

# Modeling groundwater/surface-water interactions and their effects on hydraulic barriers, the case of the industrial area of Mantua (Italy)

## *Modellazione delle interazioni tra acque superficiali e sotterranee e loro effetto sulle barriere idrauliche, il caso dell'area industriale di Mantova*

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### Riassunto

La città di Mantova è un buon esempio di area urbana con un intricato sistema idrico superficiale, che determina complesse interazioni tra acque superficiali e sotterranee. In tale contesto è situato il Sito di Interesse Nazionale (SIN) “Laghi di Mantova e Polo Chimico”, dove un’intensa attività di pompaggio viene svolta attraverso pozzi industriali e barriere idrauliche. Al fine di stabilire le interazioni tra le acque sotterranee e il sistema idrico superficiale, valutandone la relazione con le attività di prelievo, è stato realizzato un modello numerico di flusso in transitorio (Gennaio 2016 - Dicembre 2018), utilizzando MODFLOW-2005 e il pacchetto Streamflow-Routing (SFR2), adottando un approccio partecipativo. I risultati mostrano come, in funzione delle condizioni di minimo/massimo idrogeologico e dei valori di portata dei canali superficiali, la relazione tra acque superficiali e sotterranee possa variare nel corso dell’anno, influenzando anche il funzionamento delle barriere idrauliche. I decisori potranno utilizzare in futuro il modello calibrato per garantire una gestione ottimale delle attività di pompaggio all’interno del SIN.

### Abstract

*The town of Mantua is a good example of an urban area with an intricate surface water system leading to complex groundwater/surface-water interactions. In this context, the Site of National Interest (SIN) “Laghi di Mantova e Polo Chimico”, is characterized by intense pumping activity by means of industrial wells and hydraulic barriers. In order to establish the interactions between groundwater and the surface water system, evaluating their relation with the pumping activities, a transient groundwater numerical model was developed (January 2016 - December 2018) using MODFLOW-2005 and the Streamflow-Routing (SFR2) package, following a participatory approach. Results show how, depending on the minimum/maximum groundwater conditions and the discharge values of the surface channels, the relation between groundwater/surface-waters can vary during the year, also affecting the operation of the hydraulic barriers. The stakeholders could use the calibrated model in the future to ensure optimal management of the pumping activities within the SIN.*

## Introduction

In recent years, interest in evaluating the interactions between groundwater and surface waters increased (Lewandowski et al. 2020). Particularly, it is well recognized that these components constitute a surface-subsurface continuum (Dahl et al. 2007). To protect and properly manage water resources, it becomes necessary to comprehend and quantify exchange processes and pathways between groundwater and surface water (Kalbus et al. 2006). This aspect is more important when well pumping and human activities can alter this relation, influencing the amount and direction of groundwater exchanged between these two water body types (Barlow and Leake 2012; Stefania et al. 2018). The town of Mantua is a good example for assessing complex groundwater/surface-water interactions and their role on pumping wells since: 1) it is covered by an intricate surface water network and 2) it hosts the Site of National Interest (SIN) “Laghi di Mantova e Polo Chimico” where numerous companies have wells and hydraulic barriers that abstract large amounts of groundwater. This work presents a 3D numerical model aimed at a) providing a detailed reconstruction of the complex groundwater/surface-water interactions and b) simulating the global pumping in the SIN area and its relation with groundwater/surface-water interactions. The model was realized in transient conditions using MODFLOW-2005 (Harbaugh 2005), the SFR2 Package

(Niswonger and Prudic 2005) to reproduce the surface water network and MODPATH 7 (Pollock 2016) to trace the groundwater flowpaths. To actively engage with stakeholders, thus involving them in conceptualization, suggesting scenarios and proposing management solutions (Castilla-Rho 2017), the model was realized adopting a participatory modelling approach. To do so, information on the modeling workflow was regularly shared with the companies located within the SIN, through the organization of five technical committees.

## Materials and Methods

### Study Area

Mantua has historically developed a complex system for surface waters management that has always protected the city against flooding and guaranteed navigation in the main lakes and rivers. In the early 1200s, the city was surrounded by four artificial lakes: Lake Superiore, Lake di Mezzo, Lake Inferiore and Lake Paiolo. The Mantua lakes are fed by the Mincio River, which flows from Lake Garda to the Po River. In the 18<sup>th</sup> century, to favour urban development, the Lake Paiolo was drained. Nowadays, three lakes (Superiore, di Mezzo and Inferiore) and numerous hydraulic works, including draining channels, characterize the local water system (Fig. 1). The surface water network includes a vast number of manmade channels used for agriculture and land

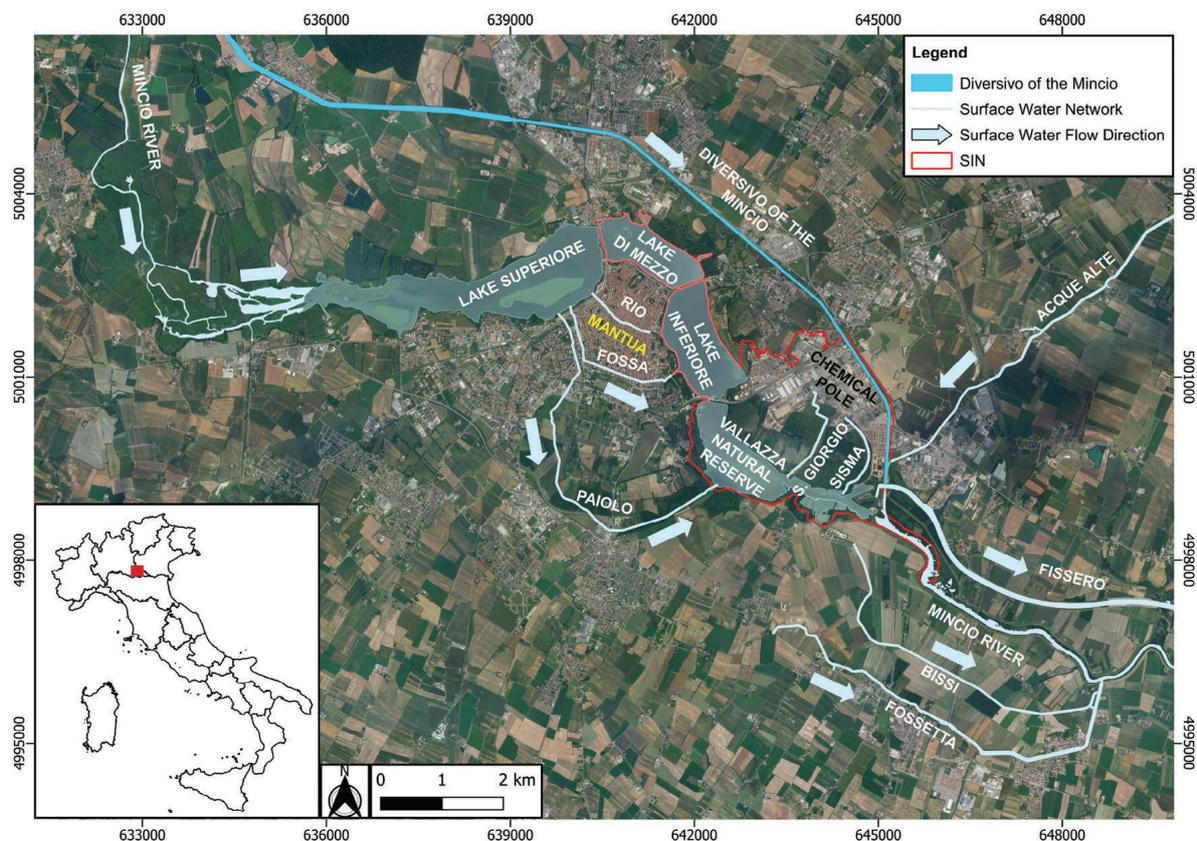


Fig. 1 - Geographical setting of the study area and main elements of the surface water network. Grid coordinates are expressed in WGS84 / UTM zone 32 N (EPSG: 32632).

Fig. 1 - Inquadramento geografico dell'area di studio e principali elementi del reticolo idrico superficiale. Le coordinate della griglia sono espresse in WGS84 / UTM zona 32 N (EPSG: 32632).

reclamation operations. The Diversivo of the Mincio acts as the most important draining channel, collecting excess water from the Mincio and other surface channels, thus keeping the hydraulic head of the lakes regulated and preventing flooding episodes. Downstream of Lake Inferiore, it is located the Vallazza Natural Reserve, an area of wetlands of high environmental interest. The SIN is placed between the left side of lakes di Mezzo and Inferiore and the Diversivo: thus, due to its proximity to the Vallazza Natural Reserve, it deserves particular attention from the hydrogeologic point of view.

### Conceptual model

#### Hydrogeologic Setting

To reconstruct the lithostratigraphy of the area, 1756 lithologs were collected, and used, from three different databases: ARPA (Regional Environmental Protection Agency), with 1194 logs located within the SIN; CASPITA (Regione Lombardia 2016), with 468 logs; TANGRAM (Bonomi et al. 2014), with 94 logs. The use of these 3

different databases, having different density distribution of lithologs, leads to an uneven distribution of lithostratigraphic data (Fig. 2).

Based on these data, 22 lithostratigraphic sections were realized: 14 at model scale (A-G, 1 to 7), 8 at SIN scale (H-N, 8 to 11) (Fig. 3a-3b), showing the presence of two main aquifers and an aquitard (Fig. 3c-3d):

- a shallow unconfined aquifer (20-40 m thick) mainly characterized by sandy deposits, with local presence of gravels; a complex succession of clayey lenses locally separates these deposits;
- a silt and clay aquitard at 30-40 m of depth, 10-30 m thick, separating the shallow and deep aquifers;
- a deep semiconfined aquifer (20-40 m thick) starting at 40 m of depth, mainly composed of a wide distribution of sandy deposits. Its bottom is approximately located at a depth of 80 meters, where an extended silty-clayey horizon is observable. Its hydraulic head is generally two-three meters higher than the shallowest one (ARPA Mantova 2019).

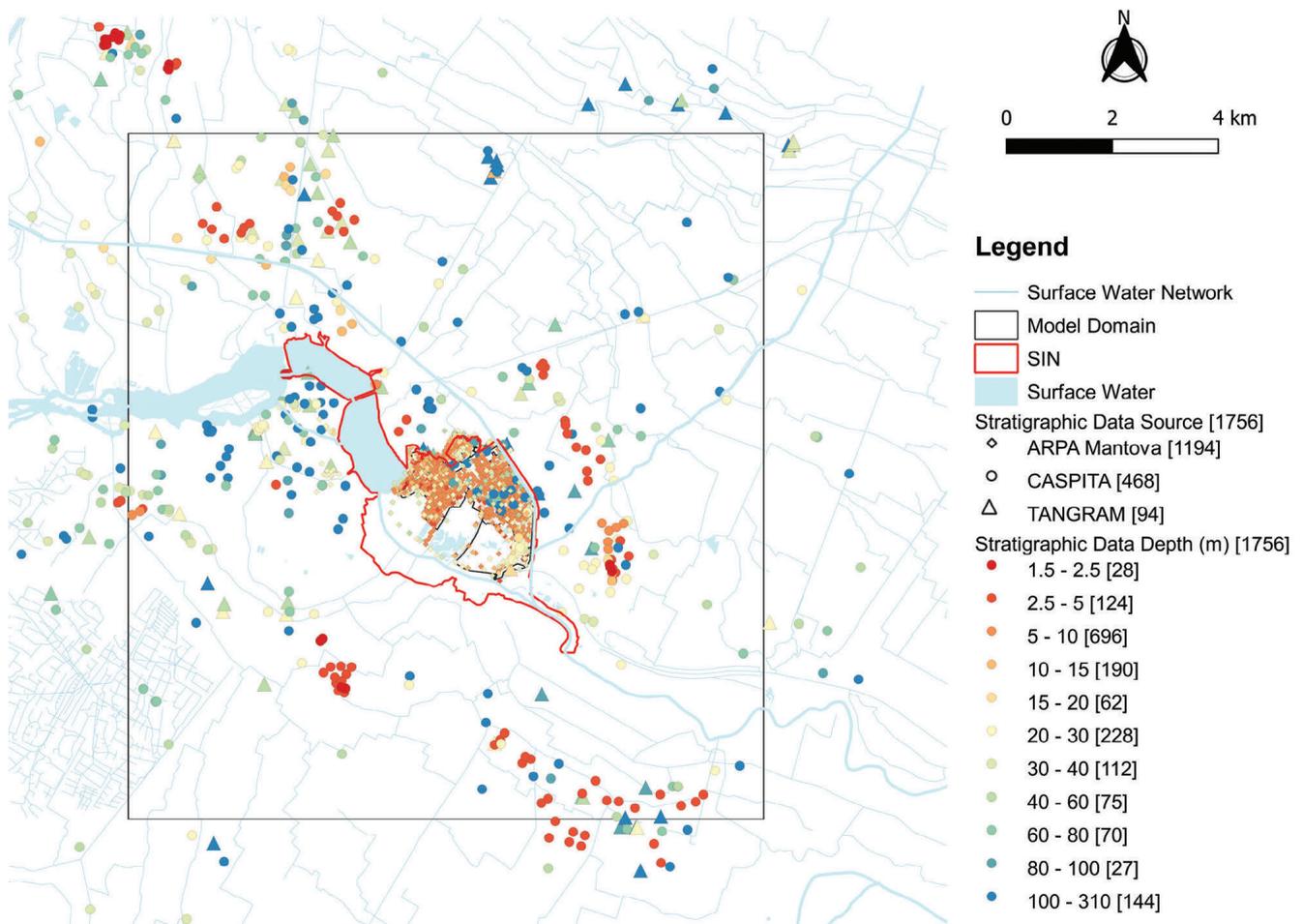


Fig. 2 - Stratigraphic data distribution inside the model area, classified according to depth.

Fig. 2 - Distribuzione delle stratigrafie presenti nell'area del modello, classificate in base alla profondità.

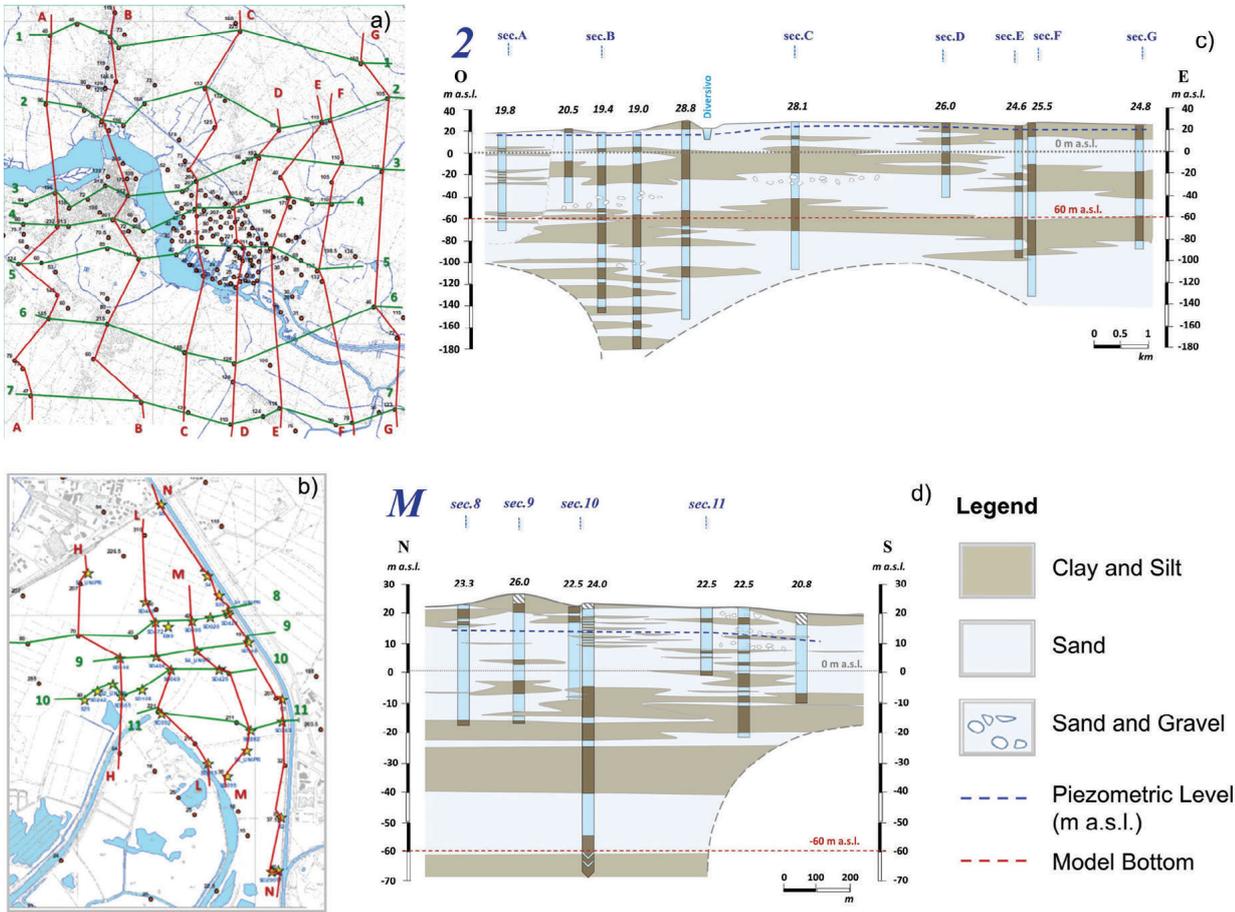


Fig. 3 - Cross sections locations at a) model scale, b) SIN scale; example of a c) W-E cross section at model scale, d) N-S cross section at SIN scale.  
 Fig. 3 - Ubicazione delle sezioni per a) scala di modello, b) scala SIN; esempio di una sezione c) O-E a scala di modello, d) N-S a scala SIN.

**Surface Water and Groundwater Systems**

The surface water network of Mantua has been progressively built over the centuries to defend the city from flooding events of the Mincio River. This human-made network of drainage and irrigation channels had altered the natural relationships between groundwater and surface water. The Diversivo is the most crucial element that guarantees hydraulic protection against flooding. Discharge values of the Diversivo were estimated for the period January 2016 - December 2018 (Fig. 4b) using monthly hydraulic head and water velocity measures at the hydrometric stations of two hydraulic sections named Brennero and Carraia (Fig. 4a). When the discharge is greater at Brennero than Carraia (flooding conditions), the Diversivo has a losing behaviour towards the aquifer (i.e. recharging the aquifer); vice versa, when the discharge is higher at Carraia (lean conditions), a gaining behaviour is identified, thus draining groundwater.

Groundwater flow direction is mainly from N-W to S-E, influenced by the lakes, the Mincio River and the numerous surface channels crossing the town (ARPA Mantova 2019). Over the entire area, the water table lies in general 5 meters below the ground level; the hydraulic head varies from 25 m a.s.l. at North to 17 m a.s.l. at South, with a minimum of 13 m a.s.l. close to Lake Inferiore (ARPA Mantova 2017). In this general framework, January and June resulted in, respectively,

a groundwater minimum and a maximum condition for all the three years analyzed.

**Well pumping**

Information about pumping wells and hydraulic barriers inside the SIN have been collected and provided by ARPA. These data concern the daily average well discharge (m<sup>3</sup>/d) for the period 2016 – 2018, well and screen depths. A total of 229 wells were considered (213 tapping the shallow and 16 the semiconfined aquifer), including 7 wells acting both as injection and extraction wells. The medium well discharge for hydraulic barrier wells is 0.48 L/s, with a maximum of 0.85 L/s. The total volumes of groundwater extracted and returned to the aquifers are reported in Table 1.

Tab. 1 - Annual discharge balance.

Tab. 1 - Bilancio annuale dei pompaggi.

Water Balance (injection and extraction wells)		
Year	Extraction (m <sup>3</sup> )	Injection (m <sup>3</sup> )
2016	4 478 178	305 552
2017	4 286 541	299 198
2018	4 214 681	304 068
Total Volume	12 979 401	908 818

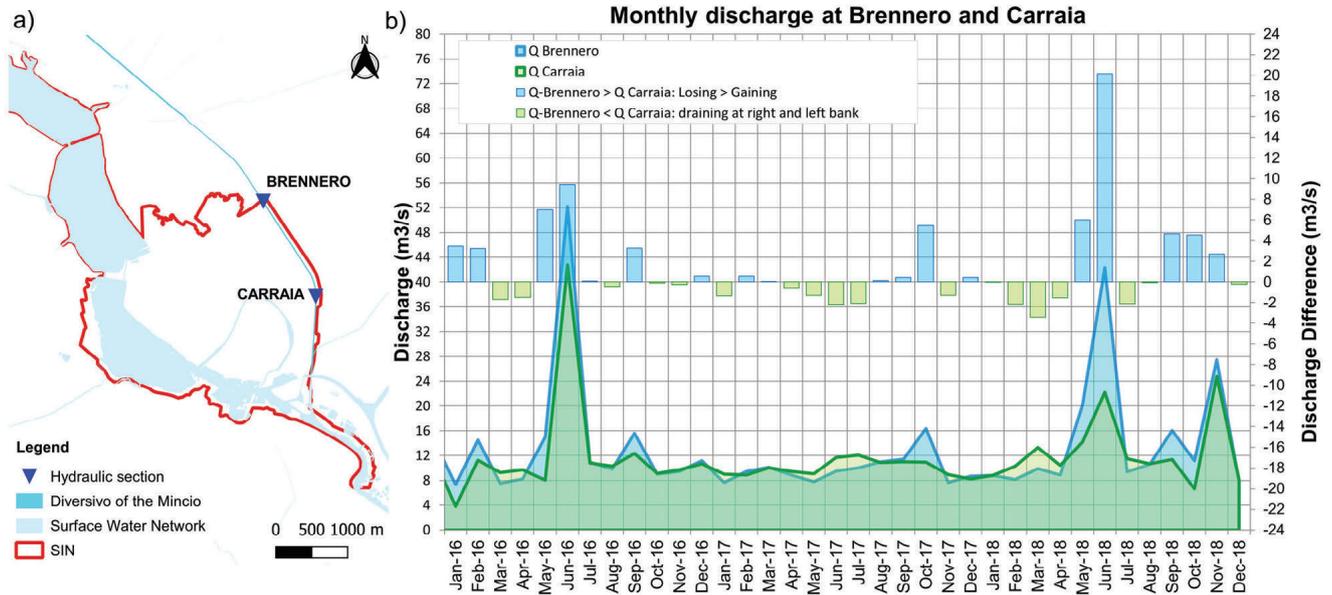


Fig. 4 - a) Location of Brennero and Carraia hydraulic sections; b) Monthly discharge at Brennero and Carraia hydraulic sections. Discharge difference indicates a losing (light blue) or draining (green) behaviour of the Diversivo.  
 Fig. 4 - a) Ubicazione delle sezioni Brennero e Carraia; b) Portate medie mensili alle sezioni Brennero e Carraia. La differenza tra le portate indica la ricarica (azzurro) o il drenaggio (verde) della falda da parte del Diversivo.

**Numerical model**

A transient numerical flow model was developed using MODFLOW-2005 (Harbaugh 2005) and Groundwater Vistas 7 (Rumbaugh and Rumbaugh 2020) as graphical user interface. The model was solved with the GMG package (Wilson and Naff 2004), analysing a 3-year period (January 2016 - December 2018) using 36 stress periods (1 per month). The initial head of the transient model has been set as a result of a training steady-state period, starting from a static piezometry.

The model domain was divided into a: (1) far-field model area, that contained all the surface water bodies controlling the groundwater flow, and a (2) near-field model area, with a grid refinement, that corresponds to the area of interest,

i.e. the SIN (Feinstein et al. 2005; Fienen et al. 2011). This approach was adopted both in the horizontal and vertical directions. Thus, the model grid (Fig. 5) has 6 277 600 cells divided into 532 rows and 472 columns, with a cell spacing ranging from 50x50 m in the far-field domain, up to 10x10 m inside the SIN. Analogously, the vertical discretization consists in 25 layers: the first 21, having a medium thickness of 2 meters, to model the shallow aquifer; the last 4 layers, having variable thicknesses from 6 to 12 meters, to model the aquitard and the semiconfined aquifer. Model bottom was set at approximately -60 m a.s.l. (80 m of depth), in correspondence with a continuous layer of low permeability deposits (Fig. 3c-3d).

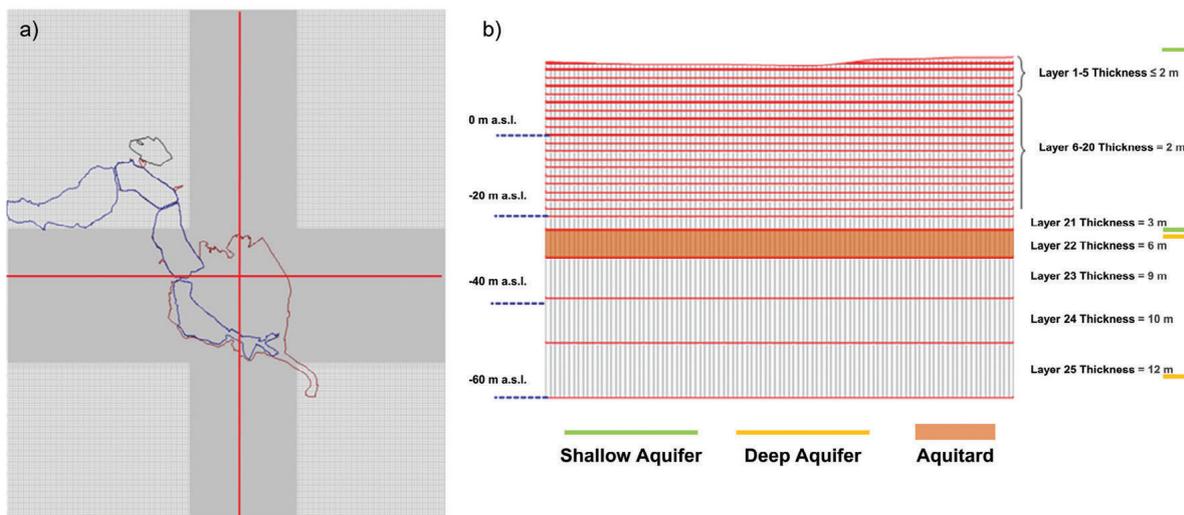


Fig. 5 - Model grid: a) map and b) cross section. The red cross in Fig. 5a points to the SIN area.  
 Fig. 5 - Griglia di calcolo del modello a) in pianta e b) in sezione. La croce rossa in Fig.5a indica l'area del SIN.

Boundary conditions (Fig. 6), used to reproduce the hydrogeologic configuration, have been represented through Neumann and Cauchy conditions:

- General Head Boundary (GHB) to model the heads at North, West and South in the study area.
- Lake (LAKE) to model Lake Superiore, Di Mezzo and Inferiore and the Vallazza Natural Reserve, thus evaluating their relation with groundwater.
- StreamFlow Routing (SFR2) to simulate, through 19 segments, the streamflow along the main channels of the hydrographic network, calculating the exchange between the surface and groundwater systems. An analysis of all the available project schemes was conducted to define the best conductance values of channels/streams, e.g., structure, geometry, materials (Lotti et al. 2021).
- Well (WEL) to model the 229 wells and hydraulic barriers within the SIN.
- Hydraulic Flow Barriers (HFB) to represent: the perimeter defense (i.e. paratie) of Mantua around Lakes di Mezzo and Inferiore (Fig. 6a); the lateral sides of Botte Sifone, an engineering work that allows the Diversivo to pass below the Fissero, thus continuing its flow towards the Mincio River; two other confinement elements inside the SIN (Fig. 6b).
- No Flow Conditions to simulate the bottom of Botte Sifone (Fig. 6c).

- Recharge (RCH): 16 zones, based on land use, were identified from the geographic database Dusaf 6.0 (Regione Lombardia 2021); their values were calculated as the contribution of precipitations, irrigations, and water network system losses. Precipitations and irrigations have been quantified using the infiltration coefficients calculated by Consorzio di Bonifica Territorio del Mincio, different for each type of irrigated area (Consorzio di Bonifica Territori Mincio 2018). Water network system losses were estimated by the companies located inside the SIN area.

As for the hydraulic conductivity, firstly, the total 1756 lithologs were numerically coded using TANGRAM (Bonomi et al. 2014), that is able to assign a percentage of textural facies to lithological units on the basis of their lithological composition (Bonomi 2009); the textural facies were defined per classes: fine-grained (sum of clays, silts and peats), medium-grained (sands) and coarse-grained (gravels and pebbles) deposits. Secondly, the coded lithologs were interpolated by ordinary kriging, using GOCAD (Geological Object Computer Aided Design, Paradigm 2009), in order to obtain continuous distribution of textural facies percentages. Thirdly, the distribution of the percentage of fine-grained sediments was transformed into distribution of hydraulic conductivity (K) values using a power law relation (Feinstein et al. 2010; Buarnè et al. 2016). Lastly, the continuous distribution of K

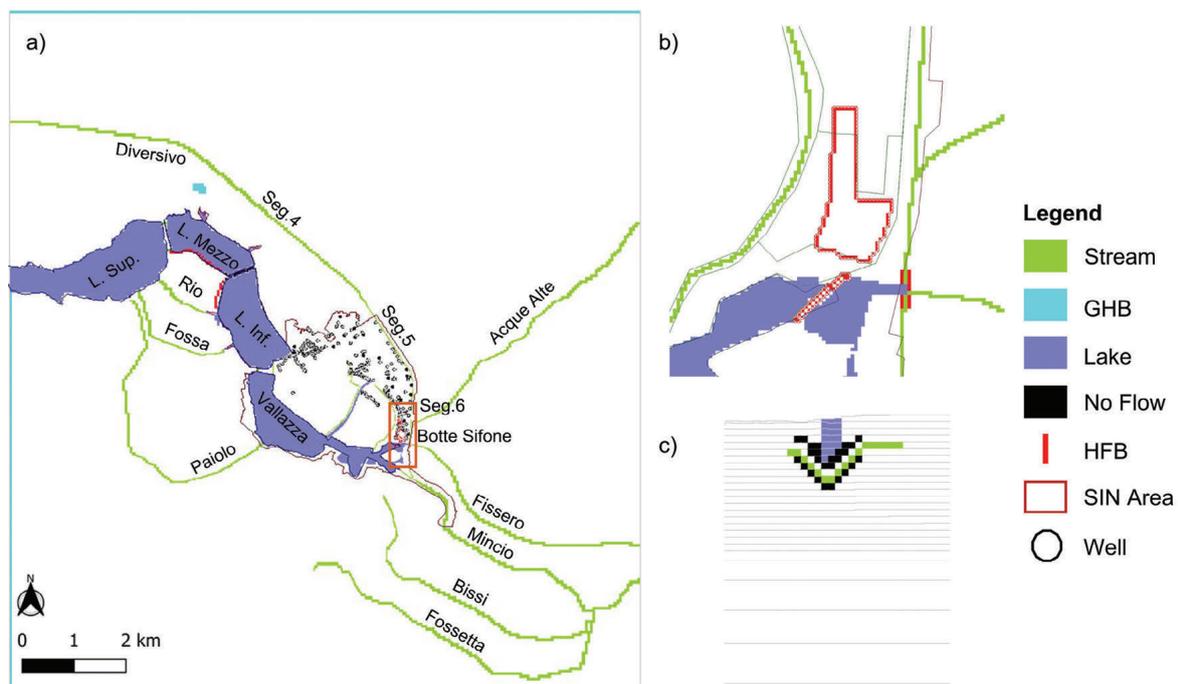


Fig. 6 - a) Boundary conditions of the model; the orange rectangle points to the sector area represented in Fig. 6(b) and 6(c); b) lateral sides of Botte Sifone and further confinement elements inside the SIN, modelled through HFB package; c) schematic cross-section of Botte Sifone. Please note that in Fig. 6(a) only the name of the SFR segments of the Diversivo has been represented.

Fig. 6 - a) Condizioni al contorno del modello; il rettangolo arancione indica l'area rappresentata in Fig. 6(b) e 6(c); b) bordi della Botte Sifone e ulteriori elementi di contenimento all'interno del SIN, modellati tramite il pacchetto HFB; c) sezione schematica della Botte Sifone. NB: In Fig. 6(a) è stato rappresentato solamente il nome dei segmenti di SFR del Diversivo.

was discretized into 24 hydraulic conductivity zones (Fig. 7). Regarding the porosity, whose assignment is required for particle tracking model, the discretization into zones was derived from the hydraulic conductivity zonation, defining 7 classes by merging the K zones on the basis of their lithology. As regards their values, they were selected from literature (Freeze and Cherry 1979; Fetter 2001).

As concerns calibration, a sensitivity analysis by adopting multiplying factors (from 0.5 to 1.5), and a “Trial and error” method were adopted to calibrate the transient model, focusing on: general head boundary (three GHBs: North, South, and West), aquifer recharge (16 classes), hydraulic conductivity (24 zones), effective porosity (areal distribution) and rivers bed conductance (19 values, one for each SFR segment). As for the hydraulic conductivity, the calibration was mainly focused on adjusting shape and values of semiconfined aquifer zones, as these were reconstructed starting from a limited amount of initial data (Fig. 2). A total of 2695 observations, monthly measured during the analysed period and referred to 83 targets, were considered: 80 targets are placed inside the SIN (4 are related to the semiconfined aquifer), while only 3 targets are located outside the SIN area.

To reconstruct the capture zone of the wells and the hydraulic barriers inside the SIN area, the particle tracking was applied on the calibrated model, using MODPATH. In particular, 36000 particles, placed on the water table inside the SIN with a mesh of 20 meters, have been traced forward from January 2016, thus reconstructing the flux for the simulated period.

**Results**

The calibrated values of GHBs were 25.5 and 27.5 m a.s.l. at North, 17.5 and 19.5 m a.s.l. at West for the shallow and deep aquifers, respectively; at South, a GHB ranging from 13.2 to 11.2 m a.s.l. simulated the Po River, located outside the model area. The hydraulic conductivity zones showed calibrated values ranging from 0.00432 m/d to 216 m/d (Fig. 7); as for the effective porosity, the values varied from 0.1 for silty clays to 0.3 for gravels. Rivers bed conductance varied from 15.12 to 57 020 m<sup>2</sup>/d.

Final average monthly values for the 16 zones of recharge are represented in Figure 8.

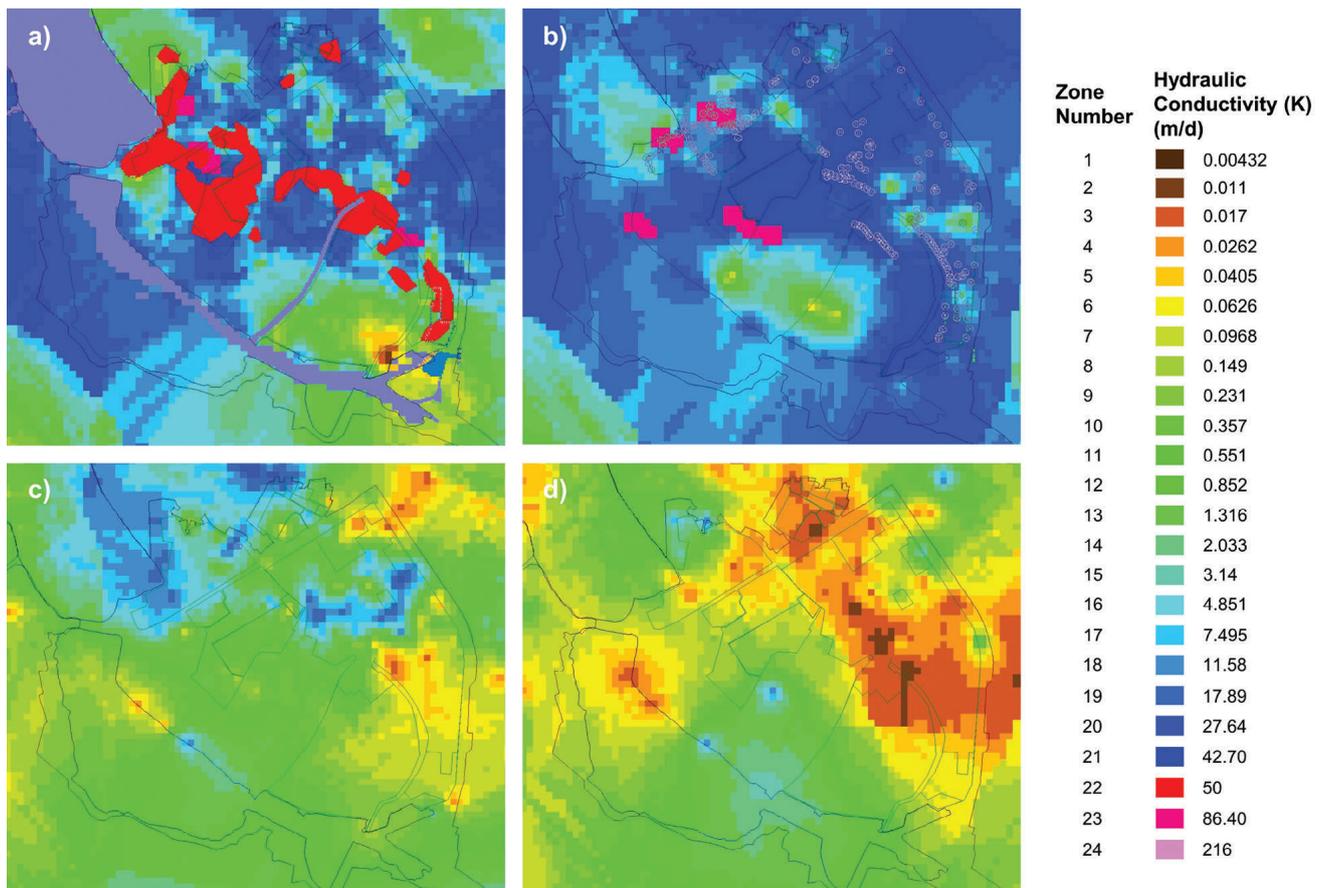


Fig. 7 - Hydraulic conductivity values for layers a) 4 b) 8 c) 16 d) 20 at SIN scale. All these layers belong to the shallow aquifer. The purple polygon in Fig. 7a) represents the deepest portions of the lakes, modeled according to their real topographic profiles.

Fig. 7 - Valori di conducibilità idraulica per gli strati a) 4 b) 8 c) 16 d) 20 a scala SIN. Tutti questi strati appartengono all'acquifero freatico. Il poligono viola in Fig. 7a) rappresenta le porzioni più profonde dei laghi, modellate secondo il loro reale profilo topografico.

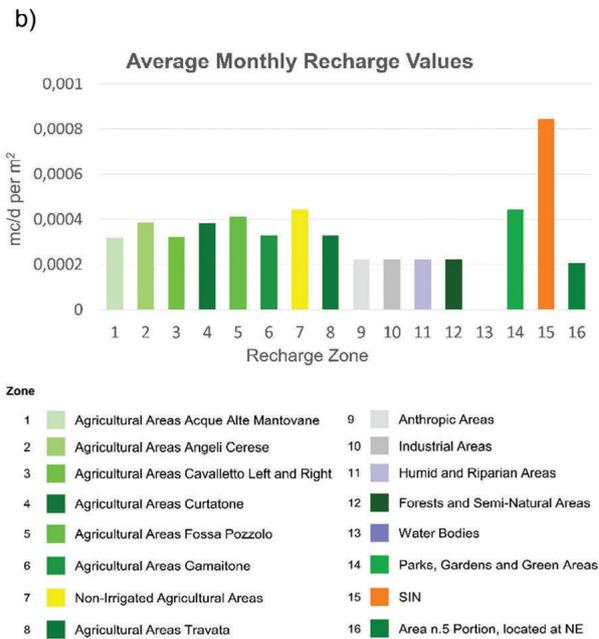
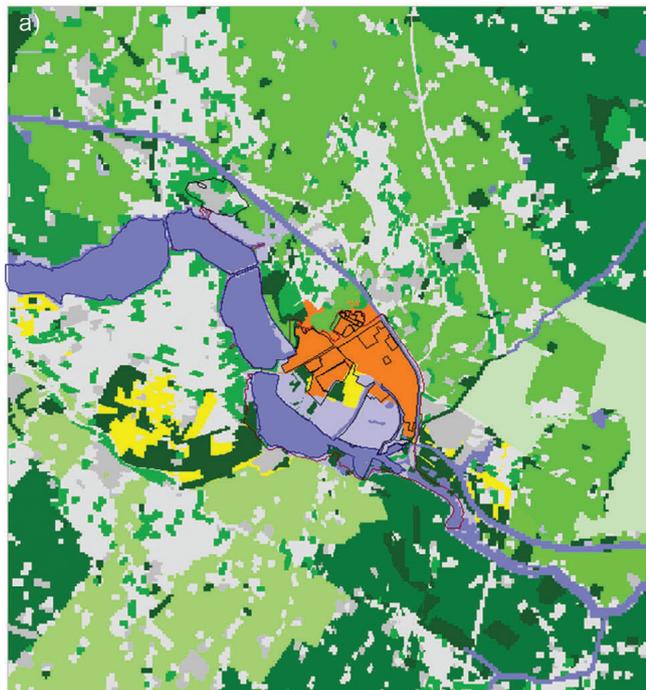


Fig. 8 - a) Areal distribution of the 16 recharge zones; b) Average monthly recharge values for the analysed period for each recharge zone. Please note that the recharge zone legend is valid both for fig. a) and b).

Fig. 8 - a) Distribuzione spaziale delle 16 zone di ricarica; b) Valore medio mensile di ricarica di ogni zona nel periodo considerato. NB: La legenda delle zone di ricarica è valida per le figure a) e b).

Considering the 83 targets, the calibrated model shows good statistics (Tab. 2, Fig. 9), with residuals ranging between -1.51 and 1.79 meters, and a nRMSE (Scaled RMSE) of 3.6%.

The response for some selected targets is visible in Fig. 10. Both targets referred to the shallow and deep aquifer, showing an hydraulic head higher than the shallowest, provided a good response.

Tab. 2 - Statistical analysis of head targets.

Tab. 2 - Analisi statistica dei target di controllo piezometrico.

Statistical Parameters	Targets
Target / Number of Observations	83/2695
Absolute Residual Mean	0.34
RSS (Residual Sum of Squares)	526
RMSE	0.44
Minimum Residual	-1.51
Maximum Residual	1.79
Range of Observations	12.15
nRMSE (Scaled RMSE)	0.036

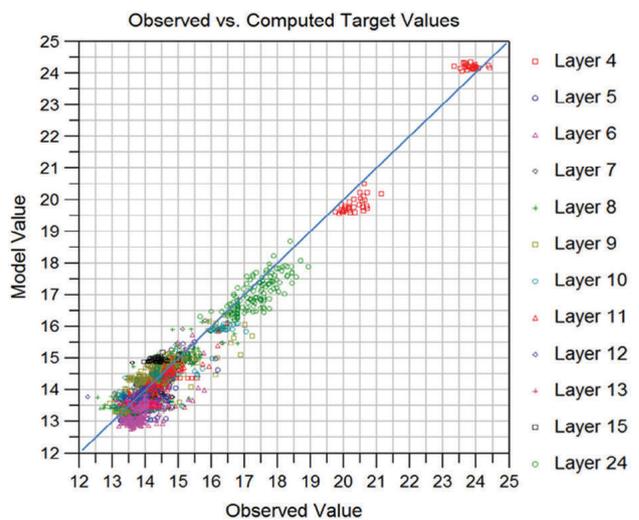


Fig. 9 - Observed (m a.s.l.) vs simulated (m a.s.l.) hydraulic head values.

Fig. 9 - Confronto tra valori di carico piezometrico osservati (m s.l.m.) e simulati (m s.l.m.).

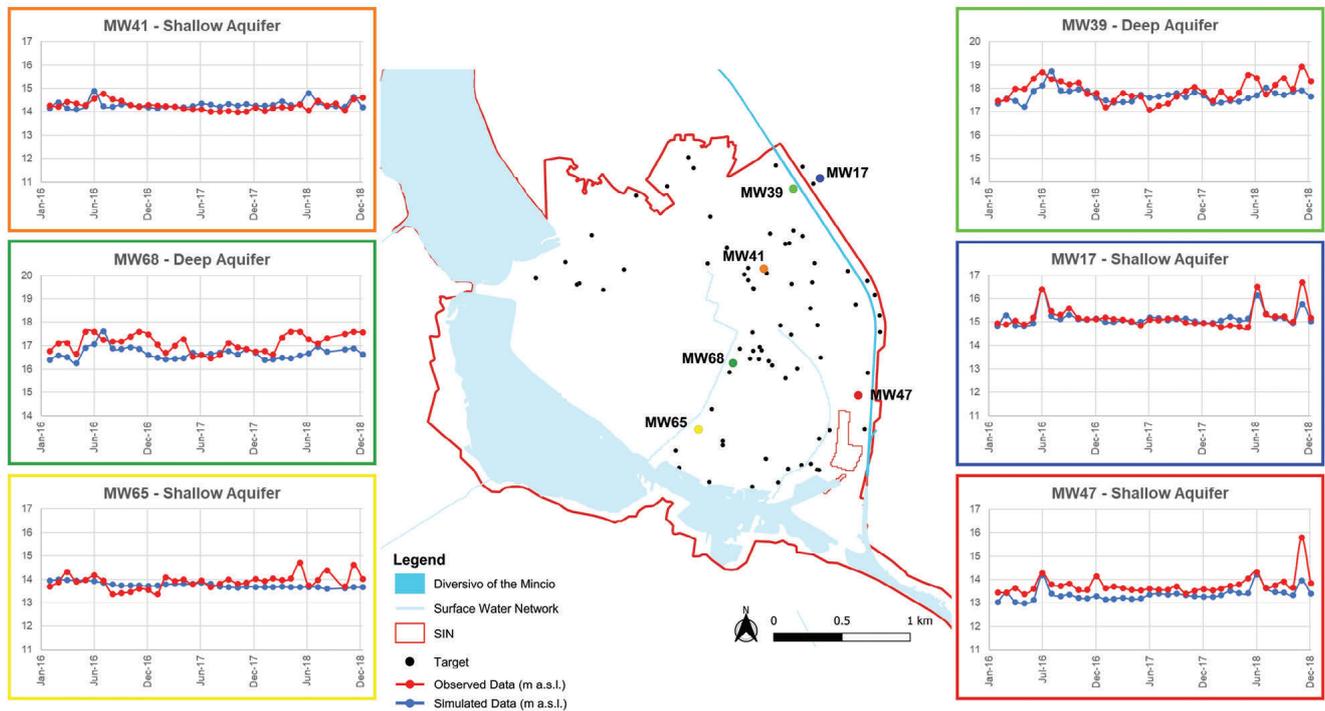


Fig. 10 - Observed (m a.s.l.) vs simulated (m a.s.l.) values for some selected targets. All the graphics have been set with an X-axis scale of 36 stress periods (months) and Y-axis scale with an interval of 6 meters.

Fig. 10 - Confronto tra valori osservati (m s.l.m.) e simulati (m s.l.m.) per alcuni target selezionati. Tutti i grafici sono stati impostati con una scala orizzontale di 36 stress period (mesi) ed una verticale di 6 metri.

Groundwater potentiometric maps for the shallow aquifer, both at model scale and at SIN scale, are reported in Fig. 11 for January 2018 (Jan18) (Fig. 11a - 11c) and June 2018 (Jun18) (Fig. 11b - 11d). These periods have been selected to represent hydraulic minimum and maximum conditions (Fig. 10). Significant differences are not visible at the model scale between the two periods: in general, hydraulic heads vary from 25 m a.s.l. at North, to 14-15 m a.s.l. close to the SIN and around the drainage channels of Mantua, then increasing up to 17-18 m a.s.l. toward South-West.

Refining the analysis to the SIN, a hydraulic maximum of 15 m a.s.l. is visible at North of the SIN in Jan18 (Fig. 11c), generating groundwater flow directions mainly towards the Diversivo and the closest hydraulic barriers; on the contrary, in Jun18 (hydraulic maximum) (Fig. 11d), flow directions are mostly towards the hydraulic barriers. Hence, the effect of the hydraulic barriers is most visible during the maximum hydraulic condition, while a draining effect of the Diversivo is predominant during the minimum groundwater condition

(Jan18), especially in the northern part of the SIN. When the flow is directed towards the barriers, a high gradient is always identified. From the central portion of the SIN, a radial flow is directed towards Lake Inferiore and Vallazza. This changing relation between the Diversivo and groundwater is particularly evident for segment 5 (Fig. 6a) of the Diversivo (Tab. 3): while segment 4 and 6 show a recharging behaviour for both the periods, segment 5 (i.e. the closest to the hydraulic barriers) acts as a drain in Jan18, while its recharging effect is visible in Jun18.

The presence of 4 deep targets inside the SIN area, showing a hydraulic head higher than the shallow targets (Fig. 10), required to refine the analysis also to the semiconfined aquifer. To do so, a map of the piezometric difference between the hydraulic heads of the shallow and semiconfined aquifer was realized in GIS environment. As reported in Fig. 12, a positive difference in hydraulic pressure between the semiconfined and the shallow aquifer was identified for Jan18 and Jun18, with values of around one meter in the central portion of the area, and up to 4 meters towards the Diversivo and Lake Inferiore.

Tab. 3 - Relation between the segments of the Diversivo and groundwater in Jan18 and in Jun18. Please note that Inflow and Outflow are referred to groundwater. Data have been extracted from the SFR output file.

Tab. 3 - Relazione tra i segmenti del Diversivo e la falda a Gen18 e Giu18. NB: Le voci di Inflow e Outflow sono riferite alla falda. I dati sono stati estratti dal file di output di SFR.

Segment Number (Length)	Jan18		Jun18	
	Inflow (m <sup>3</sup> /day)	Outflow (m <sup>3</sup> /day)	Inflow (m <sup>3</sup> /day)	Outflow (m <sup>3</sup> /day)
4 (7300 m)	50 600	/	92 000	/
5 (3300 m)	/	4 120	3 620	/
6 (980 m)	62.55	9.78	957.90	1.94

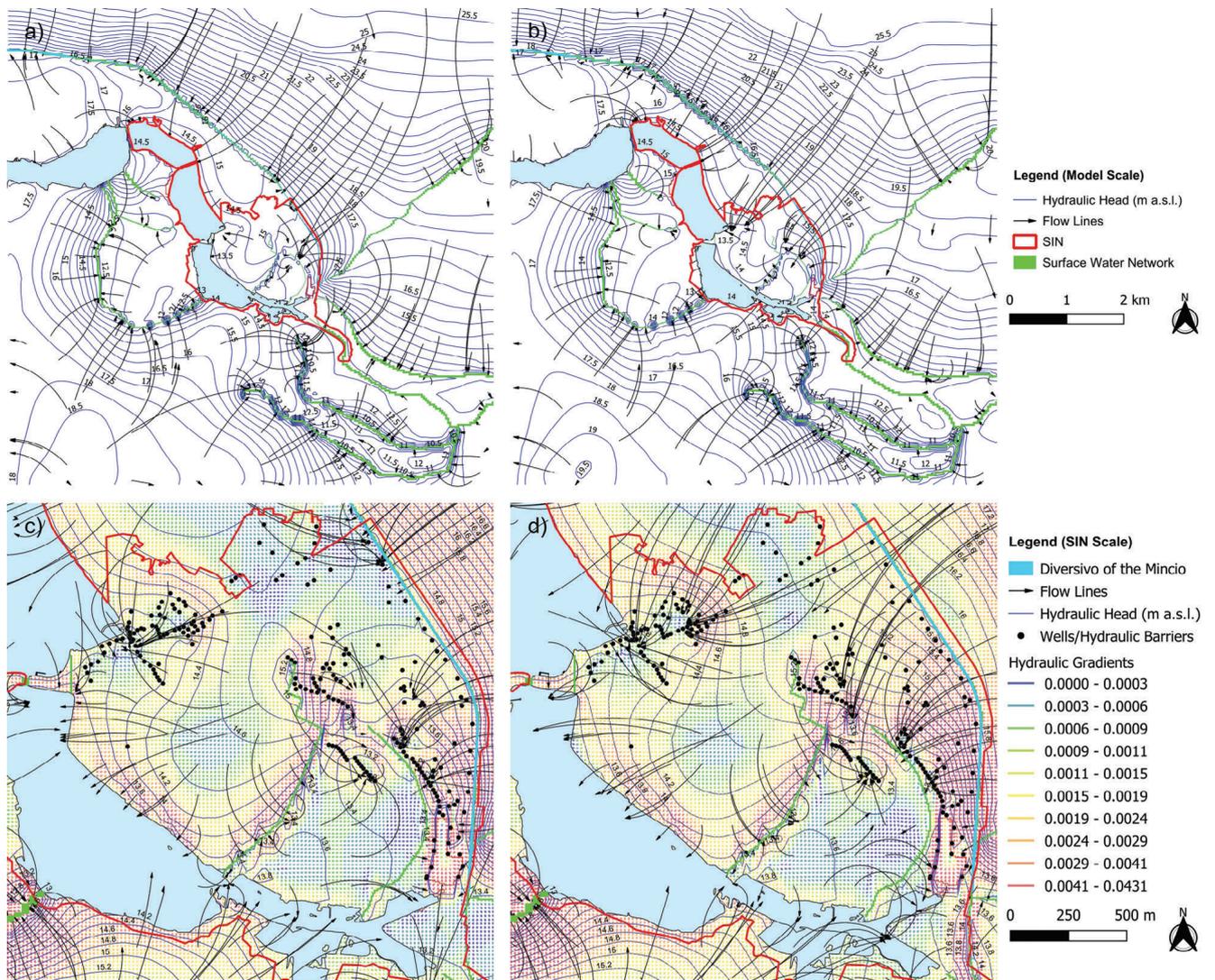


Fig. 11 - Groundwater potentiometric maps at model scale for a) Jan18 and b) Jun18. Groundwater potentiometric maps at SIN scale for c) Jan18 and d) Jun18. Colour coding in c) and d) indicates the magnitude of the hydraulic gradient.

Fig. 11 - Mappe piezometriche a scala di modello per a) Gen18 e b) Giu18. Mappe piezometriche a scala SIN per c) Gen18 e d) Giu18. La scala di colori per c) e d) indica l'intensità del gradiente idraulico.

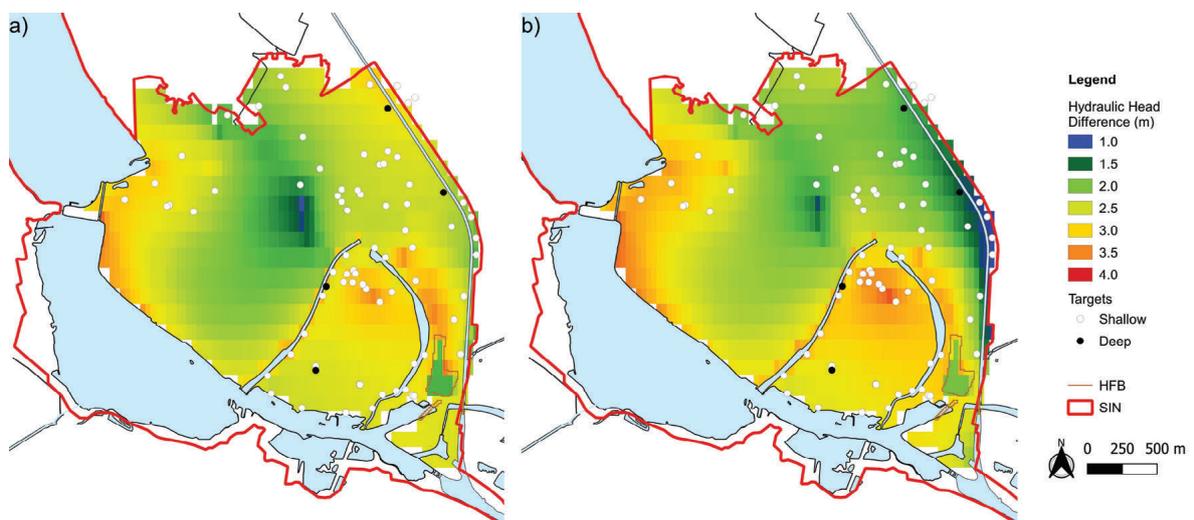


Fig. 12 - Hydraulic head difference between the deep and shallow aquifer at a) Jan18 and b) Jun18.

Fig. 12 - Differenza di carico idraulico tra l'acquifero semiconfinato e l'acquifero superficiale per a) Gen18 e b) Giu18.

Model mass balance (Tab. 4, Fig. 13) evidences almost equal recharging and draining behaviours of the lakes. Wells figure mainly as an outflow. Rivers and channels show a prevailing draining action (i.e. almost two times than their recharging behaviour). However, they also contribute, together with recharge and GHB, as the main inflows to the groundwater system. Model percentage discrepancy is low (-0.01).

MODPATH has allowed to evaluate the overall effects of the hydraulic barriers inside the SIN area for the analysed period: some flow paths where groundwater is not abstracted by any hydraulic barrier could be identified over the three years' time span (Fig. 14). At the same time, some areas close to the Vallazza are not intercepted by any well capture zone within the 3 years.

Tab. 4 - Model mass balance, averaged over all the 36 stress periods.

Tab. 4 - Bilancio di massa del modello, mediato sui 36 stress period.

Mass Balance	Inflow (m <sup>3</sup> /d)	Outflow (m <sup>3</sup> /d)	% Error
Storage	13 047	13 033	
GHB	60 947	28 458	
Lakes	10 178	10 843	
Rivers/Channels	70 207	138 099	
Wells	829	11 869	
Recharge	47 078	/	
Total	202 286	202 302	-0.01

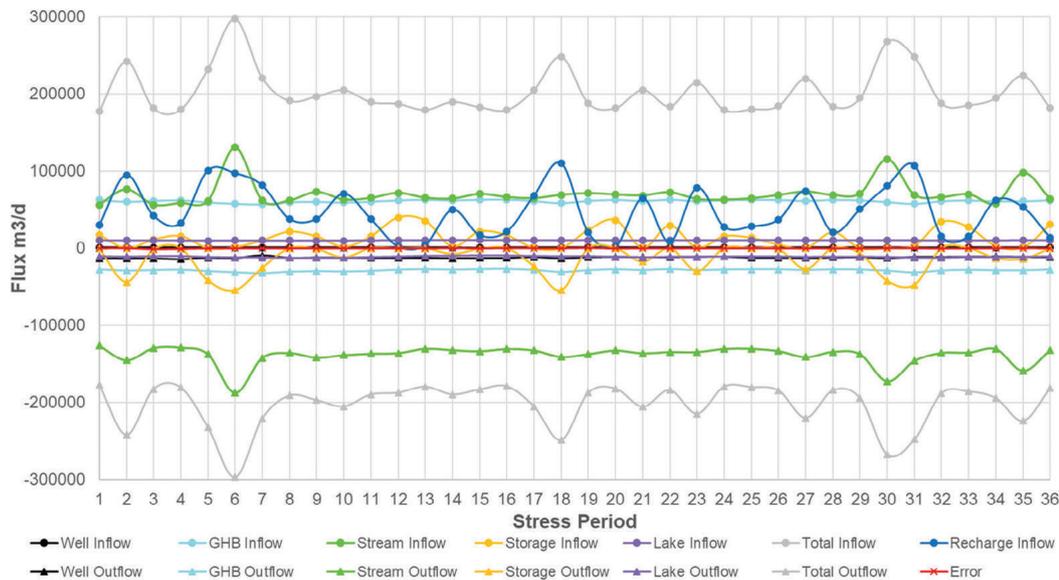


Fig. 13 - Model mass balance divided into the 36 monthly stress periods. The applied colour coding for the BCs is the same as in Fig.6.

Fig. 13 - Bilancio di massa del modello suddiviso nei 36 stress period mensili. La colorazione applicata per le condizioni al contorno è la medesima della Fig.6.

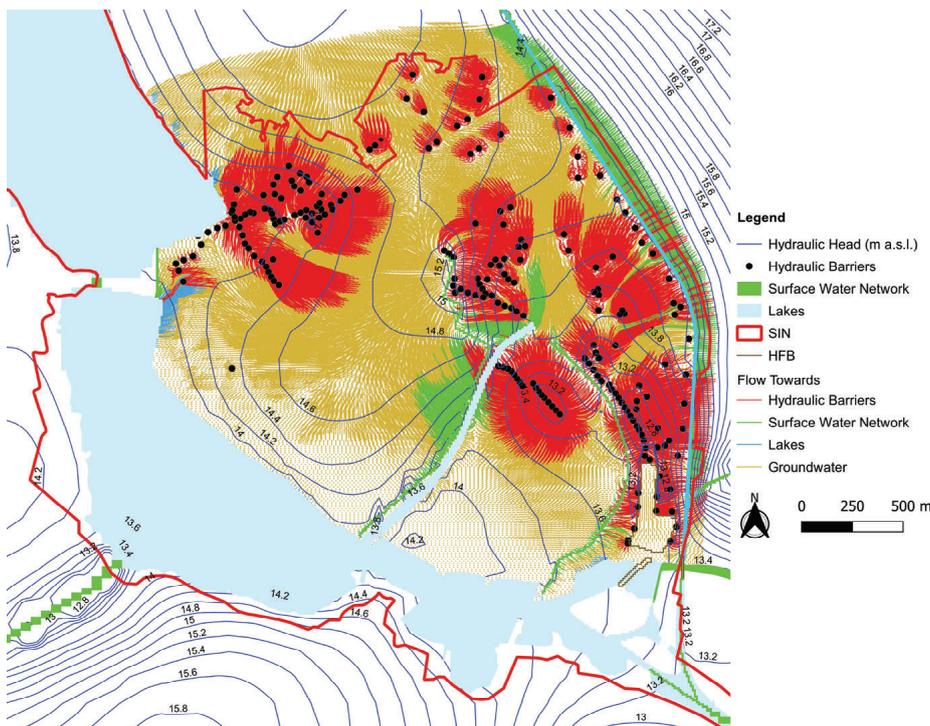


Fig. 14 - Hydraulic barriers capture zones inside the SIN with a three years' time span, starting from Jan16.

Fig. 14 - Zone di cattura delle barriere idrauliche all'interno del SIN, con un tempo di simulazione di tre anni, a partire da Gen16.

## Discussion

The transient numerical model allowed to analyse in detail the complex water system of Mantua, defining the main relations between groundwater and the surface water network, also evaluating their effects on the pumping activities conducted inside the SIN. Generally, the model provided a good representation of the system, as the scaled RMSE (3.6%) meets the international modelling criteria indicating a simulation as reliable if the scaled RMSE is less than 8% (Middlemis et al. 2000; Feinstein et al. 2010). Also, the mass balance percentage error (-0.01) is low: these results are a direct consequence of the adopted participatory modelling approach (Castilla-Rho 2017); being actively engaged in technical committees, the companies understood the effectiveness of data collection (Ferré 2017), thus sharing precise and updated information regarding daily wells discharge, that allowed both to realize a three-years model with monthly time steps and to obtain a high mass balance accuracy.

Regarding the relation between groundwater and the lakes (Fig. 11a – 11b), it was evidenced that Lake Superiore shows a draining action on its left bank, and a predominant losing behaviour on its right bank; Lake di Mezzo and Lake Inferiore both show a draining action. In the end, also the Vallazza shows a slight draining action on groundwater.

The adoption of SFR allowed to analyse interactions and exchanges between groundwater and the surface channels in a complex system. In particular, Fossa, Paiolo, Bissi and Fossetta channels (Fig. 6) all show a draining action with respect to groundwater (Fig. 11a – 11b). Acque Alte, located in the eastern part of the model, shows a draining action in its first sections, while assuming a losing behaviour in proximity of the Diversivo. The relation between the Diversivo and groundwater was analysed through monthly hydraulic measures at Brennero and Carraia hydraulic sections, thus reconstructing their discharges; as visible both in Figure 4b and in Figures 11c – 11d, it is extremely variable both in space and time: in particular, it seems strictly dependent on the Diversivo discharge. When the discharge is low, as in Jan18, the draining action is prevailing; on the contrary, when the discharge is high, as in Jun18, a losing action is predominant. In particular, this is valid for segment 5 of the Diversivo (Tab. 3). This also influences the pumping activity of the hydraulic barriers, which is enhanced when the discharge of the Diversivo is high (Fig. 11d). Given the importance of the discharges, the calibrated model highlighted the potential benefits of further scientific investigations (Ferré 2017): daily measuring both the hydrometric level and discharges at Brennero and Carraia, in addition to discharge measures at the initial segments of the Diversivo, would contribute to better understand the hydrogeologic behaviour of the area, reducing possible scientific uncertainty. Thus, ARPA plans to improve the monitoring network, by installing discharge gauges, by the end of summer 2022.

Despite the presence of just 4 deep targets inside the SIN, the role of the deep water table was analysed. In particular, the hydraulic head of the semiconfined aquifer was always

2-3 meters higher than the water table level of the shallow aquifer. The existence of such relation of hydraulic pressure could play an important role, as it could naturally impede the migration of possible contaminants from the shallow to the semiconfined aquifer. Considering the relevance of this specific issue, as for the Diversivo, a further monitoring effort will be put in place by ARPA, by drilling new deep piezometers; this could allow to further analyse the semiconfined aquifer, as it is now still poorly investigated, refining also the conceptual model as regards the exact position of the clayey aquitard that separates the shallow aquifer.

Finally, the particle tracking allowed to highlight the flow dynamics for the considered time span. In particular, some paths inside the SIN where groundwater is not intercepted by any hydraulic barrier were identified. This could depend on a double reason: a low well discharge and the narrow time period analysed that could lead to tight wells capture zones. In the framework of a possible model update or use for specific purposes (Borsi and Rossetto 2012; Chahoud et al. 2013), as the simulation period influences the particle tracking results, to obtain a better understanding over longer periods, it should be required to elaborate a longer numerical model, by collecting information about all the boundary and initial conditions over a wider time span.

## Conclusions

The interactions between groundwater and surface waters are of growing interest, as evaluating their exchanges when pumping activities are conducted in the same area. In this sense, the realization of a transient 3D groundwater numerical model for the SIN area of Mantua has allowed to:

- identify the presence of a shallow and a semiconfined aquifer. This latter showed higher hydraulic heads than the shallow one, thus preventing possible contaminations from migrating. Their modelling allowed to properly reproduce the groundwater dynamics at SIN area, as visible from model statistics;
- understand the dynamics of groundwater/surface-water interactions, evidencing the key role of the discharge and the hydraulic head of the Diversivo of the Mincio in changing its relationship with the water table (gaining/losing), also affecting the hydraulic barriers efficiency;
- reconstruct the complex piezometric dynamic of the analysed area, evaluating the efficiency of the hydraulic barriers;
- evidence the importance of participatory modelling, as the companies' engagement increased the accuracy and amount of data available to reconstruct with good results the hydrogeologic system.

The calibrated model could be used in the future to operatively manage the SIN. With this aim, its final version has been provided to ARPA. Particularly, it could be applied to test the efficiency of new wells or optimize the already existing hydraulic barriers, realizing refined models focused on specific hydraulic barriers if necessary. The groundwater numerical model could also be used as starting point to

develop a transport model to evaluate the effect of possible contaminations, and identify the most effective containment measures.

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### Competing interest

The authors declare no competing interest.

### Author contributions

All authors contributed to data collection, data processing, results interpretation, writing, review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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