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A NUMERICAL GROUNDWATER FLOW MODEL OF CHIENTI RIVER VALLEY (CENTRAL ITALY): RESULTS AND BOUNDARY PROBLEMS

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EXTENDED ABSTRACT

Il basso bacino del fiume Chienti, situato nella regione Marche, dagli anni '90 è stato interessato da una diffusa contaminazione da solventi clorurati usati dalle fabbriche di calzature presenti nell'area (Pacioni *et alii*, 2010), per questo motivo dal 1997 l'area è stata sottoposta al monitoraggio da parte della USL e dell'ARPAM, poi affiancate dall'Università di Roma La Sapienza (ARPAM, 2007). Nel 2001 il basso bacino del Chienti è stato inserito nei Siti di Interesse Nazionale, per poi essere declassato nel 2013 a Sito di Interesse Regionale.

Tale bacino si instaura nel bacino periadriatico marchigiano, formato da argille, sabbie e conglomerati, che rappresenta il bedrock su cui si attesta la valle del Chienti, caratterizzata da quattro ordini di terrazzi dei quali i più antichi affiorano a monte mentre l'ultimo, insieme alle alluvioni attuali, affiora nella zona più prossima alla costa (Nanni & Vivalda, 1986). Proprio il IV ordine di terrazzi e le alluvioni attuali rappresentano l'acquifero di subalveo del basso bacino del Chienti, caratterizzato da ghiaie eterometriche in matrice limoso-sabbiosa con spessori variabili lungo la valle, spesso intercalate con limi sabbiosi e sabbie argillose e limi argillosi che, per la loro continuità verticale, rendono l'acquifero multifalda.

Sulla base del modello concettuale della circolazione idrica sotterranea (Petitta *et alii*, 2013) è stato realizzato, attraverso l'uso di Feflow (DHI-WASY GmbH, 2010) un modello numerico di flusso avente un'area di 68 km^2 e formato da un layer di copertura superficiale, due acquiferi e un interposto livello a bassa permeabilità. Per quanto riguarda le condizioni al contorno sono stati imposti limiti a flusso nullo a Nord e a Sud, constant head pari a 0 m s.l.m. lungo la linea di costa, portate in entrata pari a 0.05 m^3/g a monte e una ricarica di 227 mm/a. Dopo la validazione del modello, al fine di caratterizzare in dettaglio l'andamento della falda nella parte più bassa del bacino del Chienti e di identificare i possibili percorsi dei contaminanti al suo interno, ne è stato costruito uno di maggior dettaglio, sia in regime stazionario che transitorio, in corrispondenza dell'area del campo pozzi di Civitanova Marche.

Il nuovo modello ha un'area di 19.5 km^2, compresa tra Montecorsaro e Civitanova Marche (in direzione W-E) e tra i terrazzi fluviali a Nord e il Chienti a Sud. Al fine di riprodurre un acquifero multifalda semiconfinato, il modello è stato diviso in 4 layers e 5 slices basandosi sulla ricostruzione stratigrafica. Le caratteristiche idrogeologiche sono state imposte ad ogni layer sulla base dei dati bibliografici e dei risultati di prove di pompaggio. Al primo acquifero è stata applicata una conducibilità idraulica orizzontale (k_x) dell'ordine 10^{-3} m/s, mentre nel secondo k_x varia da $1*10^{-3}$ a $5*10^{-4}$ m/s. La ricarica applicata, ricavata dalla precipitazione efficace ottenuta con il metodo di Thornthwaite (Thornthwaite, 1948), è di 95 mm/a, in accordo con i dati climatici. Per quanto riguarda le condizioni al contorno, sul primo *slice* è stata applicata la condizione di Cauchy lungo il Chienti per simulare l'interazione con la falda, mentre a monte e a valle è stata applicata la condizione di *constant head*. Le stesse constant heads sono state applicate su tutte le restanti slices, dove è stata applicata la condizione di Dirichlet anche lungo il fiume. Sul limite Nord è stato invece imposto un flusso nullo. Infine sono stati simulati i pompaggi dei pozzi dell'acquedotto e quelli vicino alle fabbriche presenti nell'area.

Tale modello simula il reale andamento W-E della falda ottenendo un buon grado di correlazione dei livelli piezometrici con i valori simulati (RMS 0.76 nello stazionario; RMS 0.69-0.9 nel transitorio). Anche l'analisi di bilancio dimostra l'attendibilità del modello dal momento che i quantitativi di acqua in entrata e in uscita si equiparano. Da questa analisi si evidenzia inoltre l'importanza del ruolo delle condizioni di Dirichlet, mentre l'interazione falda/fiume appare limitata. Una situazione critica si osserva però nell'area SW, al contatto tra i limiti orientale e meridionale. Qui infatti si riscontra uno scambio inatteso e forse irrealistico delle acque sotterranee dovuto al contatto a 90° di diverse condizioni al contorno, combinato con un più alto gradiente idraulico e con una k_x dell'ordine di 10^{-3} m/s. Per vedere poi quali siano i percorsi e i tempi di transito di una particella che si muova per advezione, è stata applicata la funzione particle tracking, da cui emerge che una particella immessa direttamente nell'acquifero profondo arriva più velocemente al campo pozzi rispetto a una immessa in quello superficiale. Da questi simulazione emerge quindi che, sebbene il modello possa essere considerato un valido strumento per la pianificazione di interventi di bonifica, il suo potenziale utilizzo pratico richiede necessariamente la revisione dell'interazione falda/fiume e della geometria del dominio.

ABSTRACT

Since '90s the lower valley of Chienti River has been interested by a diffused contamination by chlorinated solvents (mainly PCE) used by local shoes companies. In order to analyze the feasible paths and travel times of a pollutant in the aquifer and so the possible problems that these contaminants can cause to the well field of Civitanova Marche, a detailed groundwater flow numerical model related to the drinking well field area has been developed, in steady and transient conditions, using Feflow 6.0 from Wasy inc (finite elements code).

The model has four layers and reproduces a multilayer semi-confined aquifer characterized by a shallow and a deep levels. In the first aquifer the hydraulic conductivity (k) is ranging from $1*10^{-3}$ m/s to $5*10^{-3}$ m/s (storativity 0.20); in the second aquifer k is ranging from $1*10^{-3}$ to $5*10^{-4}$ m/s (storativity $1.3*10^{-3}$); the intermediate local aquitard has k 10^{-5} m/s and storativity 10^{-2}. The recharge applied in steady model is 95 mm/y according with climatic data. In the first slice, along the Chienti River, a Cauchy boundary condition has been inserted. Constant head conditions have been applied along western (22 m a.s.l) and eastern (0 m a.s.l.) limits of all slices and in correspondence with the river location, in the slices deeper than shallow one. Along the northern limit a no-flow boundary condition inhibits flow entering or exiting from the hydrogeological basin. The model simulates the real W-E trend of groundwater flow, obtaining a good correlation between simulated and measured piezometric values (RMS 0.76 in the steady state simulation; RMS 0.69-0.9 in the transient one). The whole flow budget shows a comparable rate between entering and exiting flow from the model, but a critical situation in the SW area, at the contact between western and southern boundaries, is observed. This contact, combined with a significant hydraulic gradient (8‰) and with a hydraulic conductivity of about 10^{-3} m/s, generates an unexpected and perhaps unrealistic interchange of groundwater in that area. Detailed analysis of this local situation reveals modeling inaccuracy where different boundary conditions were applied in a boundary area characterized by complex hydrogeological setting.

Key words: *groundwater contamination, numerical model, domain geometry*

INTRODUCTION

The lower valley of Chienti River, located in the Marche region, has been interested since '90s by a diffused contamination by chlorinated solvents (mainly PCE). During the 1980s and 1990s, the main chlorinated compound used by shoe manufacturers located in the study area was 1,1,1-Trichloroethane (1,1,1-TCA), which was substituted by Perchloroethene (PCE) in the last 15 years. Since 1997 to 2005 the study area has been monitored by USL (Local Public Health Unit) and ARPAM (Regional Agency for Environmental Protection) with the aim to verify the extent and the concentration of the latest contamination by PCE and the residual one by TCA (Petitta & Pacioni, 2010); and since 2009 the public authority has been sustained by University of Rome La Sapienza. In 2001 the lower valley of Chienti River has been proclaimed National Interest Polluted Site and in 2003 the perimeter of the site that includes a land area of about 26 km^2 and a marine area of 12 km^2 has been defined. In 2013 the study area has been downgraded from National Interest Site to Regional Interest Site.

With the aim to characterize in detail the groundwater flow in the lower valley of Chienti River and to identify possible paths of contaminants in groundwater, a new detailed numerical groundwater flow model related to a drinking well field area has been developed, in steady and transient conditions, from a previous steady-state wider flow model. The numerical code used is Feflow 6.0 (DHI-WASY GmbH, 2010), which is a finite elements code that can be efficiently used to describe the spatial and temporal distribution and reactions of groundwater contaminants, to estimate the duration and travel times of chemical species in aquifers, to plan and design remediation strategies and capture techniques, and to assist in designing alternatives and effective monitoring schemes.

STUDY AREA

The lower valley of Chienti River, located in the Marche region between the districts of Macerata and Fermo, has a SW-NE trend between Trodica di Morrovalle and Civitanova Marche (Fig. 1). This valley is limited at North and South by Macerata - Montecosaro ridge and by Corridonia - Montegranaro ridge, respectively. Chienti River flows from Adriatic side of Umbria-Marche Apennines to Adriatic sea, after receiving Ete Morto

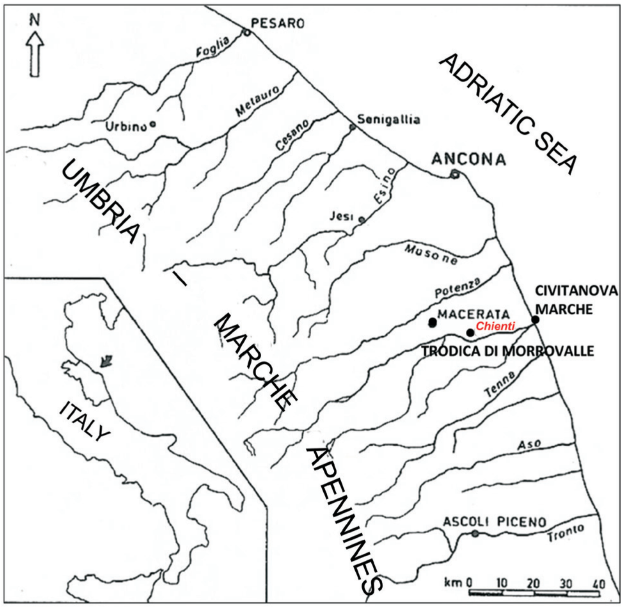


Fig. 1 - Location of lower valley of Chienti River (after Nanni & Vivalda*, 1986, modified)*

Stream, the only tributary of the study area.

The lower valley of Chienti River is established in the Peri-adriatic basin of Marche Region, which is made up Plio-Pleistocene clays, sands and conglomerates (Fig. 2). These sediments are the bedrock of the Chienti River Valley, which is characterized by four orders of fluvial terraces of which the oldest outcrops upstream, and the latest outcrops downstream of the valley (Nanni & Vivalda, 1986).

The continental sequence includes sand and silty sand, interbedded with silty-clay levels; more recent deposits are mainly silty, covered by vegetated soil. These deposits are differently located along the valley, and low permeability layers are variable in thickness and location (Fig. 3). As a consequence, alluvial deposits of the Chienti River Valley host a multilayer porous aquifer, by gravels in a sand-silt matrix. Silty-clay low-permeability lenses have locally created multilayer and perched aquifers. The aquifer is semi-confined in some locations, while at the regional scale groundwater flow is considered to be homogeneous (Pacioni *et alii*, 2010). The piezometric map (Fig. 4) shows predominant groundwater flow from west to the coastline revealing a mean hydraulic gradient of 0.5%. Evidences of river/groundwater interactions are observed along the stream and a clear piezometric depression coincides with a drinking water well-field.

As regards the climatology, the Chienti River Valley can be included in the first area described by Amici & Spina (2002) characterized by climate from wet to semiarid, with rainfall between 600 and 850 mm/year (Regione Marche, 2008).

METHODS

A hydrogeological conceptual model has been developed for the alluvial aquifer taking into account the presence of low permeability lenses, forming a multilayer semi-confined aquifer, as shown by hydrodynamic tests (pumping and flowmeter heat-pulse tests) coupled with standard and multilevel hydrochemical and isotopic samplings and physical-chemical parameter logs (Petitta *et alii*, 2013).

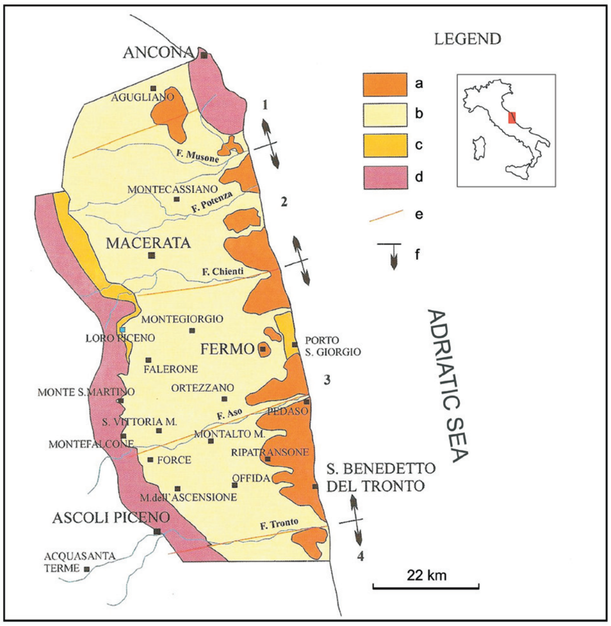


Fig. 2 - Geological model of Periadriatic Basin of Marche Region. a) upper sands and conglomerates; b) upper blue clays; c) lower blue clays; d) pre-Pliocene deposits; e) faults; f) sector limit; 1) Ancona sector; 2) Macerata sector; 3) Fermo sector; 4) Teramo sector (after Cantalamessa et alii, 2002)

After the conceptual model of groundwater flow, a numerical flow model has been realised. This regional model has an area of 68 km^2. It is constituted by a soil layer, two aquifer lay-

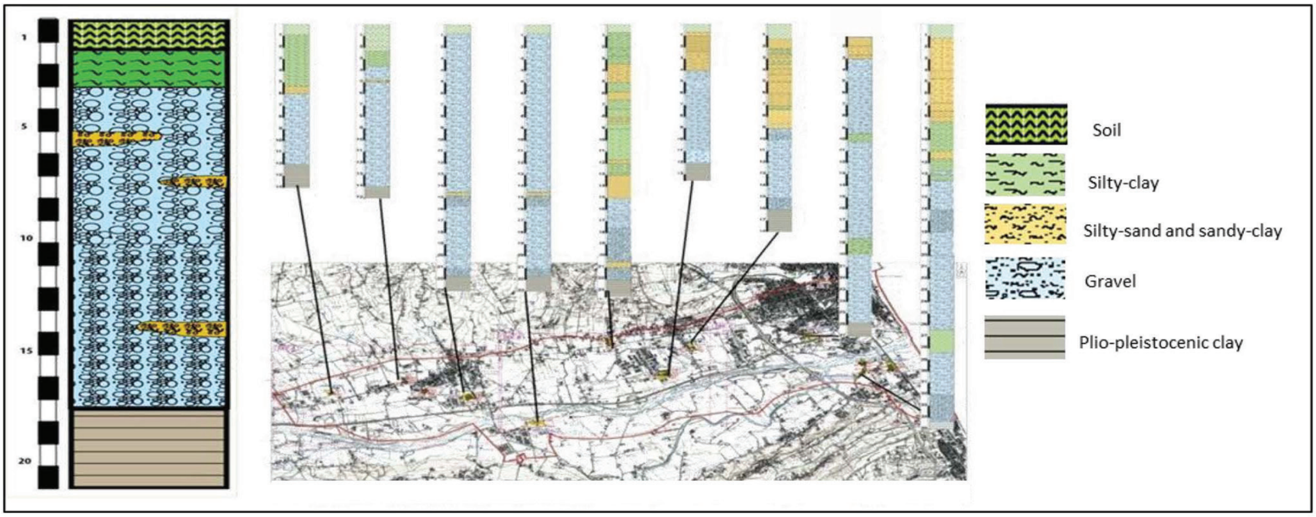


Fig. 3 - Stratigraphic distribution along the Chienti Valley (after Petitta & Pacioni, 2010)

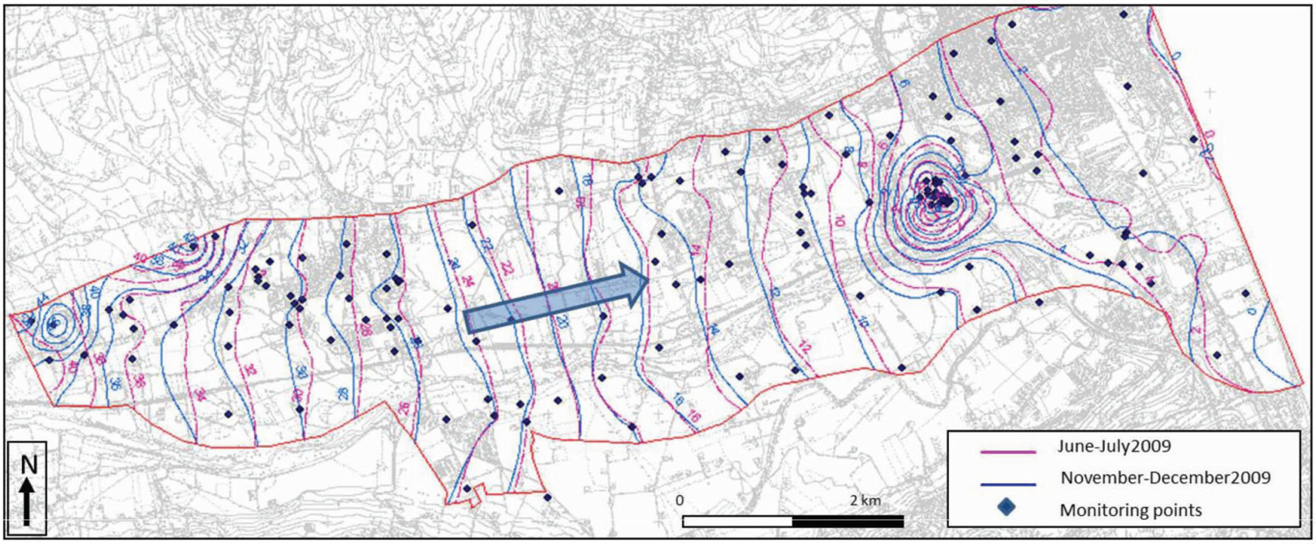


Fig. 4 - Piezometric map. In purple June-July 2009 piezometric contours; in blue November-December 2009 piezometric contours, in diamond monitoring points (after Petitta *&* Pacioni*, 2010)*

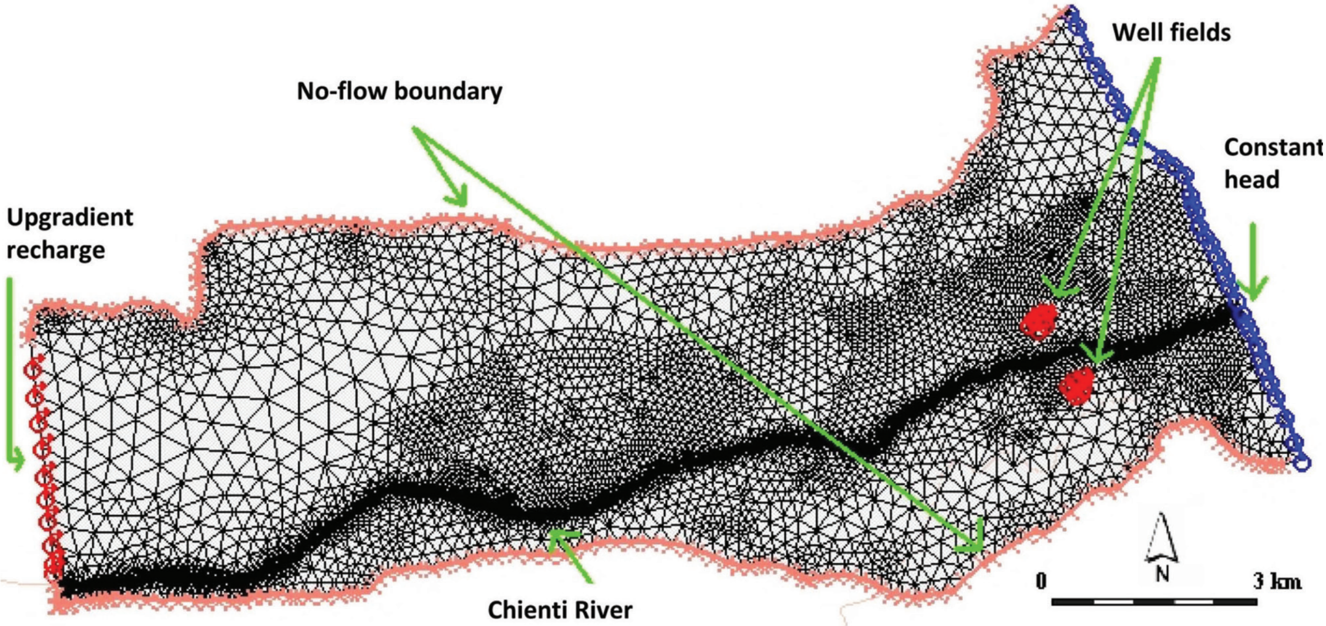


Fig. 5 - Numerical model domain and boundary conditions (after Pacioni *et alii, 2010)*

ers and one interbedded low-permeability layer. The model domain is characterized by northern and southern no-flow limits, corresponding to geological boundaries defined by terraces; a constant head of 0 m a.s.l. has been imposed along the shoreline; an inflow rate of 0.05 m^3/s coming from upgradient and rainfall recharge of 227 mm/y have been included as boundary conditions (Fig. 5). After the validation of this model (Fig. 6), a new local fine scale model has been carried out, related to the drinking well field area in steady and transient conditions, with the aim to analyze the feasible path and travel times of a pollutant in the aquifer and so the possible problems that these contaminants can cause to the drinking well field.

The fine scale model, realized with Feflow 6.0 (by DHI-WASY), covers an area of about 19.5 km^2 from Montecorsaro to Civitanova Marche (W-E direction) and from fluvial terraces at North to Chienti River at South (Fig. 7). In order to reproduce a

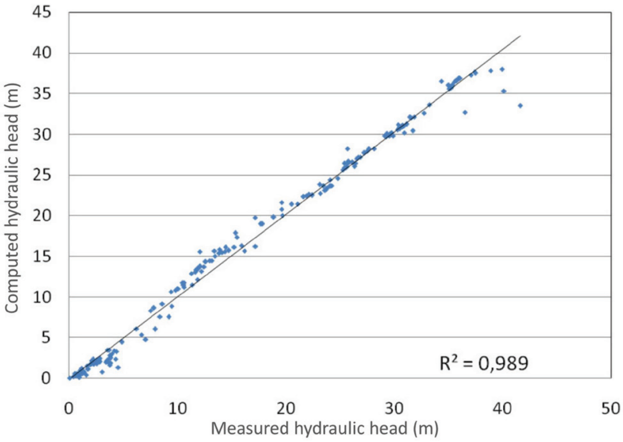


Fig. 6 - Scatter plot of simulated vs measured hydraulic heads (after Pacioni *et alii, 2010)*

multilayer semi-confined aquifer characterized by a shallow and a deep levels, the model domain has been divided in four layers and five slices: 1) layer 1 - soil; 2) layer 2 - shallow aquifer (gravels and sands); 3) layer 3 - aquitard (silts and sandy-clay silts); 4) layer 4 - deep aquifer (gravels and sands).

The topography of the slices has been reconstructed by Pacioni *et alii* (2010) analyzing and reworking about 175 stratigraphic logs available in the area and returned them to the four layers listed above. In areas where one of these levels is not present, it was still represented in the model by imposing a thickness of 10 cm, so as to be sufficient for the proper functioning of the model, but having low influence on the groundwater flow of the aquifer.

The hydrogeological characteristics have been imposed at each layer based on bibliographic data and on pumping test results. In the first aquifer the horizontal hydraulic conductivity (k_x) is ranging from 1*10^{-3} m/s to 5*10^{-3} m/s, vertical conductivity (k_z) is one order of magnitude lower and storativity is 0.20; in the second aquifer k_x is ranging from 1*10^{-3} to 5*10^{-4} m/s, k_z is one order of magnitude lower and storativity is 1.3*10^{-3} (Fig. 8); the sandwiched local aquitard has k_x 10^{-5} m/s, k_z one order of magnitude lower and storativity 10^{-2}.

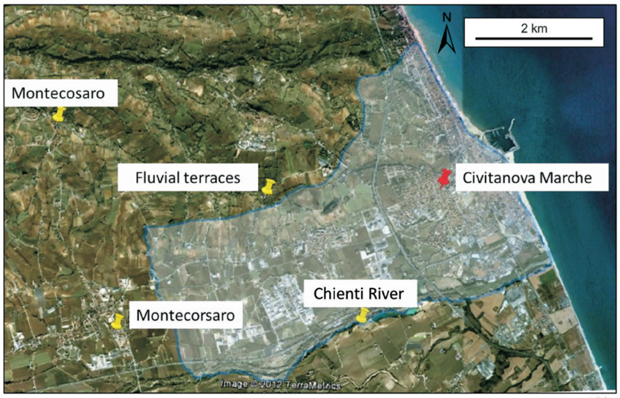


Fig. 7 - Area of fine scale numerical model (Google Maps)

The recharge applied in steady model is 95 mm/y according with climatic data; this value has been obtained from effective precipitation through Thornthwaite method (Thornthwaite, 1948), by averaging years since 2000 to 2008 and considering a C.I.P. (potential infiltration coefficient) of 50% respect with effective precipitation.

As regards the boundary conditions, in the first slice a Cauchy boundary condition has been applied along the Chi-

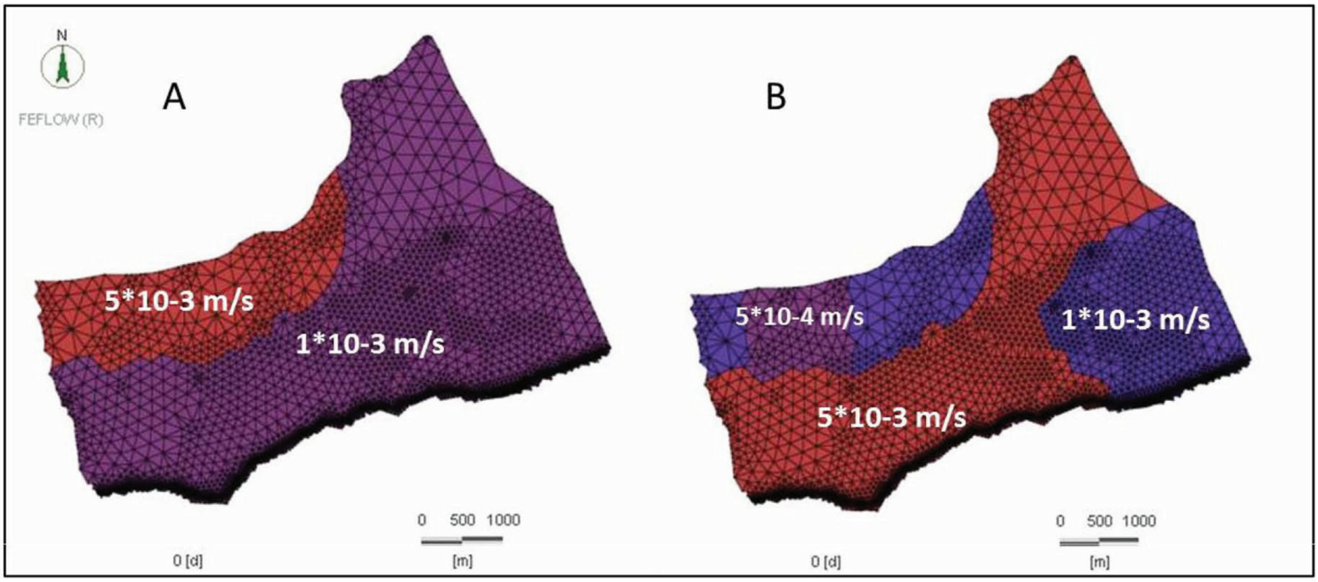
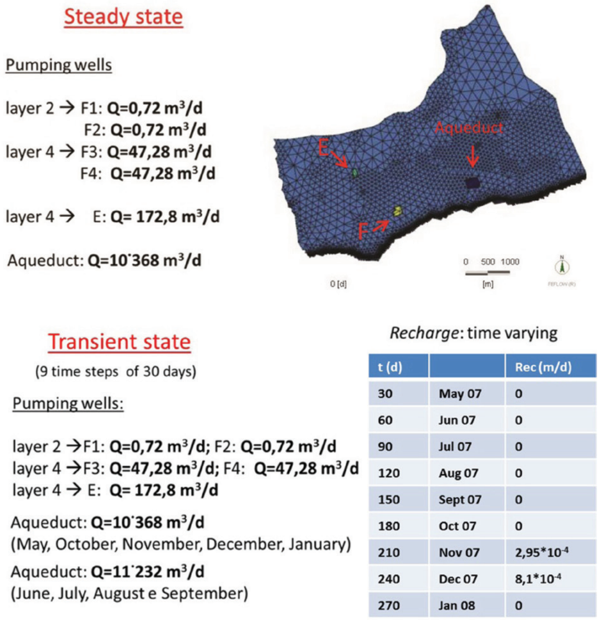


Fig. 8 - Horizontal conductivity distribution of shallow (A) and deep (B) aquifers

enti River, in order to simulate the existing interaction river/groundwater observed by discharge measurements. Constant head conditions have been applied along western and eastern limits of all slices and in correspondence with the river location in the slices deeper than shallow one. Imposed values are obtained from measured piezometric levels. Along the northern limit a no-flow boundary condition inhibits flow entering or exiting from the hydrogeological basin (Fig. 9). In the steady-state model constant head at the western limits has been evaluated 22 m a.s.l., which corresponds to the hydraulic head measured in

t (day)		Constant head (m a.s.l.)
30	May 2007	22,0
60	June 2007	21,7
90	July 2007	21,3
120	August 2007	21,0
150	September 2007	21,0
180	October 2007	21,2
210	November 2007	21,7
240	December 2007	21,8
270	January 2008	21,8

Tab. 1 - Constant head applied at western limit in the transient model



Steady state

Pumping wells

layer 2 → F1: **Q=0,72 m^3/d**
F2: **Q=0,72 m^3/d**
layer 4 → F3: **Q=47,28 m^3/d**
F4: **Q=47,28 m^3/d**

layer 4 → E: **Q= 172,8 m^3/d**

Aqueduct: **Q=10˙368 m^3/d**

Transient state

(9 time steps of 30 days)

Pumping wells:

layer 2 →F1: **Q=0,72 m^3/d**; F2: **Q=0,72 m^3/d**
layer 4 →F3: **Q=47,28 m^3/d**; F4: **Q=47,28 m^3/d**
layer 4 → E: **Q= 172,8 m^3/d**

Aqueduct: **Q=10˙368 m^3/d**
(May, October, November, December, January)

Aqueduct: **Q=11˙232 m^3/d**
(June, July, August e September)

Recharge: time varying

t (d)		Rec (m/d)
30	May 07	0
60	Jun 07	0
90	Jul 07	0
120	Aug 07	0
150	Sept 07	0
180	Oct 07	0
210	Nov 07	$2,95*10^{-4}$
240	Dec 07	$8,1*10^{-4}$
270	Jan 08	0

Fig. 10 - Rates of pumping wells in steady and transient model; recharge in the transient model

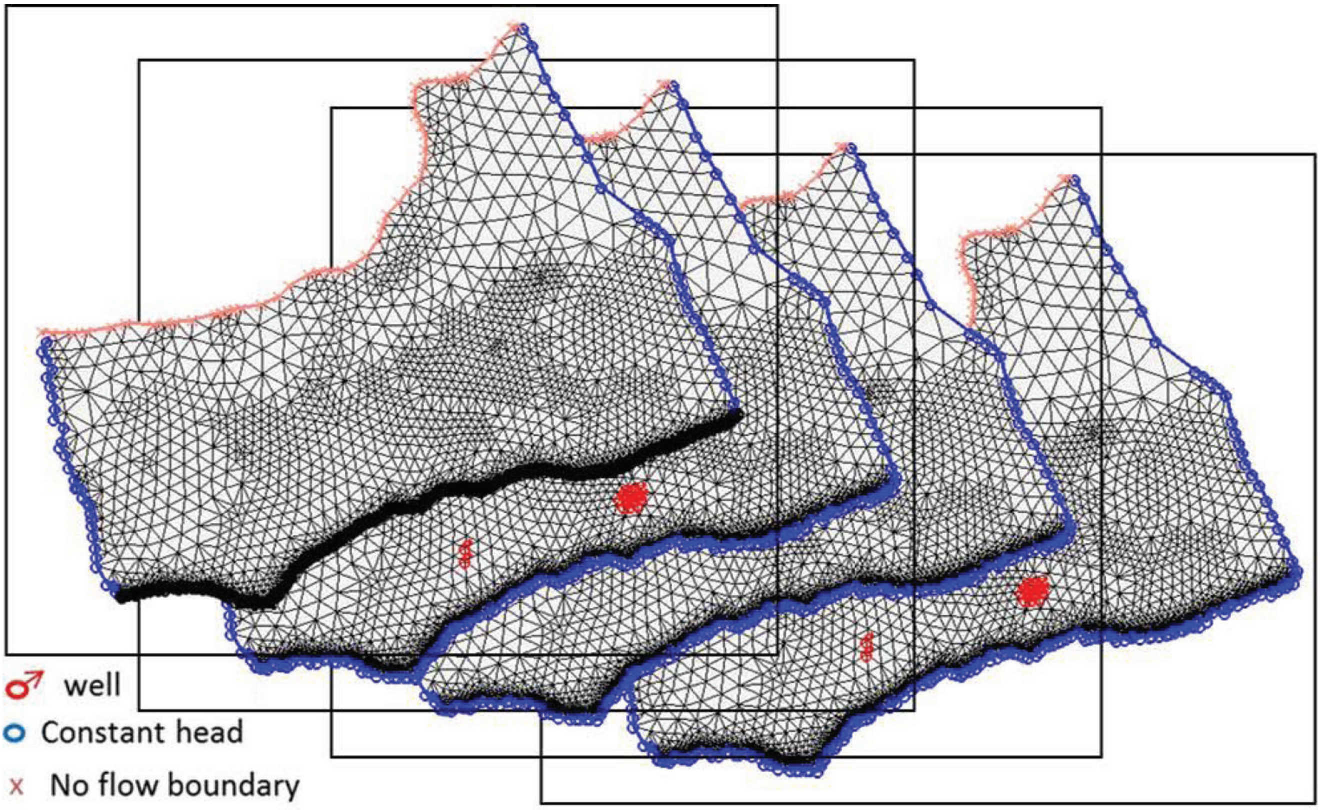


Fig. 9 - Domain and boundary conditions of the fine scale model for each slice

this section in May 2007 (ARPAM, 2007); otherwise at the eastern limit the value is 0 m a.s.l. because this limit corresponds with the shore line. In the transient model (9 time steps, each of 30 days) the constant head at eastern limit is always 0 m a.s.l., instead at western limit it varies monthly as shown in Tab.1, because of the monthly fluctuation of measured piezometric level. The model includes also the drinking well field and pumping wells of the local manufacturers (E,F) (Fig. 10). The applied flow rates in the steady and transient models are shown in figure 10, which also shows the monthly trend of applied recharge in the transient model, calculated from Thornthwaite method.

The calibration of steady-state model has been performed using the real piezometric distribution of May 2007; the transient model has been calibrated using the real piezometric distribution of May 2007, August 2007 and January 2008.

RESULTS AND DISCUSSION

The numerical model simulates the real W-E trend of groundwater flow with a progressive decrease of hydraulic heads from upstream (about 22 m a.s.l.) to downstream (0 m a.s.l.), obtaining a positive correlation between simulated and measured values (RMS 0.76 in the steady state model; RMS 0.70, 0.9 and 0.69 in the transient one, respectively at May 2007, August 2007 and January 2008) (Fig. 11). The whole flow budget shows a comparable rate between entering and exiting flow from the model. In particular, as it is shown in figure 12, most of the inflows derives from Dirchlet conditions (4.10*10^4 m^3/d) and from Recharge (5.07*10^3 m^3/d), instead a small contribution (3.10*10 m^3/d) is given by interaction river/groundwater. This situation could be attributed to the imposed condition of equal elevation between the water table and the river, based on limited data and on the assumption of a steady-state equilibrium between surface waters and groundwater. As regards outflows, for the same reason, a small contribution is given by interaction river/groundwater (8.70*10^2 m^3) and instead, major contributions are due to Dirichlet conditions (3.40*10^4 m^3/d) and Wells (1.06*10^4 m^3/d). A critical situation in the SW area, at the contact between western and southern boundaries, is observed (Fig. 13). In fact, the higher rates of inflow groundwater are in the SW area, where inflow about 24000 m^3/d of water from the most southern area of upstream, and suddenly exit about 12000 m^3/d of water from the most eastern area of southern limit (Fig. 13). This unexpected and perhaps unrealistic interchange of groundwater in that area is due to the model geometry, which shows a perpendicular contact between boundary conditions, combined with a higher hydraulic gradient (8‰) and with a hydraulic conductivity of about 10^{-3} m/s. Detailed analysis of this local situation reveals modeling inaccuracy where different boundary conditions were applied in a boundary area characterized by complex hydrogeological setting.

The particle tracking function was applied in order to analyze the possible path and travel times of a pollutant that moves by advective transport. The results of this simulation show that a particle input in the shallow aquifer travels at lower velocity than a particle input in the deep aquifer. In fact, the particles input in the shallow aquifer along a section located upstream of the

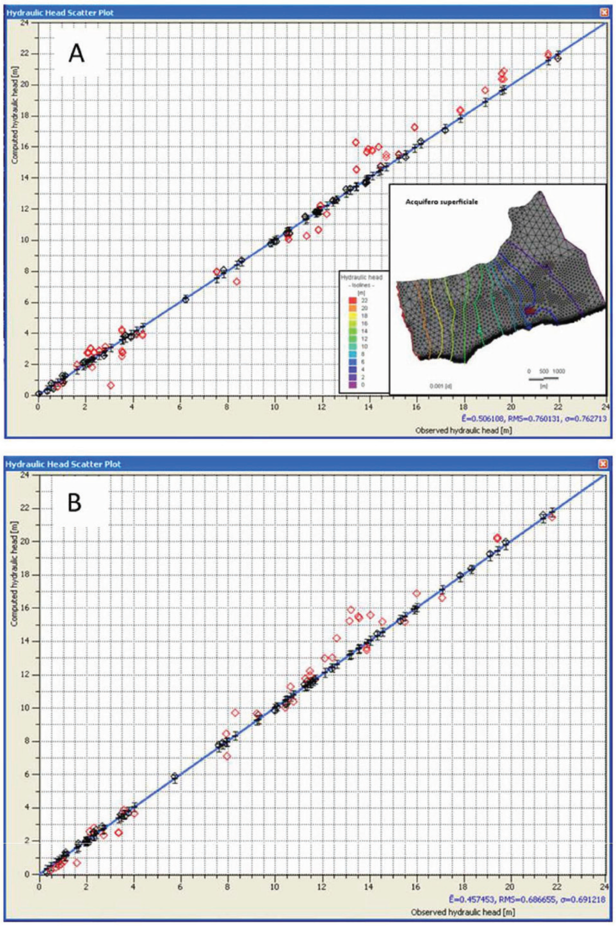
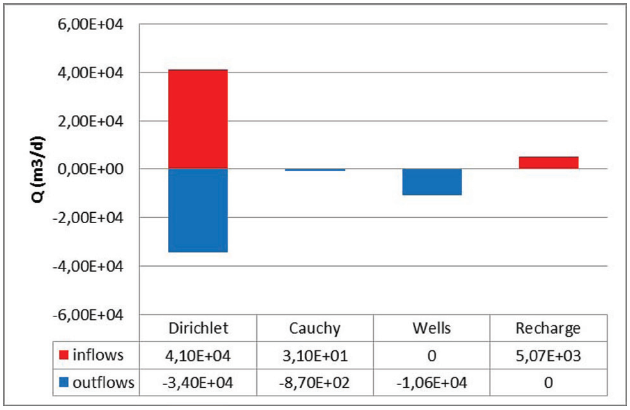


Fig. 11 - Measured and simulated hydraulic heads of the steady state model (A) (R^2 = 0,9878) and of transient model (B) (R^2 = 0,9900) (January 2008)



	Dirichlet	Cauchy	Wells	Recharge
🟥 inflows	4,10E+04	3,10E+01	0	5,07E+03
🟦 outflows	-3,40E+04	-8,70E+02	-1,06E+04	0

Fig. 12 - Budget analysis of the steady state model

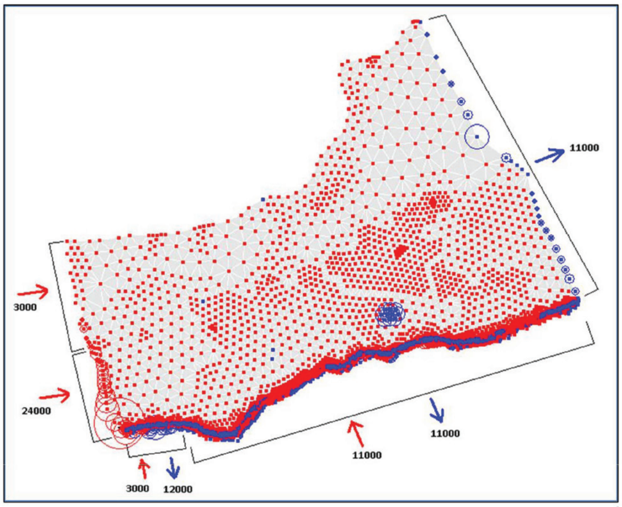


Fig. 13 - Map of the flow budget for the steady state model. Values in m³/d. Red dots represent the inflows, blue dots represent the outflows. The size of dots are proportional to the rates

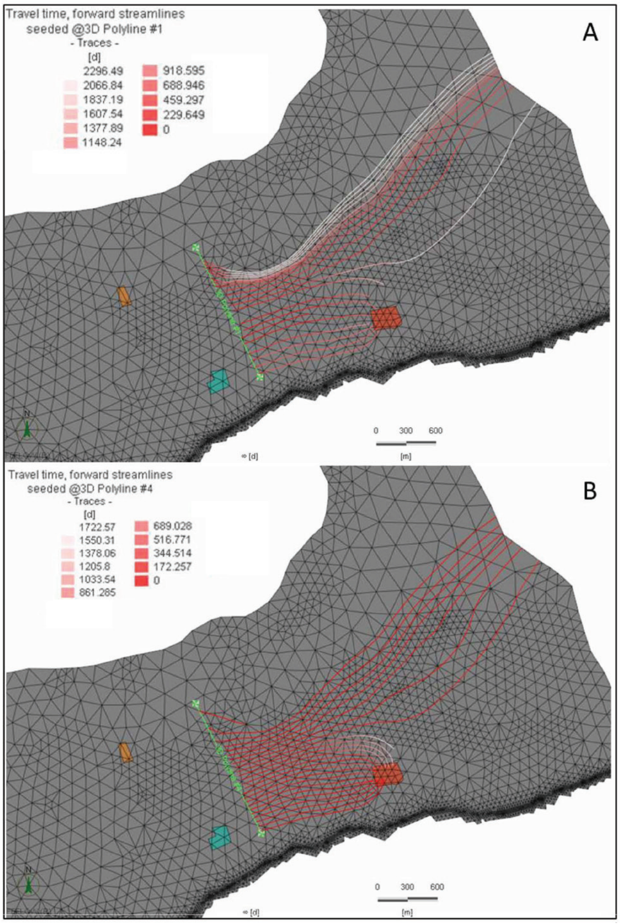


Fig. 14 - Particle tracking in shallow (A) and deep (B) aquifers. The drinking well field corresponds to the red box

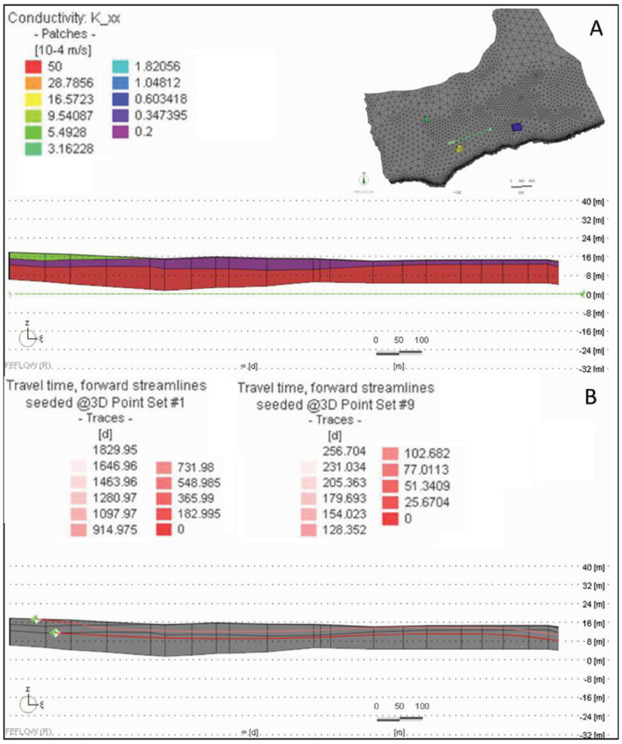


Fig. 15 - Simulation of advective transport along a transect and related section of hydraulic conductivity (A) and particle tracking (B). 3D Point Set#1 is particle input in shallow aquifer, 3D Point Set#9 is particle input in deep aquifer

Civitanova Marche drinking well field, will take two and a half years to get there; otherwise the particles input in the deep aquifer along the same section will arrive at the same goal after one and a half year (Fig. 14). This difference in the velocity is due to lower hydraulic conductivity in the shallow aquifer and then because a particle input in the shallow aquifer must pass through the aquitard ($k_x=10^{-5}$ m/s, $k_z=10^{-6}$ m/s) between shallow and deep aquifer before reaching the drinking well field (Fig. 15).

CONCLUSION

The alluvial aquifer of lower valley of Chienti River, in the past polluted National Interest Site and now polluted Regional Interest Site, is contaminated by chlorinated solvents (mainly PCE) and for this reason it has been continually monitored during the time by USL, ARPAM and University Sapienza of Rome. The analysis have carried to reconstruction of a conceptual model of groundwater flow. According to it, in the area there is a main aquifer constituted of gravelly sediments in a sandy matrix with high values of trasmissivity. This aquifer is often interbedded by variable thicknesses of fine sediments which locally can act as aquitard and isolate perched aquifers.

Based on this conceptual model and on a large-scale numerical model, a new local fine-scale numerical model has been carried out, both in steady and transient conditions, applied to the lower valley of the Chienti River, with the aim to analyze the feasible path and travel times of a pollutant in the aquifer and so the possible problems that these contaminants can make to the well field of Civitanova Marche.

Both models coherently reproduce the flowpath having W-E direction, with an high correlation coefficient between simulated and measured water table. Hydrological budget analysis allows to confirm the important role of Dirichlet conditions, while river/water table interaction appears to be very limited. This situation could be attributed to the imposed condition of equal elevation between the water table and the river, based on limited data and on the assumption of a steady-state equilibrium between surface waters and groundwater.

The perpendicular contact on the SW boundary, combined with a higher hydraulic gradient (8‰) in this area and with a hydraulic conductivity of about 10^{-3} m/s, generates an unexpected and perhaps unrealistic interchange of groundwater in that area. Detailed analysis of this local situation reveals modeling inaccuracy where different boundary conditions were applied in a boundary area characterized by complex hydrogeological setting. All collected data, coupled with the numerical model, can be used as management tools for planning an effective remediation project and also to ensure the protection of drinking well field, requiring a carefully revision of the simulation model. In detail, the river/water table interactions seem to have a significant uncertainty at the actual stage of knowledge and also a revision of the geometry of the domain is required in order to avoid problems linked to the intersection of different boundary conditions in a complex hydrogeological setting.

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