Aquifer protection from overexploitation: example of actions and mitigation activities used in the Maggiore Valley (Asti Province, NW Italy)

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The groundwater overexplotation is a worldwide problem and it causes serious consequences such as land subsidence, saltwater intrusion, devastating effects on natural streamflow, groundwater fed wetlands and related ecosystems.
The Maggiore Valley (NW Italy) was analysed in this paper because it is considered as a clear example of overexploitation in Italy. In this area a decrease of the piezometric level of more than 40 m and a large reduction of an artesian area were registered, due to a high increase of groundwater withdrawal from the beginning of XX century. Because the exploited confined aquifer is the only source of water for human consumption in the area, Maggiore Valley wellfield is considered of regional importance and numerous actions have been launched to protect and preserve it. After a detailed hydrogeologic reconstruction of the area, a groundwater flow model was implemented. Then, the simulation of new groundwater withdrawal configurations (groundwater extraction decrease, redistribution of the well location and a combination of both of them) were investigated, in order to simulate a different quantitative management of the groundwater resources. The results of all the simulations highlighted a positive impact on the piezometric level. Consequently, a reduction of groundwater withdrawal from Maggiore Valley wellfield and a concurrent supplementary feed (interconnection, 100 L/s) from the Monferrato Aqueduct, were realized. This operation leads to a partial rising of the piezometric level up to 8 m from 2012 and 2016.
In addition, geophysical studies were conducted to identify the best area for some wells relocation. A combined use of Electric Resistivity Tomography (ERT) sections and Time Domain Electromagnetic (TDEM) soundings permitted to depict the depth and lateral continuity of the uppermost part of the Quaternary deposits, hosting the near surface aquifers, and to choose the most suitable zone from a hydrogeological point of view.
Keywords: *overeploitation, groundwater, piezometric level decline, mitigation, Italy.*

Protezione degli acquiferi dal sovrasfruttamento: esempi di azioni e attività di mitigazione utilizzate in Val Maggiore (Provincia di Asti, Italia Nord Occidentale). *Il sovrasfruttamento delle acque sotterranee è un problema molto diffuso e può causare gravi conseguenze come subsidenza del terreno, intrusione salina, effetti negativi sui deflussi superficiali, sull'alimentazione di aree umide e dei relativi ecosistemi.*
In questo lavoro viene analizzata la Val Maggiore (Italia NW) in quanto rappresenta un chiaro esempio di sovrasfruttamento delle risorse idriche sotterranee in Italia. In quest'area sono stati registrati un abbassamento del livello piezometrico di oltre 40 m e una considerevole riduzione di un'area artesiana, dovuti ad un aumento degli emungimenti a partire dall'inizio del XX secolo. Poiché, nella zona, l'acquifero confinato sfruttato rappresenta l'unica risorsa di acqua per il consumo umano, il campo pozzi di Val Maggiore è considerato di importanza strategica e sono state effettuate numerose azioni per proteggere e preservare le acque sotterranee.
Dopo una dettagliata ricostruzione idrogeologica dell'area, è stato implementato un modello di flusso idrogeologico. In seguito, sono state considerate nuove configurazioni dei prelievi delle acque sotterranee (diminuzione degli emungimenti, ridistribuzione dell'ubicazione dei pozzi e una combinazione di entrambi), con lo scopo di simulare gli effetti di una differente gestione delle risorse idriche sotterranee. I risultati di tutte le simulazioni evidenziano un impatto positivo sul livello piezometrico. Di conseguenza, sono state realizzate una riduzione dei prelievi delle acque sotterranee nel campo pozzi della Val Maggiore e un simultaneo apporto supplementare dall'Acquedotto Monferrato ("interconnessione", 100 l/s). Questa operazione ha portato ad un parziale innalzamento del livello piezometrico di circa 8 m dal 2012 al 2016.
Inoltre, sono stati condotti degli studi geofisici per identificare l'area migliore per la rilocaliz-

1. Introduction

1.1. Water needs

Globally, a significant increase in water needs has been recorded in the last century, and thus an intensification of water withdrawal for domestic, agricultural and industrial sectors (FAO, 2016). However, while world population increased 4.4 times, water withdrawal increased 7.3 times over the last century. Thus, global water withdrawal increased 1.7 times faster than world population.

The largest increase in water withdrawal took place between 1950 and 1960 (4.2 percent per year), while it was only just 0.5 percent per year during the period 2000-2010 (fig. 1a).

At global level, the withdrawal ratios are 69 percent agricultural, 12 percent municipal and 19 percent industrial. These numbers, however, are biased strongly by the few countries, which have very high water withdrawals. The water withdrawal ratios, indeed, vary much between regions, going from 91, 7 and 2 percent for agricultural, municipal and industrial water withdrawal respectively in South Asia to 5, 23 and 73 percent respectively in Western Europe (FAO, 2016).

The importance of agricultural water withdrawal is highly dependent on both climate and the place of agriculture in the economy. Figure 1b shows the water withdrawal ratios by continent, where the agricultural part varies from more than

zazione di alcuni pozzi. Un uso combinato di Tomografie Elettriche (ETR) e sondaggi Elettromagnetici nel Dominio del Tempo (TDEM) ha permesso di rappresentare la continuità e la profondità della parte più alta dei depositi quaternari, ospitanti gli acquiferi posti a minore profondità, e di scegliere la zona più adatta da un punto di vista idrogeologico.

Parole chiave: *sovrasfruttamento, acque sotterranee, abbassamento del livello piezometrico, mitigazione, Italia.*

80 percent in Africa and Asia to just over 20 percent in Europe.

1.2. Groundwater resources

Although globally the water demand can be met by surface water availability (i.e., water in rivers, lakes and reservoirs), in regions with frequent water stress and large aquifer systems groundwater is often used as an additional water source (Wada et al 2010). Compared with surface water, groundwater use often brings large economic benefits per unit volume, because of ready local availability, high drought reliability and generally good quality requiring minimal treatment (Burke & Moench 2000).

Some areas are highly dependent on groundwater; in example in Mexico City, one of the world most populated city, there is no nearby surface water and 95% of the population uses groundwater for all the water needs. In Denmark 99% of the drinking water of the entire country comes solely from groundwater (IGRAC, 2018).

Intensive groundwater abstraction commenced from the 1950's following major advances in geological knowledge, waterwell drilling and pump technology. Based on estimates at country level (IGRAC, 2018; Margat, 2008; Siebert *et al.*, 2010; FAO. 2016) the world's aggregated groundwater abstraction as per 2010 is estimated to be approximately 1,000 km^3 per year, of which about 67% is used for irrigation, 22% for domestic purposes and 11% for industry. The global groundwater abstraction rate has at least tripled over the last 50 years and is still increasing at an annual rate of between 1% and 2% (Van der Gun, 2012).

1.3. The concept of overexploitation

If groundwater abstraction exceeds natural groundwater recharge for extensive areas and long time, overexploitation or persistent groundwater depletion can occur (Gleeson *et al.*, 2010). Overexploitation may be defined as the situation in which, for some years, average aquifer abstraction rate is greater than, or close to the average recharge rate (Custodio 2000). However, the rate and extent of recharge areas are often very uncertain, and they may be modified by human activities and aquifer development. In practice, an aquifer is often considered as overexploited when some persistent negative results of aquifer development are felt or perceived, such as a continuous water-level drawdown, progressive water-quality deterioration, increase of abstraction cost, or ecological damage (Custodio 2000).

According to an estimate, 20% of the world's aquifers are over-exploited (Gleeson *et al.*, 2012; WWAP, 2015). Groundwa-

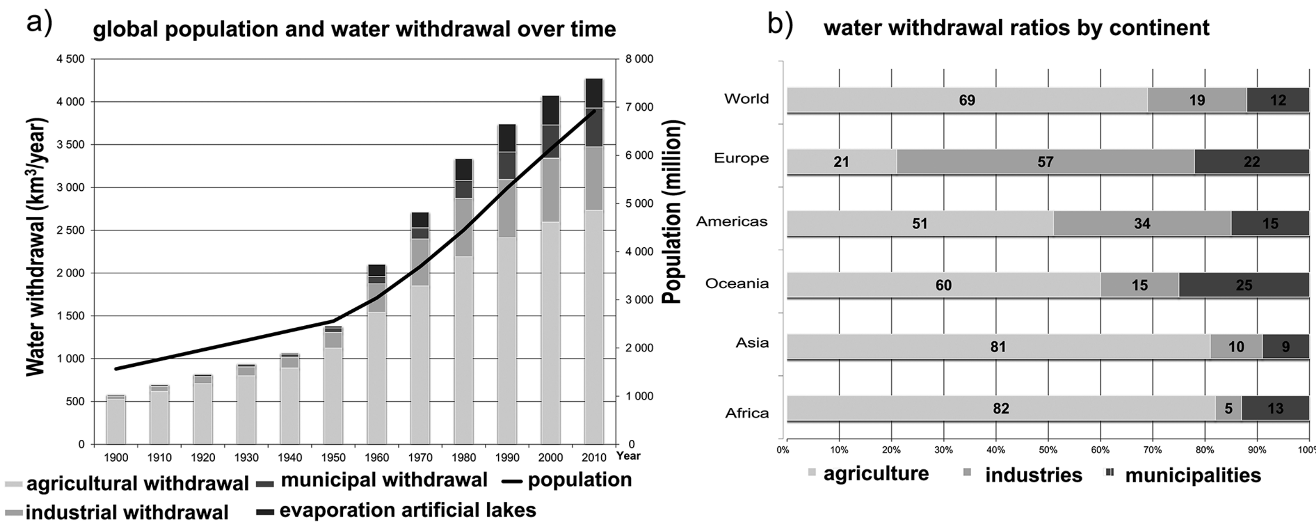

Fig. 1. a) Global population and water withdrawal over time. Three types of water withdrawal are distinguished: agricultural (including irrigation, livestock and aquaculture), municipal (including domestic) and industrial water withdrawal. b) Water withdrawal ratios by continent (FAO, 2016). *Water that evaporates from artificial lakes or reservoirs associated with dams is considered as a fourth type of anthropogenic water use.*
A) Popolazione globale e prelievi d'acqua nel tempo. Sono distinte tre tipologie di prelievi di acqua: agricolo (include irrigazione, allevamento e acquacoltura), civile (incluso uso domestico) e industriale. b) Percentuali di prelievi di acqua per continente (FAO, 2016). Le acque che evaporano da laghi artificiali o bacini associati a dighe sono considerate come un quarto tipo di uso antropico delle acque.

ter overexploitation situation are described in all the continents (Dijon & Custodio 1992, Johnson 1993, Uchuya 1993, Avanzini *et al.* 1997, Bromley *et al.* 2001, Esteller & Diaz-Delgado 2002, Kallioras *et al.* 2010, Ambrosio *et al.* 2009). Overexploitation leads to serious consequences such as land subsidence and saltwater intrusion in coastal areas (USGS, 2013). Land subsidence occurs when groundwater has been over-exploited from porous sediments, such as fine-grained materials. It generally results in substantial damage, including loss of ground surface altitude, cracking of buildings, failure of underground pipelines (Huang *et al.* 2012). Occurrences of land subsidence have been globally reported, such as Italy (Teatini *et al.* 2005; Sappa *et al.*, 2005), Spain (Molina *et al.* 2009), USA (Holzer and Galloway 2005), Mexico (Ortiz-Zamora and Ortega-Guerrero 2010), India (Sahu and Sikdar 2011), Thailand (Phienwej *et al.* 2006), China (Li *et al.* 2006; Shi *et al.* 2007).

Moreover the lowering of groundwater levels can have devastating effects on natural streamflow, groundwater fed wetlands and related ecosystems (WADA *et al.* 2010), with significant impacts on local economies and human well-being (WWAP, 2015).

2. The study area: the Maggiore Valley wellfield

The Maggiore Valley study area was analysed because it was considered as a clear example of overexploitation in Italy. This area is located in Piedmont, NW Italy. It is generally hilly and forms part of the Monferrato Hills range.

The Maggiore Valley wellfield consists of more than 40 wells (De Luca *et al.* 2018), concentrated in a very limited area (fig. 2), and it has a strategic role in Piedmont, because it provides drinking water to more than 43 municipalities. The most important town is Asti, with about 76.000 inhabitants.

Most of the wells are located in Maggiore Valley, but also the Traversola Valley is interested although at a lesser extent. Thus in the following, the wellfields will be defined as Maggiore Valley wellfield.

2.1. Hydrogeologic setting of the study area

The exploited aquifers of Maggiore Valley wellfield are represented by confined and semiconfined aquifers in the Asti Sands (Pliocene) (fig. 4a). This hydrogeologic unit consists of marine sandy sediments, alternated with lenses of fine sand, sandy gravel, clayey sand, silty-sandy and silty-clayey levels with very low permeability. The alternation between sediments with a good permeability and sediments with a scarce permeability creates the conditions for a multi-layered aquifer system. In this system, the various aquifers can intercommunicate through semi-permeable levels.

The thickness of the Asti Sands ranges between 150 and 200 m at Maggiore Valley. This thickness decrease eastward and southward. Under the Poirino Plateau, located westward, the thickness increase (in the Po Plain also more than 400 m). Previous pumping tests indicated a hydraulic conductivity in Asti sands of about 3.10^{-4} m/s (Ajassa *et al.* 2011).

The Asti Sands are located on the top of the Lugagnano Clay unit (Pliocene). It consists of sandy-marly clays and, having a very low or negligible permeability, represents an aquiclude.

The main groundwater flow direction of Pliocene marine aquifer is from west to east. In correspondence to Maggiore Valley wellfield, the piezometric surface highlights a deep cone of depression (fig. 2).

While in the north of the study area the depth of the water table ranges between +6 m above ground level (artesian area), in the

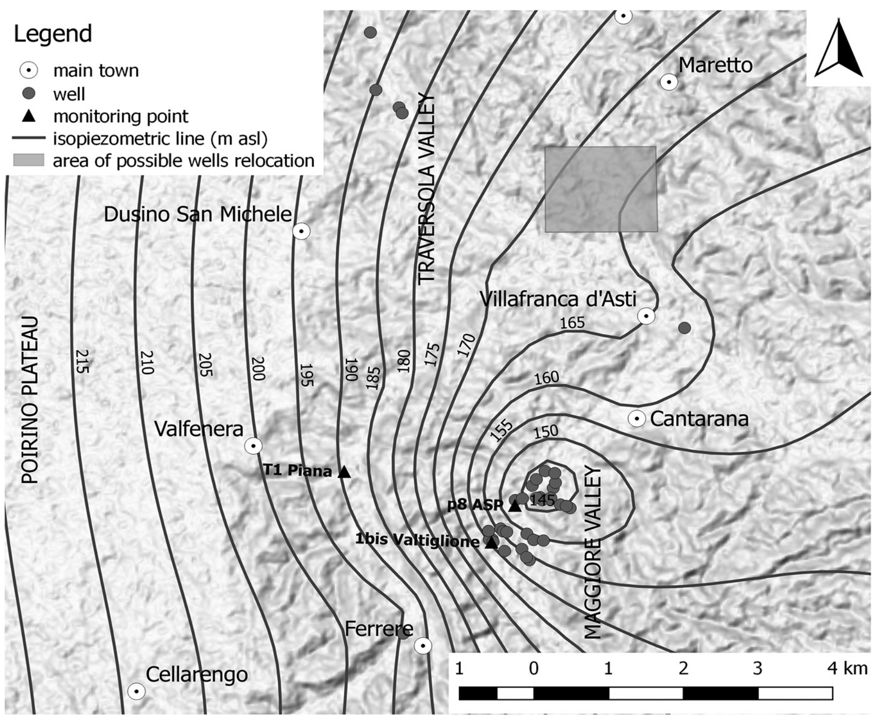

Fig. 2. Location of the study area. The piezometric map is referred to April-June 2013.
Ubicazione dell'area di studio. La carta piezometrica è riferita ad aprile-giugno 2013.

center of the cone of depression the piezometric levels reached –50 m below ground level.

More details about the hydrogeologic setting at a regional scale can be found in Lasagna *et al.* (2014) and De Luca *et al.* (2018).

2.2. Past groundwater withdrawals

The marine Pliocene aquifer was exploited intensively since the early XX century. However, while at the beginning of the 1900 the groundwater withdrawal was about some L/s, it gradually increased up to about 600 L/s (fig. 3). As an example, over the period 1996-2009, the extraction rate increased from 13.4 to 14.4 Mm^3/year (Lasagna *et al.* 2014).

This situation created an overexploitation of the aquifer, revealed by: i) a significant decrease of the piezometric level; ii) a reduction of the artesian area located in the north of the study area.

In the recent years (2000-2010), some monitoring wells in the Maggiore Valley recorded a yearly drawdown of about 0.8 m. From the beginning of the XX century until 2012, the decrease of the piezometric level in some areas was about 50 m (Lasagna *et al.* 2014, De Luca *et al.* 2018).

3. Mitigation activities

The exploited confined aquifer is the only source of water for human consumption in the area. Thus, the Maggiore Valley wellfield is considered of regional importance. These are the reasons why certain actions have been launched to protect and preserve the aquifer. More specifically, the managers of the Integrated Water Service (EGATO5 Astigiano Monferrato), with the advice of the Earth Sciences Department (University of Turin), put into effect the following activities aimed at the protection of groundwater resources.

3.1. Hydrogeology reconstruction of the study area

The hydrogeological reconstruction of the Maggiore Valley and surrounding areas was the first step. Indeed any effective strategy for the aquifers' protection must be based on a good knowledge of the hydrogeological setting and the current state of exploitation and use of groundwater resource. Particularly, the main analysed elements for the study areas were the lithostratigraphic structure, the hydrogeological parameters, the piezometric maps, the recharge features, the water quality, the changes in the piezometric levels over time, the number and type of wells, the withdrawals from the wells. A description of the hydrogeologic setting of Maggiore Valley and surrounding and related information can be found in the previous paragraphs and more in detail Lasagna *et al.* (2014).

3.2. Simulation of new groundwater withdrawal configurations

In order to mitigate the overexploitation situation in the Maggiore Valley wellfield, a different quantitative management of the groundwater resources was necessary. Thus, a groundwater flow model was implemented (fig. 4b), to analyse the aquifer response to various pumping strategies and to determine sustainable solutions.

After the calibration of a preliminary groundwater flow simulation, four different scenarios were simulated to explore the best option to mitigate the problem. The scenarios simulated a groundwater extraction decrease, a redistribution of the well location and a combination of both of them. More specifically, a withdrawal reduction of 110 l/s (20% of current water withdrawal) and 150 L/s were simulated. In Figure 5 two possible scenarios are reported. In Scenario 3 a relocation of 8 wells from Maggiore valley wellfield to northern sectors are simulated. In Scenario 4 a water withdrawal re-

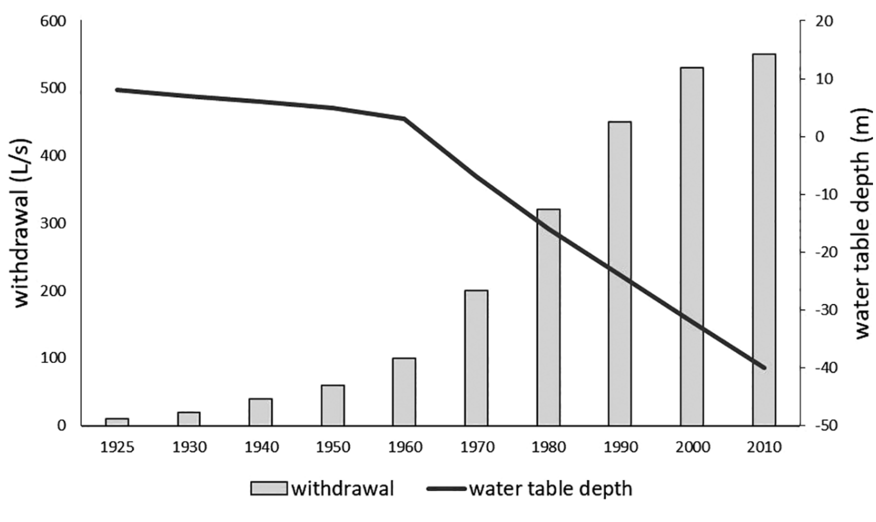

Fig. 3. Water table depth vs withdrawal in Maggiore Valley wellfield in the years 1925-2010 (data from ATO5, 2016).
Profondità della superficie piezometrica e prelievi dal campo pozzi della Val Maggiore nel periodo 1925-2010 (dati tratti da ATO5, 2016).

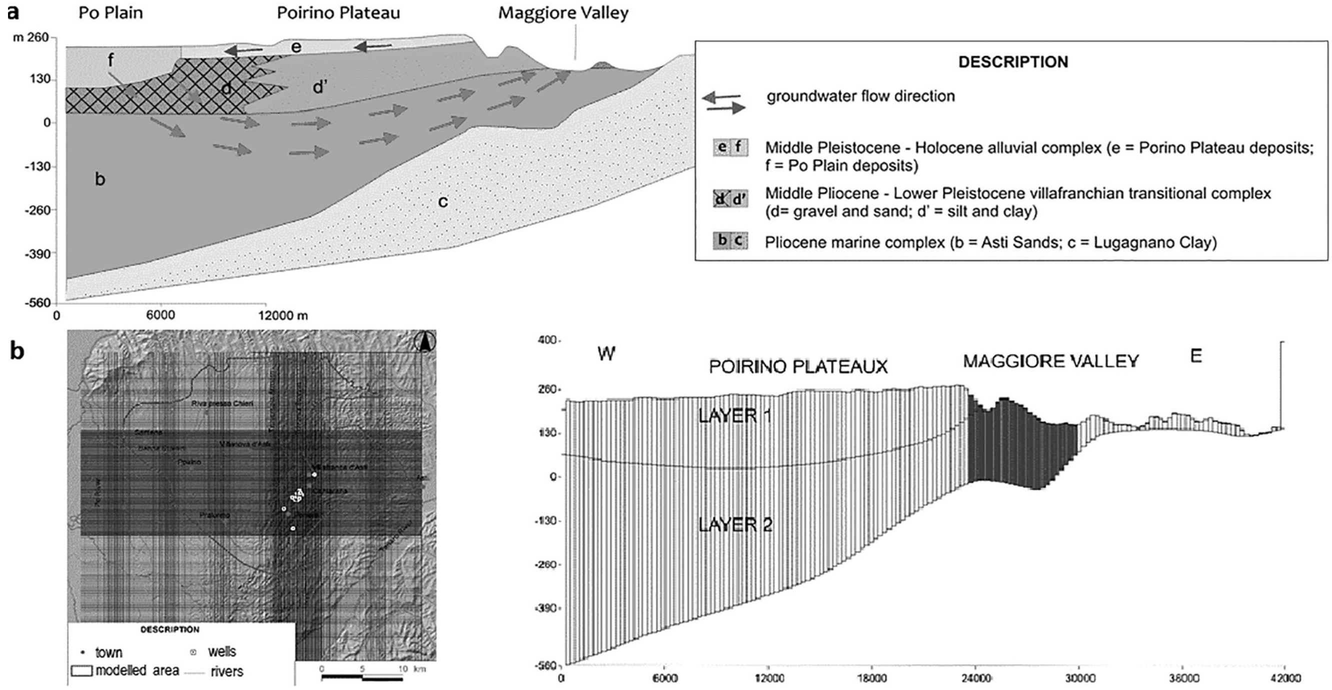

Fig. 4. a) Schematic hydrogeological cross section of the Maggiore Valley and surrounding areas. The aquifer exploited by the Maggiore Valley wellfield is represented by the Pliocene marine sandy complex. b) Discretization of the study area in plant and cross section for the implementation of the mathematical model. A grid mesh refinement was used within the Maggiore Valley wellfield area.
a) Sezione idrogeologica schematica della Val Maggiore e delle aree circostanti. L'acquifero sfruttato dal campo pozzi della Val Maggiore è rappresentato dal complesso delle sabbie marine del Pliocene. b) Discretizzazione dell'area di studio in pianta e sezione per l'implementazione del modello matematico. In corrispondenza del campo pozzi della Val Maggiore è stata utilizzata una griglia più fitta.

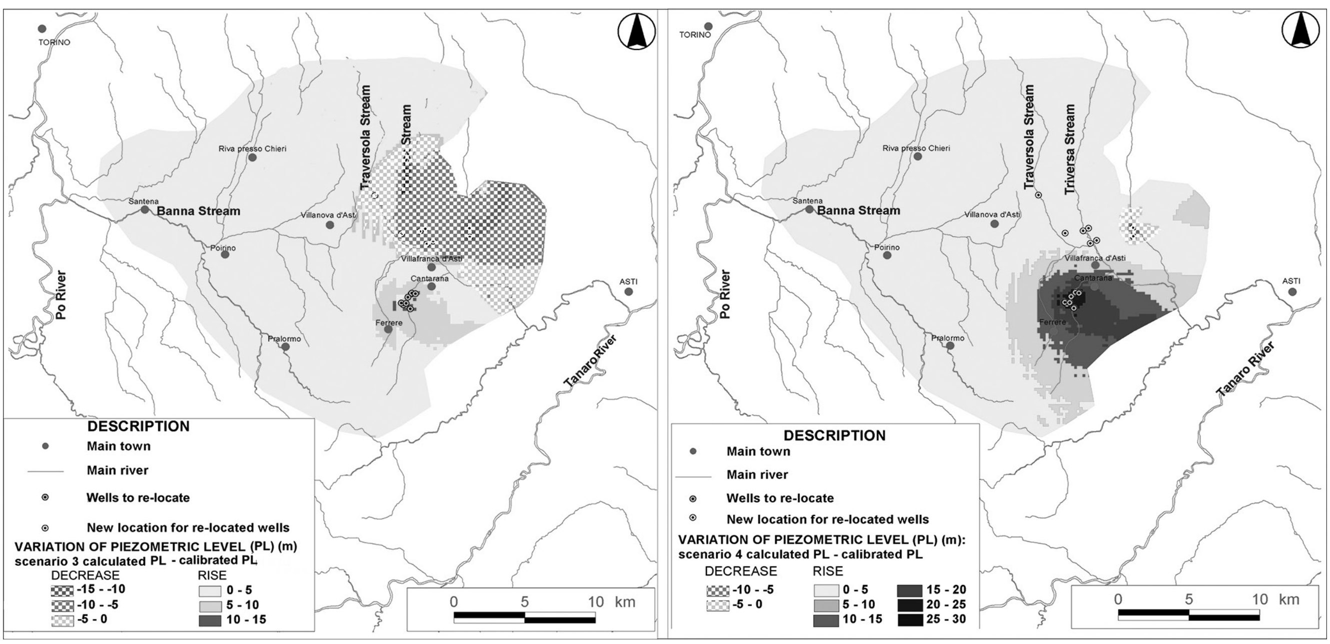

Fig. 5. Piezometric level changes evaluated with a groundwater flow model (modified from Lasagna *et al.*, 2014). Examples of new withdrawal configurations in the Maggiore Valley. Scenario 3 represents the results following a relocation of 8 wells from Maggiore valley wellfield to northern sectors. Scenario 4 analyses a water withdrawal reduction of 110 L/s in the Maggiore Valley wellfield plus a concurrent relocation of 8 wells.
Variazioni del livello piezometrico valutate con un modello di flusso idrico sotterraneo (modificato da Lasagna et al., 2014). Esempi di nuove configurazioni di prelievo in Val Maggiore. Lo scenario 3 rappresenta il risultato dopo la rilocalizzazione di 8 pozzi dal campo pozzi della val Maggiore a settori più settentrionali. Lo scenario 4 analizza una riduzione degli emungimenti di 10 l/s nel campo pozzi della Val Maggiore oltre alla contemporanea rilocalizzazione di 8 pozzi.

duction of 110 L/s in the Maggiore Valley wellfield plus a concurrent relocation of 8 wells are modelled.

The results of all the simulations highlighted a positive impact of the piezometric level, in some instances, up to 30 m. Particularly, the relocation of wells in nearby areas, with a concurrent water withdrawal reduction, proved to be an appropriate solution. The results of the simulation model are more widely described in Lasagna *et al.* (2014).

3.3. Strategies and interventions for groundwater preservation

In order to ensure the water resources necessary for users and to mitigate the overexploitation situation, the following interventions have been planned and/or realised:

- reduction of groundwater withdrawal and concurrent supplementary feed from the Monferrato Aqueduct, located north of the study area (**interconnection**);
- **relocation** of some wells of Maggiore Valley wellfield that involves a decrease of 10-25% of withdrawals in the area of the current wells.

The interconnection of Maggiore Valley aqueduct with the Monferrato aqueduct consists of a 17 km long pipe. It guarantees a regular water supply to the population of about 100 L/s. The interconnection was completed and became operative in 2012. Moreover, a reduction of groundwater withdrawal in the Maggiore Valley wellfield was achieved. These actions led to a partial rising of the piezometric level, up to 8 m from 2012 and 2016. In this period some decreases of the piezometric level were registered, especially in the summertime (i.e. summer 2015) due to climatic conditions that required high water consumption.

In Figure 6 the variation of the water table depth vs groundwater withdrawal is reported. More specifically, it is possible to observe a reduction of groundwater withdrawal in the Maggiore Valley wellfield (blue column) up to about 12 Mm^3/year. Moreover, the additional supply from the interconnection, starting from 2012, is reported (green column). The red line represents the water table depth that decreases starting from 2012 of about 8 m (from –45 m bgl to –37m bgl).

In Figure 7 a detailed trend of the water table depth in three piezometers located in the Maggiore Valley and surrounding areas is reported. More specifically the modification of the groundwater level is described starting from the year of the interconnection with Monferrato aqueduct. In the figure, it is possible to observe a decreasing of the water table depth, with different values in the three piezometers. In the piezometers T1 Piana and p8 ASP, located in the wellfield or in the surrounding, a high increase of the piezometric level can be observed. In the piezometer T1 Piana the decrease is about 12 m from June 2012 and October 2014, while in the piezometer p8 ASP is about 10 m from June 2012 and February 2016. The decrease of the water table depth is less evident in the piezometer 1bis Valtiglione, that is located far from the wellfield area.

In addition to the interconnection, a study was performed to identify the best area for wells relocation. More specifically, geophysical surveys were conducted within the Maggiore and Traversola Valleys, to depict the depth and lateral continuity of the uppermost part of the Quaternary deposits, hosting the near surface aquifers. Combined use of Electric Resistivity Tomography (ERT) sections and Time Domain Electromagnetic (TDEM) soundings allowed obtaining a pseudo-3D representation of the subsurface.

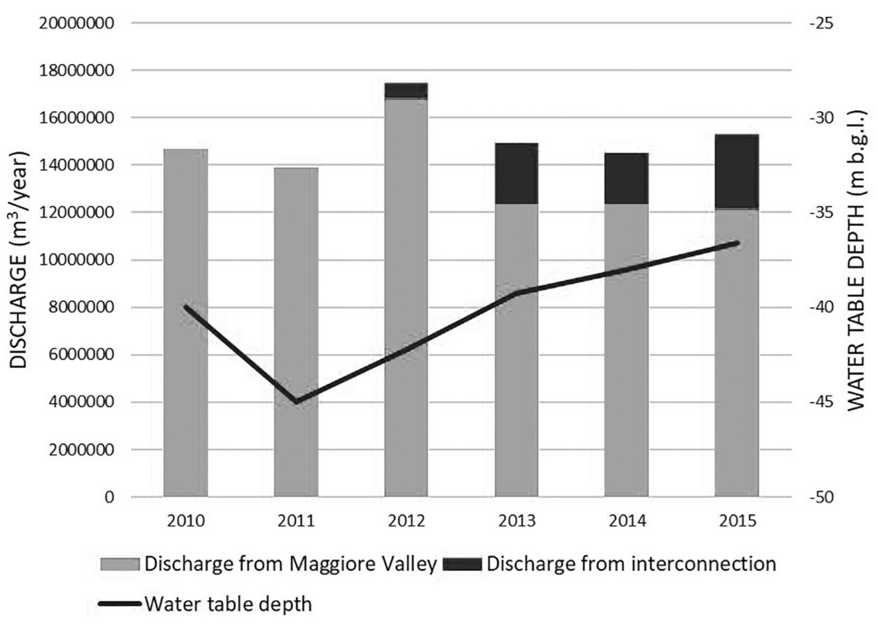

Fig. 6. Variation of the water table depth vs groundwater withdrawal. The total withdrawal is divided according to the source (Maggiore Valley wellfield and interconnection). The water table depth is the average of the entire Maggiore Valley.

Variazione della profondità del livello piezometrico e delle portate di prelievo. Il prelievo totale è suddiviso in funzione della provenienza dell'acqua emunta (campo pozzi della Val Maggiore e interconnessione). La profondità del livello piezometrico rappresenta la media dei livelli piezometrici dell'intera Val Maggiore.

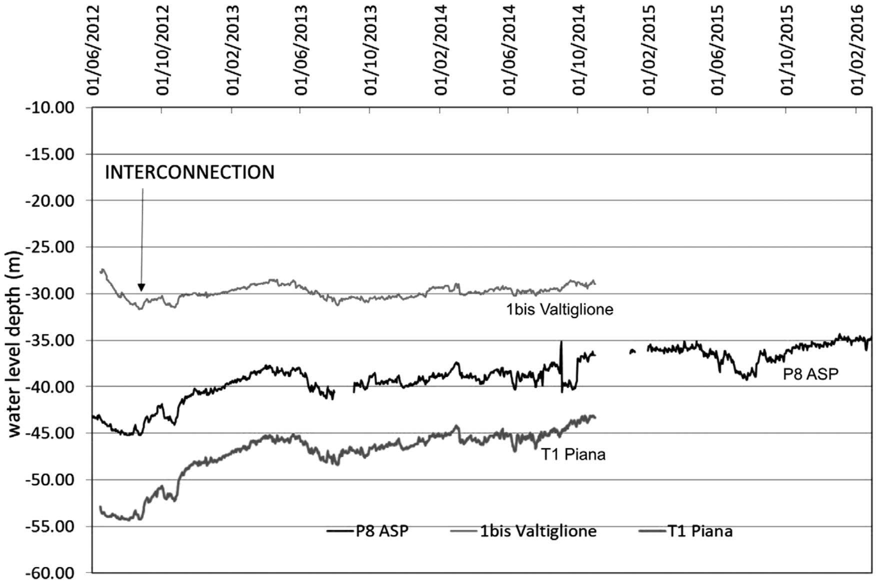

Fig. 7. Modification of the water table depth in three piezometers in the Maggiore Valley and surrounding areas after the interconnection with Monferrato aqueduct. Piezometer P8 ASP represents the reference data of groundwater level, due to its location in Maggiore Valley.
Variazione della profondità del livello piezometrico in tre piezometri della Val Maggiore e delle aree circostanti dopo le interconnessioni con l'acquedotto del Monferrato. Il piezometro P8 ASP rappresenta il livello piezometrico di riferimento ubicato in Val Maggiore.

Two areas were studied with geophysical survey (Villafranca and Dusino San Michele) that represent the most suitable zones from a hydrogeological and logistical point of view. Indeed, there areas are located in the artesian areas, north and west of Maggiore Valley respectively. Moreover they are suitable for a new wellfield because in proximity to existing pipes, with high expansion capabilities, and for the possibility of building a new treatment plant.

In Villafranca area, the aquifer formation is more laterally continuous, whereas in Dusino San Michele area it is discontinuous, laterally less extended and locally missing. Thus even if both of studied areas show a possible aquifer layer, on the basis of geophysical surveys (fig. 8), the Villafranca area was chosen for future relocation of some water wells.

At last, a pilot well will be drilled here in 2019 to verify the hydrogeological features and the productivity of the aquifer identified by the geophysical surveys.

4. Discussion and conclusions

Maggiore Valley wellfield in NW Italy is a typical example of groundwater overexploitation. The increasing water demand from the beginning of the XX century up to now created the condition for a high decrease of the piezometric level (in some areas from + 6 m a.g.l. to – 50 m b.g.l.) and a large reduction of an artesian area, located at the north of the study area.

Because the exploited aquifer is the only source of water for human

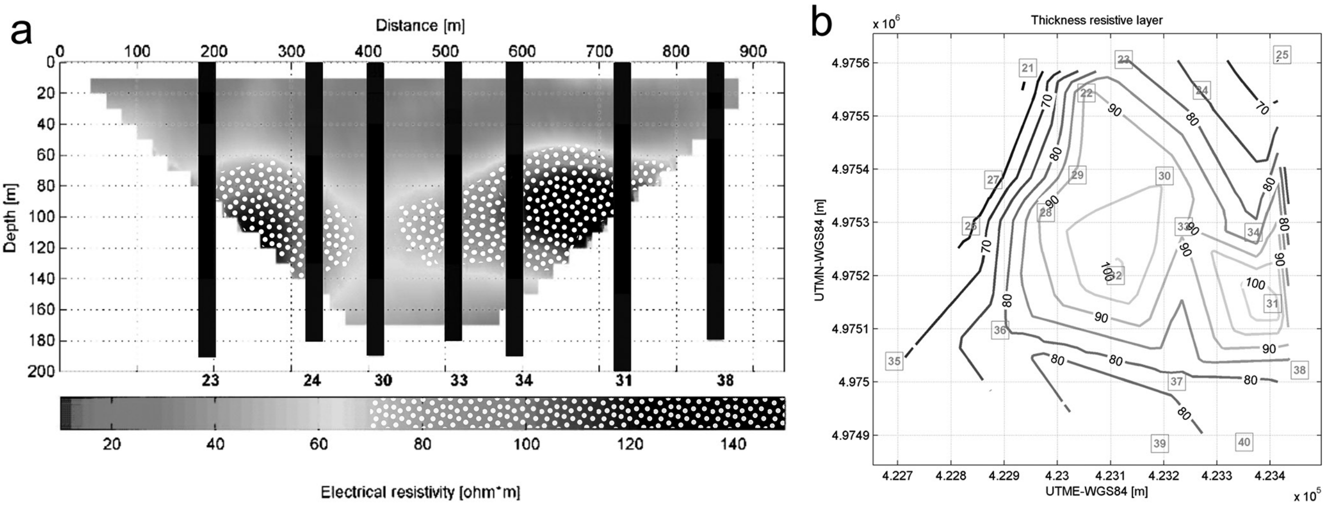

Fig. 8. a) ERT results in Villafranca area and location of the TDEM soundings nearest to the resistivity section (number at the bottom of each column indicates the name of the sounding). b) Maps of the thickness of resistive layer, identified as the aquifer formation in the Villafranca area (modified from De Luca *et al.*, 2018).
a) Risultati di una tomografia elettrica (ERT) nell'area di Villafranca e ubicazione dei TDEM più vicini alla sezione di resistività (il numero alla base di ogni colonna indica il nome del sondaggio). b) Carta degli spessori dei livelli resistivi, identificati come la formazione acquifera dell'area di Villafranca (modificato da De Luca et al., 2018).

consumption in the area, numerous actions have been launched to protect and preserve it.

The main activities concerned the reduction of groundwater withdrawal, with a concurrent supplementary feed from the Monferrato Aqueduct, located north of the study area, and a relocation of some wells of Maggiore Valley wellfield.

To study the consequences of a different quantitative management of the groundwater resources, a groundwater flow model was implemented. It permitted to analyse the aquifer response to various pumping strategies and to determine the most sustainable solutions.

The reduction of groundwater withdrawal plus the interconnection with Monferrato aqueduct led to a partial rising of the piezometric level, up to 8 m from 2012 and 2016.

Moreover, a geophysical study was performed to identify the best area for wells relocation. The Villafranca area, located north to Maggiore Valley wellfield, was chosen for future relocation of some water wells, because it is located in the artesian areas and the aquifer formation is resulted more laterally continuous respect to other studied areas. Additionally this area is suitable also for logistic reasons (in proximity to existing pipes and with high expansion capabilities).

The creation of a new wellfield represents a guarantee for the continuity of the water service distribution in a medium-long term context. Moreover, it is essential because it allows to the piezometric level of Maggiore Valley wellfield to rise. A further decrease of the water table, indeed, would have rendered some of the wells unusable.

At last, a pilot well will be drilled here in 2019 to verify the hydrogeological features and the productivity of the aquifer identified by the geophysical surveys.

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