome of Project MIUR – Dipartimenti di Eccellenza 2018–2022.

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