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Artificial Recharge of Phreatic Aquifer in the Mereto Di Tomba Area (Upper Friuli Plain)

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Abstract

The Mereto di Tomba area in the upper Friuli plain was selected to evaluate the impacts of artificial recharge (AR) and to develop reliable models for managing AR activities using an infiltration basin, about 5.5 m deep and 45×7 m^2 wide. Alluvial deposits compose the unconfined aquifer with an estimated thickness no less than 100 m. The depth to the water table averages 50 m. Hydrogeological and geophysical investigations were performed supporting the aquifer conceptual model. The expected AR efficiency has been simulated by a three-dimensional variably-saturated finite-element model. Preliminary data of AR testing are presented.

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Keywords: Water reborn techniques; phreatic aquifer; geophysical and hydrogeological studies; finite element three-dimensional variably-saturated flow model; upper Friuli Plain.

1. Introduction

In the last decades (1999-2008), the total amount of water abstracted for potable use in Italy has increased up to 9.1 millions of cubic metres charged for 85% to groundwater and Friuli-Venezia Giulia is the region characterized by the greatest increment of withdrawals, about 10% [1].

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The Friuli Plain, that extends for about 2900 km^2 (Fig. 1), is the most important regional aquifer system; it's economically remarkable, either because underground water resources are present in fertile and densely populated areas, or because the presence of confined aquifer systems in the low plain enables preservation of the underground water good quality. The plain is formed by Quaternary deposits of increasing thickness in the NE-SW direction (ranging from 50 to 900 meters) with an average 2.5 ‰ gradient to the right side of the Tagliamento River. In the past years the regional aquifer has experienced an average lowering of the phreatic level equal to 2.5 m. Moreover a few meters decrease of piezometric head in the shallowest portion of the confined aquifer system and a southward migration of the spring line of about 1 km was observed. This trend, as well as the increase in water withdrawal, was caused by a marked precipitation variability with a larger number of extreme events and longer dry periods. The WARBO LIFE+ Project, supported by the European Union, is aimed at implementing large-scale use of AR in Italy, where water directives still strongly limit its application.

The Mereto di Tomba area in the upper Friuli plain was selected to evaluate the AR impacts and to develop reliable models for managing AR activities. In this area, where the analysis of long-term phreatic levels (1967-2013) has shown a decrease of the unconfined aquifer level of about 3.5 m, an infiltration basin, about 5.5 m deep and 45x7 m^2 wide, was built in the early 2000s, but the possibility of implementing the recharge has been allowed only very recently.

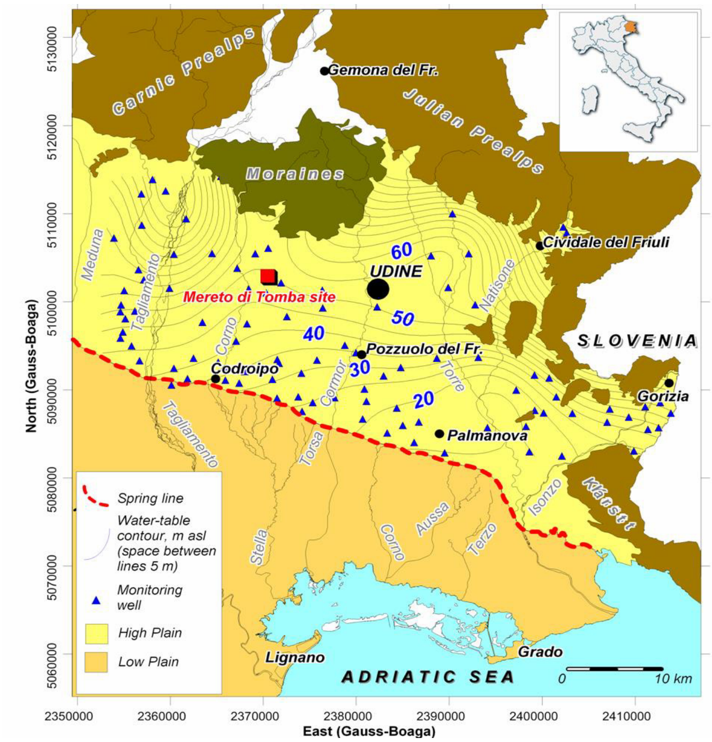

Fig. 1. Main hydrogeological features of the Upper Friuli Plain.

The first infiltration experiment began in December 2013, using the water coming from Canale San Vito, a nearby irrigation channel fed by Tagliamento River, had a duration of 39 days and an inflow rate of 610 m^3/day. The second infiltration test is ongoing since March 2014. The paper presents the preliminary results of aquifer monitoring and simulation.

2. Hydrogeological setting of the Mereto site test

The site test is located in the Upper Friuli Plain on the left side of the Tagliamento River. Five 70 m deep (PZ1, PZ6, PZ8, PZ10, PZ11) and one 59 m deep (PZ12) wellbores drilled in the nearby of the infiltration basin are available to characterize the unconfined aquifer. The 15 m thick top layer is mainly composed of gravels with sand, silt and clay fractions, below which a 10 m thick gravel with clay unit is located. Then, a 20 m thick cemented gravel and a 24 m thick fractured conglomerate horizons are detected. Moving southward the aquifer becomes locally confined by a low-permeability compact conglomerate horizon that probably represents the aquifer bottom in the Mereto area.

2.1 Geophysical characterization

In order to improve the geological knowledge of the Mereto pond, an integrated geophysical survey has been carried out. Three investigation techniques have been performed: Ground Penetrating Radar (GPR) for the shallow subsoil layer (a few meters thick), Electrical Resistivity Tomography (ERT) for first tens of meters and High Resolution Reflection Seismic (HRRS) for deeper soil. Inside the pond, seven parallel GPR profiles (30 m long and 1 m apart each) and two ERT profiles (with 60 electrodes spaced 0.8 m, for a total length of 47.20 m, and 6 m apart) have been collected. A georadar GSSI SIR2000, equipped with 200 MHz monostatic antenna and a LGM 4 Punkt light up georesistivimeter (Lippmann Geophysikalische Messgerate) have been used. A seismic profile outside the pond has been acquired by a MiniVib IVI T-2500 mounted on a small truck. A linear up-sweep from 10 Hz to 220 Hz, with a tapering of 10% and 12s length, has been applied. Data have been collected by means of 10 Hz single geophones (5 m interval) using a DMT Summit acquisition system (sample rate 1 ms) and energizing every 5 m. Being the seismic profile close to a road with a noisy air power line degrading the signal, the predictive deconvolution method has been performed before correlation in real time [2].

GPR detected a first reflector at a depth of 1 m and a second reflector between 2 and 3 m depth (Fig. 2). Such electromagnetic discontinuity is characterized by a constant slope moving southward. The ERT investigation identified several structures with a resistivity range from 800 to 1500 Ωm, as well as the second GPR discontinuity. The revealed features can correspond to cemented or compact gravel lens, related to fluvio-glacial deposits. Below them, the decrease of resistivity is presumably connected to the presence of wet sandy-clayey lithologies, that represent a limit for GPR penetration. The stacked seismic profile, parallel to the major side of the infiltration pond, detected a first discontinuity at a depth of about 50 m below the ground surface. Further unconformities have been detected between 50 and 140 m depth, as well as a strong seismic reflector at about 250 m from the ground surface, in agreement with the presence of Miocene molassa, indicated in the Mereto area, below the Quaternary deposits [3].

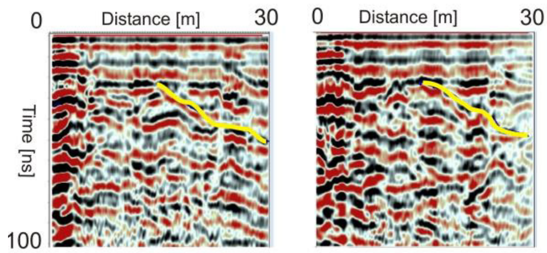

Fig. 2. Two parallel GPR profiles. The yellow undulating discontinuity shows a constant slope moving southward.

2.2. Monitoring activity

The water levels weekly measured in 20 monitoring wells in the Mereto area starting from November 2012 were collected to study the groundwater behavior [4]. In the piezometers near the infiltration basin, the water level ranges from 55 to 46 m below the ground surface depending on the season. New piezometers located at shallow depths (15.50 m) show the presence of a perched aquifer about 14 m deep. The regional water table map (Fig. 1) shows that the site is characterized by the convergence of two groundwater flow directions. Around the infiltration basin instead, a NE-SW flow direction with a gradient of 10^{-3} can be highlighted (Fig. 3); such behavior indicates that in the Mereto area the aquifer is fed by the groundwater inflow coming from the moraine amphitheatre.

During the same period of piezometric monitoring, physic-chemical measurements with multi-parametric probe and samplings for chemical analysis in ion chromatography were carried out. The water of the channel Canale San Vito, which will be used for the artificial recharge, was also sampled. Groundwaters show a temperature between 13 and 14 °C and an electrical conductivity ranging from 550 to 700 µS/cm. Notice that the channel water is characterized by a lower electrical conductivity ranging between 490 and 453 µS/cm. All waters belong to the calcium-bicarbonate facies; the nitrate concentration is very low in the Canale San Vito, while groundwater has generally high nitrate values which in some cases exceed the 50 mg/L limit , according to the Italian legislation (D.Lgs.152/2006). The sulfate content ranges between 77 and 13 mg/L with a decreasing trend in the WE direction, and the lowest values, less than 35 mg/L, found in piezometers near the infiltration basin.

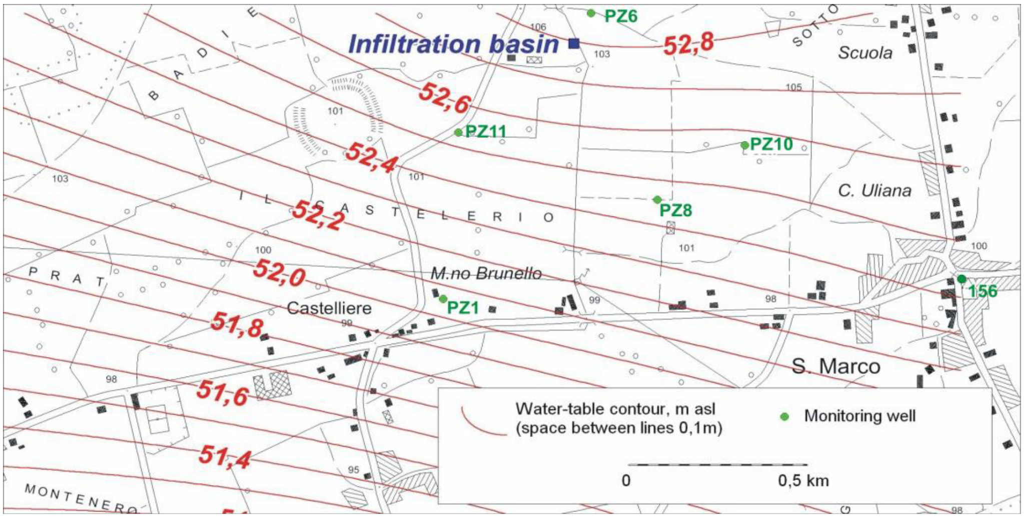

Fig. 3. Water-table map of Mereto area.

During the recharge test, which began on December 13, 2013 and protracted over a period of 39 days, no significant changes of the water level were recorded in the deep PZ6 and PZ12 wells, respectively 50 m and 10 m apart from the infiltration basin (Fig. 4). On the contrary, a phreatic variation was highlighted in the shallow piezometer A1 placed at the northern edge of the basin, with a groundwater level rise of about 2.5 m.

From the third week until the end of the infiltration test, a decrease in both the electrical conductivity (of the order of 100-150 µS/cm) and the content of dissolved nitrates (of the order of 55 mg/L), chlorides (of the order of 3 mg/L) and sulphates (of the order of 40 mg/L) occurred in well PZ12 in agreement with the chemical characteristics of Canale San Vito. Water sampled in piezometer A1 shows hydrochemical features identical to those of the channel water. Well PZ6 did not showed changes instead.

2.3 Conceptual model

Analysis of the wells and piezometer logs showed the presence of the aquifer in a fractured conglomerate at a 50 m depth, and suggested a seemingly homogeneity of the superficial deposits, however, with some clay intercalations. The characterization of the vadose zone was carried out through an infiltration test [5] and sieve analysis [6,7], giving an overall permeability in the order of 10^{-4} m/s. The properties of the conglomerate, where the saturated zone is located, were estimated between 1.8 to 4.2×10^{-4} m/s through a pumping test using the Logan approach [8]. No further methods were used, due to the physical constraint in installing larger pumps for a measurable effect on the aquifer. Also, no more hydraulic variables could be estimated.

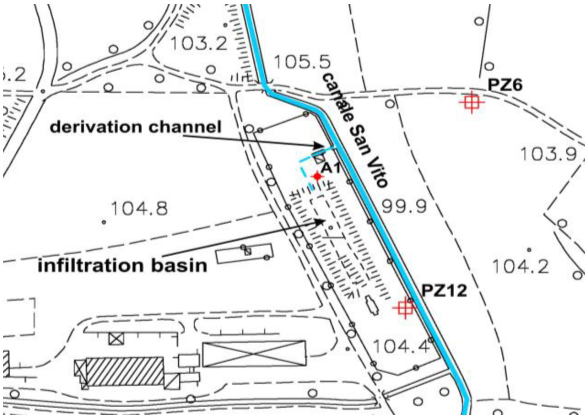

Fig. 4. The Mereto site test.

On the basis of the interpretation of geophysical profiles, chemical water analyses and piezometric data, a preliminary conceptual model was developed in order to foresee the recharge effects. The recharge rate would be on the order of 118 l/s (calculated through the Green-Ampt approach [9]) and the aquifer would present variations in the water table up to 400 m downstream of the influence area according to the Jacob-Bears (adapted by USEPA [10]), Krijgsmann and Lobo Ferreira [11] and Wyssling [12] approaches.

Table 1. Experimental influence radius (m) of the artificial recharge pond.

Days of operation	Jacob-Bears	Krijgsmann – Lobo Ferreira			Wyssling		
		Downstream	Upstream	Radius	Downstream	Upstream	Radius
15	20.0	14.7	11.0	22.9	14.0	11.2	86.1
30	29.5	22.1	14.5	22.9	20.8	15.1	86.1
45	37.0	28.3	16.8	22.9	26.4	17.8	86.1
60	44.0	33.8	18.5	22.9	31.4	20.0	86.1
75	50.0	39.0	19.8	22.9	36.1	21.8	86.1
90	56.0	44.0	20.8	22.9	40.5	23.3	86.1
105	61.5	48.7	21.7	22.9	44.7	24.6	86.1
120	67.0	53.2	22.4	22.9	48.7	25.8	86.1
135	72.0	57.6	23.0	22.9	52.6	26.8	86.1
150	77.5	62.0	23.5	22.9	56.5	27.8	86.1
165	82.0	66.2	23.9	22.9	60.2	28.7	86.1
180	87.0	70.3	24.3	22.9	63.9	29.5	86.1

The following assumptions were taken: i) infiltration was considered to occur in a single point, instead of an area; ii) the aquifer thickness was unknown but estimated in 100 meters; iii) the effective porosity was considered equal to 0.19 [13]; iv) the recharge is carried out continuously over 180 days; v) the recharge would occur with the pond totally filled with water.

Later on, experimental data coming from the infiltration test suggested that the vertical hydraulic conductivity in the vadose zone is likely to be an order of magnitude lower than the previous estimate, around 1.9×10^{-5} m/s (calculated through the Green-Ampt approach [9]). Furthermore, the shallow piezometers (15.5 m) confirmed the presence of a perched aquifer and of low permeability materials. With these new data, the influence radius was recalculated, showing that the influence radius of the experiment reach not more than 30 m (Table 1).

3. Modeling of artificial recharge

The recharge test carried out between December 13, 2013, and January 21, 2014, has been simulated by the three-dimensional variably saturated Finite Element FLOW3D simulator [14]. FLOW3D solves Richard's equation that, for a three-dimensional system, can be written as:

$$\sigma(S_w)\frac{\partial \psi}{\partial t} = \nabla \cdot \left[K_s K_r(S_w)(\nabla \psi + \eta_z)\right] + q_s \tag{1}$$

where $\sigma(S_w) = S_w S_s + \varphi \partial S_w / \partial \psi$, S_w is water saturation, S_s is the aquifer specific storage coefficient, φ is porosity, ψ the pressure head, ∇ the gradient operator, K_s the hydraulic conductivity tensor, $K_r(\psi)$ the relative hydraulic conductivity function, $\eta_z=(0,0,1)^T$, z is the vertical coordinate directed upward, and q_s represents distributed source or sink terms (volumetric flow rate per unit volume). Eq. (1) is highly nonlinear due to the pressure head dependencies in the storage and conductivity terms, and is linearized in the code using either Picard or Newton iterative schemes. Soil characteristics are specified using van Genuchten's model [15] providing the relative hydraulic conductivity as a function of the water saturation.

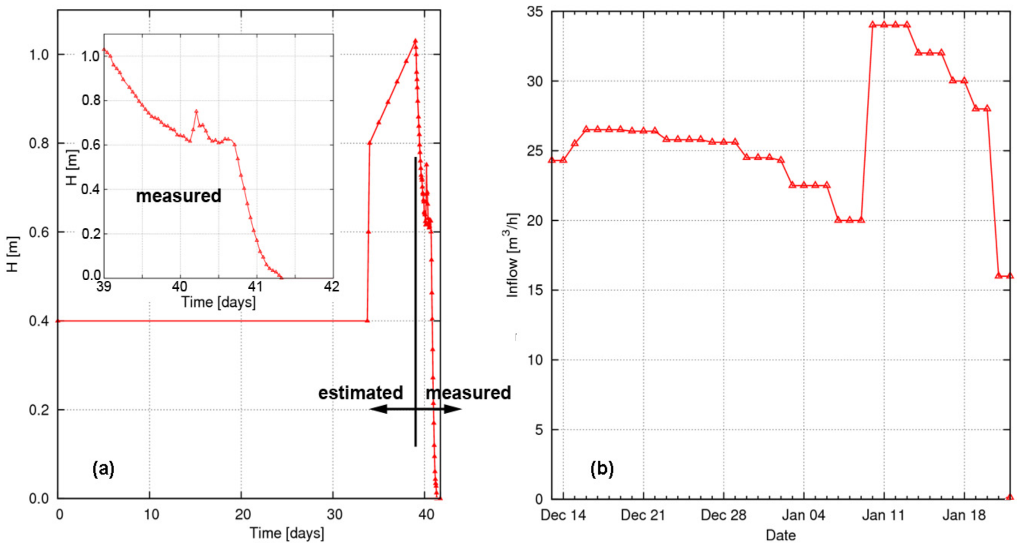

Fig. 5. Behavior versus time of (a) the water level above the pond bottom and (b) the water inflow in the pond.

A 3D tetrahedral FE grid, consisting of 551'978 nodes and 3'272'223 tetrahedral, was generated using the lithostratigraphic sequence provided by the few boreholes and the regional structure of the subsurface given by the seismic survey acquired during the project. The sedimentary sequence has been subdivided in four layers denoted as A1, A2, A3 and A4, characterized from top to bottom by the presence of gravel, gravel with traces of clay, gravel and fractured conglomerates. The model domain (Fig. 6) has an aerial extent of 500×800 m and is confined on top by the ground surface and a basement with an elevation of 35 m asl on bottom. The 3D high-resolution mesh accurately represents the ground topography, the pond geometry and the lithostratigraphic sequence.

For a detailed description of the model set-up, refers to [16]. The water table in undisturbed condition has been set so as to match the elevation of 52 m asl in correspondence of the pond, using the average regional north to south gradient equal to 0.1% as provided by the available piezometric measurements. Then hydrostatic pressure has been prescribed. Zero fluxes have been used on the domain bottom and ground surface outside the pond. Within the pond, the measured behavior vs time of the water level has been used (Fig. 5a). Concerning the van Genuchten parameters, the values were computed using the Rosetta software [17] on a few grain-size distribution curves representative of the Mereto sandy-gravel soil. K_s in unit A1 has been calibrated to reproduce the measured water volume flowed into the pond (Fig. 5b). Then, it has been assumed $K_{s,\mathrm{A3}} = K_{s,\mathrm{A1}} = 1.1\times10^{-5}$ m/s, $K_{s,\mathrm{A2}} = K_{s,\mathrm{A1}}/10$, and $K_{s,\mathrm{A4}} = 1.1\times10^{-4}$ m/s as provided by the interpretation of a few pumping tests.

The modeling results are summarized in Fig. 6. The relatively-low permeable unit A2 plays an important role on the lateral diffusion of the water plume. A temporary perched aquifer develops and the underlying saturated zone located in the conglomerate unit is recharged only in a second stage. The numerical outcomes match satisfactorily the rise of the water levels measured in a few piezometers drilled in the pond surrounding. A negligible variation of the main water table has been observed, with the perched aquifer that rises significantly during the infiltration period and quickly reduces once the pond becomes empty.

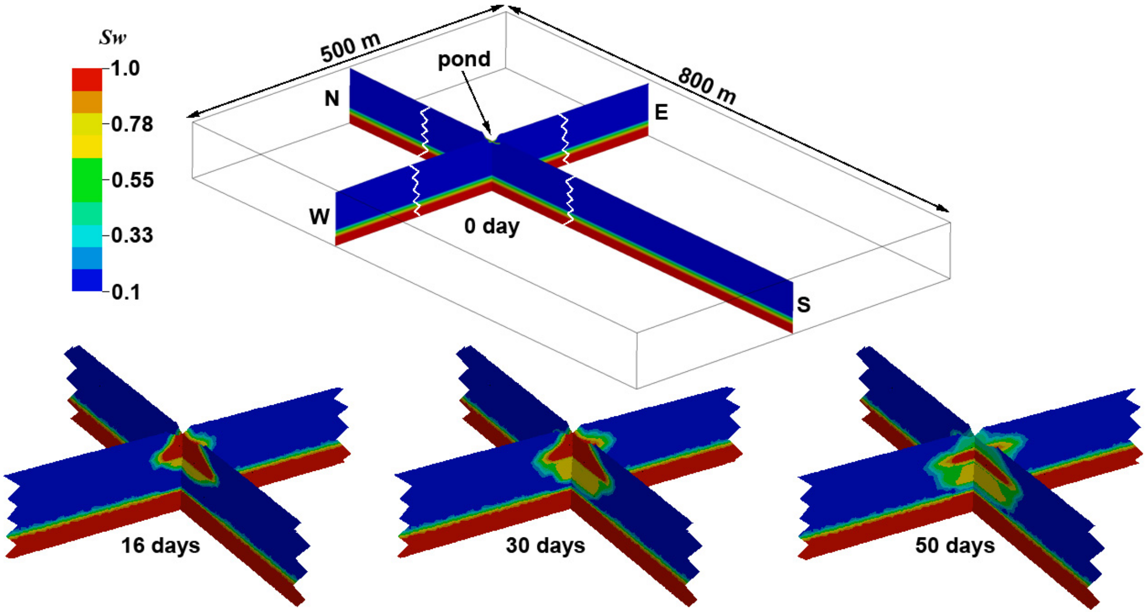

Fig. 6. Water saturation along a N-S and a W-E vertical section through the infiltration pond at the infiltration begin and after 16, 30 and 50 days of infiltration.

5. Conclusions

The use of artificial recharge to store underground surplus surface waters can be expected to increase because of the growing water demand. The Project WARBO aims at facilitating the AR regulation in Italy by testing its application to mitigate the groundwater level drop in the Mereto site where the unused surplus surface water, which is usually lost during the winter-spring season, is utilized. A multidisciplinary approach involving geophysical, hydrogeological and geochemical methodologies to characterize aquifer structure and surface/underground water, was necessary to improve the numerical models and the process understanding. The results from the infiltration tests will be evaluated and used to develop guidelines to support the decision makers for further applications in similar climate, geological, environmental and socio-economic conditions.

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