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HYDROGEOLOGICAL NUMERICAL MODELING OF THE SOUTHEASTERN PORTION OF THE LUCCA PLAIN (TUSCANY, ITALY), STRESSED BY GROUNDWATER EXPLOITATION

Abstract - R. Giannecchini, M. Ambrosio, A. Del Sordo, M-T. Fagioli, A. Sartelli, Y. Galanti, *Hydrogeological numerical modeling of the southeastern portion of the Lucca Plain (Tuscany, Italy), stressed by groundwater exploitation*.

In the hydrogeological field, the numerical modeling is well known as a powerful tool to set up a management strategy that can prevent groundwater mining. To overcome its somehow "exoteric fame", it needs as many as possible of local field tests in order to become real world common practice in groundwater management. The Lucca Plain aquifer shows a severe piezometric drop associated to an unregulated competition between agriculture, industry, public and private drinking water wells. It was chosen to test a finite difference numerical model capability as a crisis analysis and forecasting tool and as a regulatory action technical support benchmark. The southern Lucca Plain geological and hydrogeological conceptual model was translated into a MODFLOW grid. Public and private pumping wells were monthly surveyed from January 2007 to October 2008. Calibration allowed the numerical model to achieve a good statistical correspondence with reality. The resulting virtual reality highlighted the heavy hydrogeological stress affecting the area, where pumping rate significantly exceeds the recharge in the studied period. The sensibility analysis highlighted rainfall recharge and pumping rate as the more sensitive values among the input data. Since the calibration process implied a remarkable increase of the officially declared pumping rate, numerical modeling, when a lot of calibration data are available, showed promising capability of back-analysis to estimate the real pumping rate for a given area.

Key words - groundwater flow, numerical modeling, exploitation, water-resource conservation, Tuscany, Italy

Riassunto - R. Giannecchini, M. Ambrosio, A. Del Sordo, M-T. Fagioli, A. Sartelli, Y. Galanti, *Modello idrogeologico numerico del settore sud-orientale della Piana di Lucca (Toscana, Italia) caratterizzato da sfruttamento intensivo delle risorse idriche.*

In campo idrogeologico la modellazione numerica è un potente strumento che permette di simulare le caratteristiche di sottosuolo rispetto alla circolazione idrica, e quindi di effettuare previsioni sul comportamento del sistema in seguito a sollecitazioni naturali ed antropiche. Peraltro, un efficace modello numerico su cui basare una corretta strategia di gestione della risorsa idrica presuppone una approfondita conoscenza delle caratteristiche idrogeologiche del sito oggetto di studio. La falda contenuta nell'acquifero in ghiaie del settore sud-orientale della Piana di Lucca mostra un generale abbassamento del livello piezometrico causato da ingenti prelievi idrici che localmente causano un'inversione della direzione naturale del deflusso, allargando il fronte di richiamo delle acque di falda. In questo contesto è stato scelto di testare la capacità di un modello con codice di calcolo MODFLOW al fine di individuare eventuali aree di crisi della risorsa idrica. I livelli piezometrici per l'implementazione del modello sono stati misurati mensilmente da gennaio 2007 a ottobre 2008 in pozzi pubblici e privati. La calibrazione del modello ha permesso di ottenere una buona corrispondenza tra il comportamento reale e simulato della falda. La modellazione numerica ha evidenziato lo stress idrogeologico a cui è sottoposta l'area, dove il prelievo supera significativamente la ricarica nel periodo esaminato. L'analisi della sensibilità ha individuato le precipitazioni efficaci e il tasso di emungimento come i parametri più significativi all'interno del modello. Considerando che durante la calibrazione sono stati incrementati i valori degli emungimenti dichiarati ufficialmente dai gestori dei pozzi, la modellazione numerica, quando sono disponibili molti dati di input, mostra anche una promettente capacità di *back-analysis* per la stima del reale tasso di sfruttamento della risorsa idrica in una determinata area.

Parole chiave - flusso idrico sotterraneo, modellazione numerica, risorse idriche, sfruttamento idrico, Toscana, Italia

Introduction

Groundwater is the world most extracted raw material with withdrawal rates currently in the estimated range of 982 km^3/year (Margat & Van der Gun, 2013) and represents the most important, safest and reliable source of drinking water in many areas of the world, widely exploited also for industrial and agricultural use (Zhu & Balke, 2008; Smith *et al.*, 2016). Alluvial plains commonly house the most important aquifers available for water supply, for either drinking use, or industrial and irrigation use. On the other hand, owing to their greater logistic and economical convenience for settlements and communication, the plains are usually particularly exposed to significant social and economic development. Nevertheless, such development often does not consider the real requirements and resources (not only of water nature) availability that a territory could actually fulfil. This can determine stress conditions (Vorlicek *et al.*, 2004; Qiuhong *et al.*, 2006; Taniguchi *et al.*, 2009). Dragoni & Polemio (2009) estimated the water withdrawal by wells in plain areas of northern Italy in about 85%, while the groundwater resource in Italy represents the 85-90% of the total.

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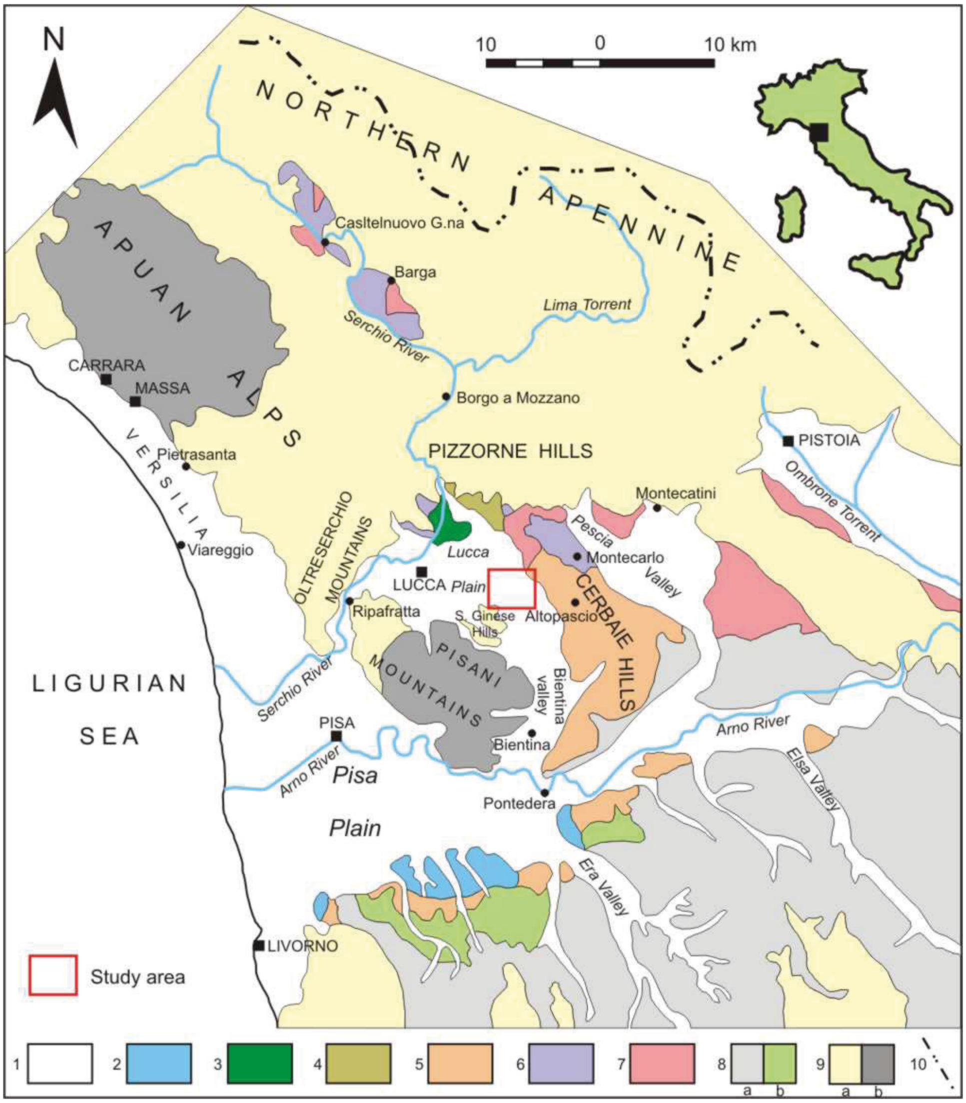

Figure 1. Geologic sketch map. 1) Post-würmian alluvial deposits; 2) Vicarello Sands Fm. (upper Pleistocene); 3) Serchio gravel (Würm II); 4) Lacustrine and fluvial-lacustrine deposits (2nd cycle, medium Pleistocene); 5) Altopascio-Cerbaie fluvial deposits (medium Pleistocene); 6) Montecarlo pebbles and Macigno Fm. pebbles of Garfagnana (post-Villafranchian); 7) Lacustrine deposits (1st cycle, up. Ruscinian-up. Villafranchian); 8) Marine deposits (a: low.-medium Pliocene; b: low. Pleistocene); 9) Substratum (a: Miocene neo-autochthon sediments, Tuscan Units, Ligurian Units; b: Apuan Alps and Pisani Mountains metamorphic rocks); 10) Apennine watershed (after Puccinelli, 1991; modified).

The problem of the water resource management is certainly worldwide topical. The social and economic relevance of water determined the common noun of "blue gold". Furthermore, in the last decades many authors stressed a gradual and progressive decrease of the springs discharge, both in Italy (Sauro, 1993; Cambi & Dragoni, 2000; Fiorillo *et al.*, 2007, Passadore *et al.*, 2012; Doveri *et al.*, 2019) and in several other countries, as China (Ma *et al.*, 2004; Qian *et al.*, 2006; Guo *et al.*, 2019), France (Labat *et al.*, 2002), Germany (Birk *et al.*, 2004), Romania (Oraseanu & Mather, 2000), India (Negi & Joshi, 2004; Kaur & Rishi, 2018), Turkey (Ozyurt & Bayari, 2008). According to other authors (e.g. Meenzel & Burger, 2002; Drogue *et al.*, 2004) this phenomenon could be associated also to the global climatic change.

The numerical modeling approach to aquifers and water resources started many years ago, but the limited capacity of computers did not let significant results. At present, more and more powerful machines and software allow to reproduce complex realities, providing realistic simulations if based on copious and robust input data. Numerous are the example in literature, regarding both porous and fractured aquifers (e.g.

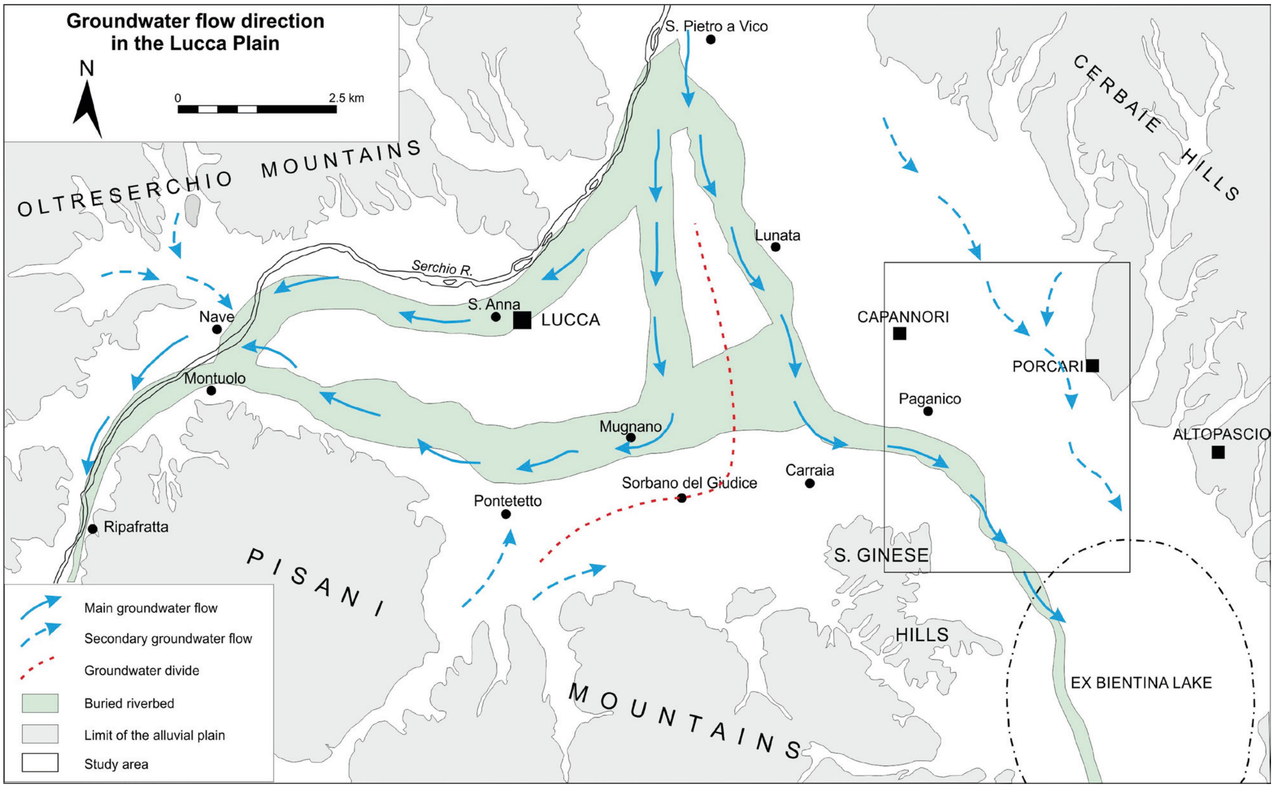

Figure 2. Chief and secondary groundwater flow directions in the LP (after Nardi *et al.*, 1987; modified).

Brunner *et al.*, 2010; Rani & Chen, 2010; Alam *et al.*, 2011; Passadore *et al.*, 2012; El Mezouary *et al.*, 2015; Chen *et al.*, 2017; Masetti *et al.*, 2017).

Here, an example of the groundwater numerical modeling applied to the Lucca Plain (LP; northwestern Tuscany) aquifer is presented. For many centuries the hydrogeological and hydraulic problems of the LP have been the centre of attention of either inhabitants or offices delegated to the water resource management. The local aquifer, mainly characterized by gravels and pebbles in sandy matrix, host a very rich aquifer, abundantly fed by infiltration of the Serchio River and by superficial and underground water inflows from the neighboring hills and mountains. Since remote ages, this apparently inexhaustible aquifer was exposed to considerable withdrawal (Ambrosio *et al.*, 2010). Several aqueduct feeding wells-fields were drilled, attending to a population greater than local inhabitants, while in recent times this water richness attracted many highly water-requiring industries, in particular paper mills. In fact, in the LP resides one of the most important European paper industry poles. The progressive aquifer depauperation also produced "side effects", such as subsidence (Canuti *et al.*, 2005), micro-sinkholes (Dell'Aringa *et al.*, 2010, 2014) and drying up of many Roman-type superficial wells.

Since the Eighties (Nardi *et al.*, 1987) the quantitative evaluation and sustainability assessment of the water resource of the LP are not available, also owing to scarcity and inaccuracy of underground data. At present, more careful geological and hydrogeological information is available, allowing at applying techniques of numerical modeling.

Based on an efficient hydro-stratigraphic database and a significant series of water table surveys carried out on a sample area of the plain, the applicability of the groundwater numerical modeling was verified. Moreover, the potentiality of the calibration instruments in the individuation and quantification of the unlikely determinable water stresses (e.g. not declared pumping) was tested.

Setting

The modeling area is included in the southeastern portion of the LP and was selected for high groundwater exploitation, including several water wells-fields, industrial poles (paper), numerous domestic wells, drainage canals and wide agricultural areas. It is bounded by the Cerbaie hills to the E and the Pisani Mountains (S. Ginese hills) to the SW; in the latter, the Macigno Formation (a sandstone with interbedded siltstone flysch) prevails.

The LP is included in the northern portion of a wide NW-SE tectonic depression (Trevisan *et al.*, 1971)

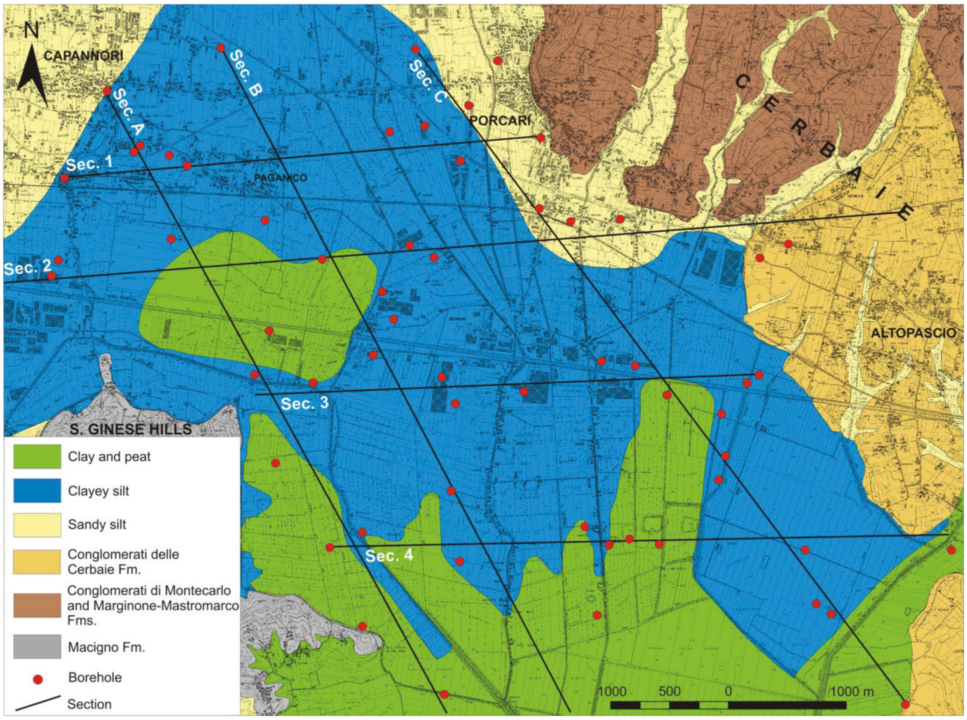

Figure 3. Geologic map of the study area. The litho-stratigraphic logs and the geological-hydrogeological sections used in modeling are also located (after Nardi *et al.*, 1987; modified).

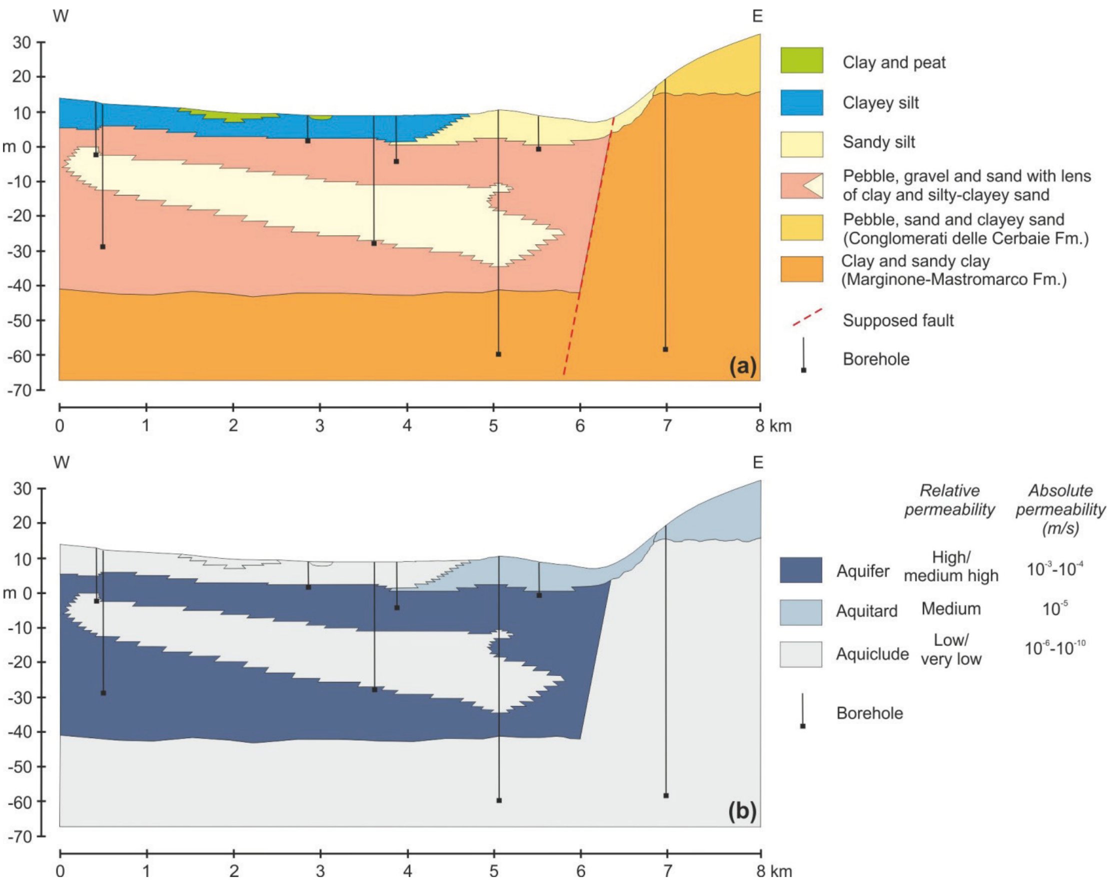

Figure 4.a) An example of litho-stratigraphic section (no. 2 in Fig. 3) used to implement the numerical model. b) The same section 2 converted into hydro-stratigraphic section on the basis of the hydraulic conductivity of the deposits.

and bounded by the Pizzorne hills (N), Cerbaie hills (E), Bientina valley (SE), Pisani Mountains (S), Oltreserchio Mountains (W-SW). Since Pliocene, the depression was filled by lacustrine sediments of the Lucca-Montecarlo-Vinci cycle (upper Ruscinian-upper Villafranchian, 1st lacustrine cycle *Auctt.*), overlapped by fluvial sediments of the Altopascio-Cerbaie cycle (medium Pleistocene) and by the Paleo-Serchio River Quaternary alluvial deposits (Puccinelli, 1991; Fig. 1).
The present course of the Serchio R. only partially corresponds with the ancient one (Federici & Mazzanti, 1988). In fact, since Pleistocene a dense canals network crossed the LP; the main of such canals flowed southward, flowing into the Arno River. The progressive raising of the Arno R., owing to its aggradation, caused the Serchio R. obstruction and the formation of lacustrine areas, in particular close to Bientina (*ex* Sesto or Bientina Lake). As consequence, the Serchio R. stopped to flow towards Bientina, turning towards Ripafratta and flowing directly to the sea.
The hydrogeological structure of the LP is strictly linked to its paleogeographic evolution. The coarse gravel deposited by the ancient Paleo-Serchio R. forms the main aquifer, unconfined to the North and semiconfined or confined southward. In fact, the gravel outcrops in the northern portion of the plain and deepens towards the South, covered by finer materials (silty-sandy, silty-clayey and peaty-clayey from North to South; Nardi *et al.*, 1987). The aquifer is mainly formed of gravel, sand and pebbles, including lens of clay and silty-clayey sand. The impermeable bedrock of the aquifer is mainly formed of the Pleistocene clay of the 1st Lucca-Montecarlo-Vinci lacustrine cycle. The thickness ranges from 10-15 m (northern portion) to 40 m (southeastern portion, *ex* Bientina Lake area; Nardi *et al.*, 1987).
The most important groundwater flows of the LP follow the ancient and buried riverbeds of the Paleo-Serchio R. that, from S. Pietro a Vico village, run along three paths: Lunata-Paganico-Bientina; Mugnano-Montuolo; S. Anna-Nave (Fig. 2).

Data quality and space-time distribution

The stratigraphic (borehole logs) and hydrogeological (hydraulic conductivity, transmissivity, storage coefficient, effective porosity) investigation was based on searching for information mainly in technical documentation, publications, archives, etc. The data density resulted higher close to towns, villages, industrial areas and well-fields.
The piezometric surface data were collected by means of 11 monthly field surveys from December 2007 to October 2008 on approximately one hundred wells and piezometers. The hydrometric level of the local ditches and drainage canals was contextually measured. One of the most critical data was instead the total pumping rate, particularly important for the realistic estimation of the output in the water budget. In fact, many industrial water wells were not regularly registered in the Public Administration archive. Moreover, the local aqueduct management society did not provide the real pumping rate of the well-fields, but only some generic information, such as pump capacity, pump working time, etc. The pumping rate associated to agricultural activity was approximately obtained directly interviewing the irrigation wells and boreholes owners.
Finally, rainfall and thermometric data related to the modeling period December 2007 - October 2008, collected by 13 meteorological stations in the study area and surroundings, were provided by the Tuscany Region Hydrologic Service.

Hydrogeological conceptual model

The hydrogeological model was mainly based on Nardi *et al.* (1987) and Baldacci *et al.* (1994), and updated using many stratigraphic data resulting from new boreholes. In particular, the superficial geologic data were mostly obtained by Nardi *et al.* (1987) and by the official Tuscany Region geologic cartography (CARG Project), improved and modified according to the new litho-stratigraphic boreholes data collected during this research (Fig. 3).
In order to define the hydrogeological model, seven litho-stratigraphic cross sections (three NW-SE and four E-W) were drawn (Fig. 3). Then, basing on the mean hydraulic features of the deposits, the litho-stratigraphic sections (Fig. 4a) were converted into hydrogeological sections (Fig. 4b), grouping together deposits with close hydrogeological properties, independently from their chrono-stratigraphic classification.
Fig. 4a shows, as example, the litho-stratigraphic cross section no. 2 (see Fig. 3 for location). An impermeable basement is recognizable, formed of clay and sandy clay of the Marginone-Mastromarco Fm. (Lucca-Montecarlo-Vinci lacustrine cycle, 1° lacustrine cycle *Auctt.*). The aquifer system lies above this Formation by an erosional contact. As already explained, the aquifer is mainly constituted by gravel, sand and pebbles, interbedded by discontinuous horizons and lens of clayey silt with sand and clayey sand; the hydraulic conductivity (K) ranges from 2×10^{-5} m/s to 8×10^{-3} m/s for the aquifer and is approximately 5×10^{-8} m/s for the silty-clayey lens.
From the northern portion of the study area to the southern one, silt with sand ($K \approx 10^{-5}$ m/s), silt ($K \approx 10^{-6}$ m/s) and silt with peat ($K \approx 10^{-7} \div 10^{-8}$ m/s) overbed the

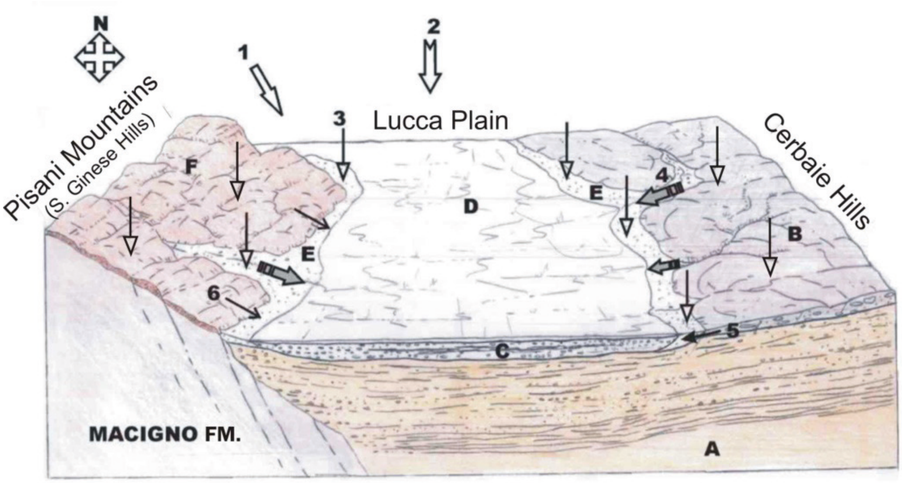

Figure 5. Hydrogeological schematic model (after Baldacci *et al.*, 1994; modified) of the Lucca Plain included between S. Ginese and Altopascio to the S and Paganico to the N (A: clay and sandy clay – Marginone-Mastromarco Fm.; B: pebbles, sand and clayey sand – Conglomerati delle Cerbaie Fm.; C: gravelly-sandy deposits of the Paleo-Serchio R.; D: silty-clayey deposits with peat; E: alluvial fan deposits; F: colluvium; 1: recharge by Paleo-Serchio R. Quaternary coarse deposits; 2: recharge by northern hills; 3: direct infiltration; 4: lateral recharge by Pisani Mountains and Cerbaie torrents; 5: lateral recharge by aquitards; 6: lateral recharge by colluvial covers of the S. Ginese Hills-Pisani Mountains). Arbitrary scale.

aquifer. To the East the aquifer is laterally bounded by clay and sandy clay of the Marginone-Mastromarco Fm., surmounted with an erosional contact by the Conglomerati delle Cerbaie Fm. (pebbles, sand and clayey sand partially cemented; $K \approx 5\times10^{-5}$ m/s), belonging to the Altopascio-Le Cerbaie lacustrine cycle.
To the NW of the study area the aquifer continues in the LP, while to the SW it is bounded by the Pisani Mountains, in this area (S. Ginese hills) mainly formed of the Macigno Fm. (sandstone and siltstone interbedded by phyllite).
Fig. 5 shows the hydrogeological model of the study area (after Baldacci *et al.*, 1994; modified). Above the impermeable base (lacustrine deposits), the aquifer is surmounted by finer deposits mainly referable to silt, typical of distal flooding area. The aquifer system is significantly fed by the Paleo-Serchio River Quaternary alluvial coarse deposits, directly linked to the Serchio R. (see also Fig. 2) and, subordinately, by the runoff from Cerbaie hills and Pisani Mountains. Smaller recharge is attributable to the arenaceous (Macigno Fm.) bedrock of the S. Ginese Hills (Pisani Mountains), scarcely permeable, while the bedrock of the Cerbaie hills supplies a greater contribution.

Water table measurement

A correct numerical modeling calls for a careful calibration of the output. Calibration consists in the comparison between the modeling results, namely the piezometric map resulting from the numerical model, and the really observed piezometric data. In order to fulfil such need, 11 monthly on-site piezometric surveys were carried out from December 2007 to October 2008 on 97 observation wells. The latter were selected on the basis of the Lucca Province database, verifying their location, accessibility and functionality. Most of them are "Roman-type" dug wells or ring-wells, characterized by large diameter and small depth (max 15 m) and located in the northern portion of the study area. Drilled wells are instead present in the southern part, where the aquifer is deeper.
The analysis and comparison of the 11 piezometric maps (linear interpolation method) powerfully highlighted the groundwater overexploitation areas. Independently from the season, wide and deeply depressed areas of the water table are recognizable around the well-fields. Fig. 6 shows the piezometric maps in April (water table high stage) and October (low stage) 2008. In October the depression related to the Pacconi well-field does not appear. This is not due to a local raising of the piezometric level (e.g. well-field deactivation), but to data lack for the impossibility of getting in the well-field. This could be also the reason for which the water table depression is not present around the Paganico well-field.
From April to October a general lowering of the piezometric surface (about 1 m to the N and 3 m to the S) is evident. The difference between North and South area is probably due to the higher groundwater pumping from the latter.
In the previously described hydro-stratigraphic context of the area, the groundwater flow should be mainly directed towards SE (*ex* Bientina lake – see Fig. 2); nevertheless, the considerable pumping involving this area induces a significant SE-NO flow, as already highlighted by Nardi *et al.* (1987), in a direction opposite to the natural one.

Numerical modeling

The modeling process starts developing a conceptual model simpler than reality. A mathematical model is then constructed to simulate the conceptual model. If the conceptual model is complex, a complex mathematical model is required, complicating also the mathe-

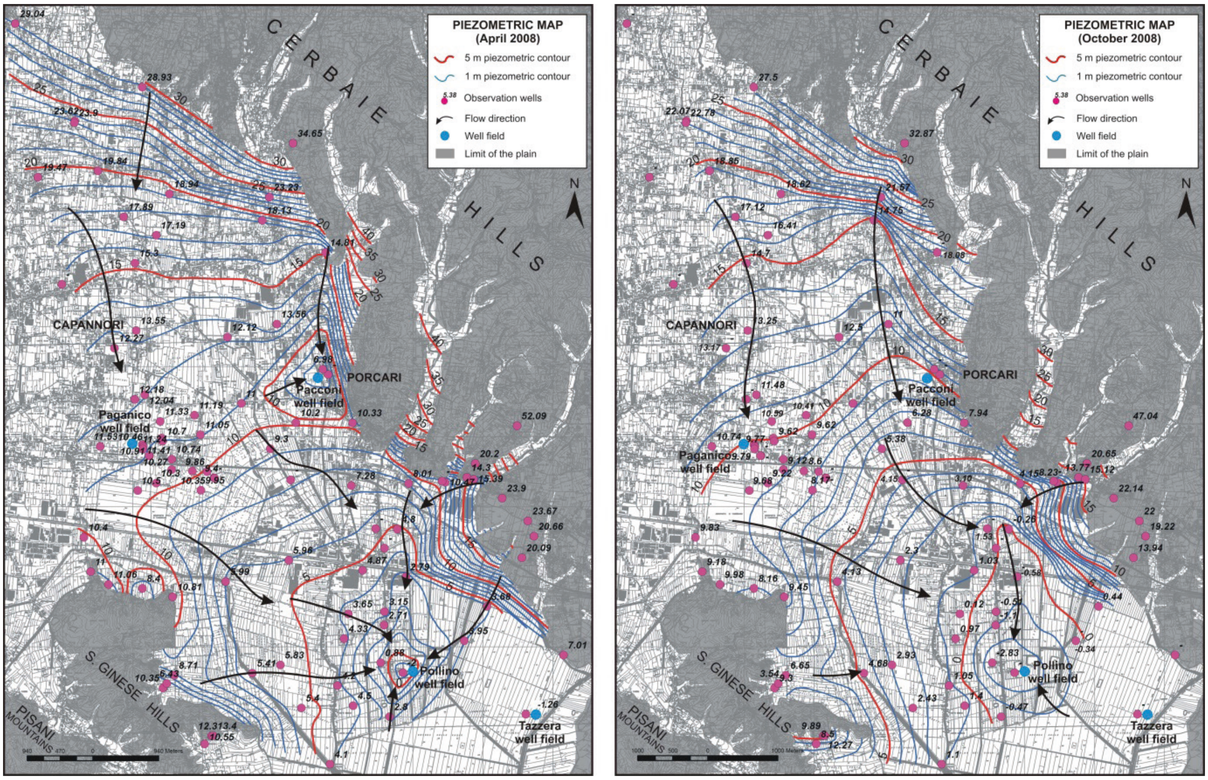

Figure 6. Piezometric surface map in high (April 2008) and low (October 2008) stage (after Ambrosio *et al.*, 2010; modified).

matical computation. Therefore, the transformation of every physical reality in a calculated numerical model implies a series of simplifying hypotheses, whose importance is in inverse relation to data number, distribution homogeneity and quality. This is certainly the main problem in groundwater numerical modeling (Voss, 2011).

At present, most approaches for groundwater flow modeling are mainly based on three possible methods: finite differences, finite elements, or analytic elements. Every method has strengths and weaknesses and no one method is the right tool for every problem (Fitts, 2002). In relation to the case study, the finite difference approach was used by means of Visual MODFLOW (Waterloo Hydrogeologic). It uses the calculation engine MODFLOW, arranged for the USGS by Trescott & Peter (1975) and Trescott *et al.* (1976a, 1976b), and revised by McDonald & Harbaugh (1988), Harbaugh & McDonald (1996a, 1996b), Harbaugh *et al.* (2000). In the difference finite method the continuous system described by the partial-differential equation of groundwater flow (McDonald & Harbaugh, 1988) is replaced by a finite series of discrete points both in space (cells) and time (stress periods).

$$\frac{\partial}{\partial x}\cdot\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\cdot\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\cdot\left(Kz\frac{\partial h}{\partial z}\right)+W=Ss\frac{\partial h}{\partial t}$$

where:
Kx, Ky, Kz: values of hydraulic conductivity along the x, y, z coordinate axes, assumed to be parallel to the major axes of hydraulic conductivity (Lt^{-1}); h: potentiometric head (L); W: volumetric flux per unit volume representing sources and/or sinks of water, with $W < 0$ for flow out of the groundwater system, and $W > 0$ for flow in (T^{-1}); Ss: specific storage of the porous material (L^{-1}); t: time (T).

The resulting equation is the continuity equation (2):

$$\sum Qi = Ss\cdot\frac{\Delta h}{\Delta t}\cdot\Delta V$$

where:
Qi: flux discharge of every cell (L^3t^{-1}); Ss: specific storage of the porous material (L^{-1}); $\Delta h/\Delta t$: variation of the potentiomentric head in time (Lt^{-1}); ΔV: variation of volume of every cell (L^3).

The continuity equation establishes that the sum of the flow in and out of a single cell corresponds to the volume variation of the groundwater contained in the same cell (storage). All the external disturbances (e.g. pumping, evapotranspiration, drainage, etc.) add a term in the continuity equation, with negative or positive sign depending on water supply or withdrawal from every cell.

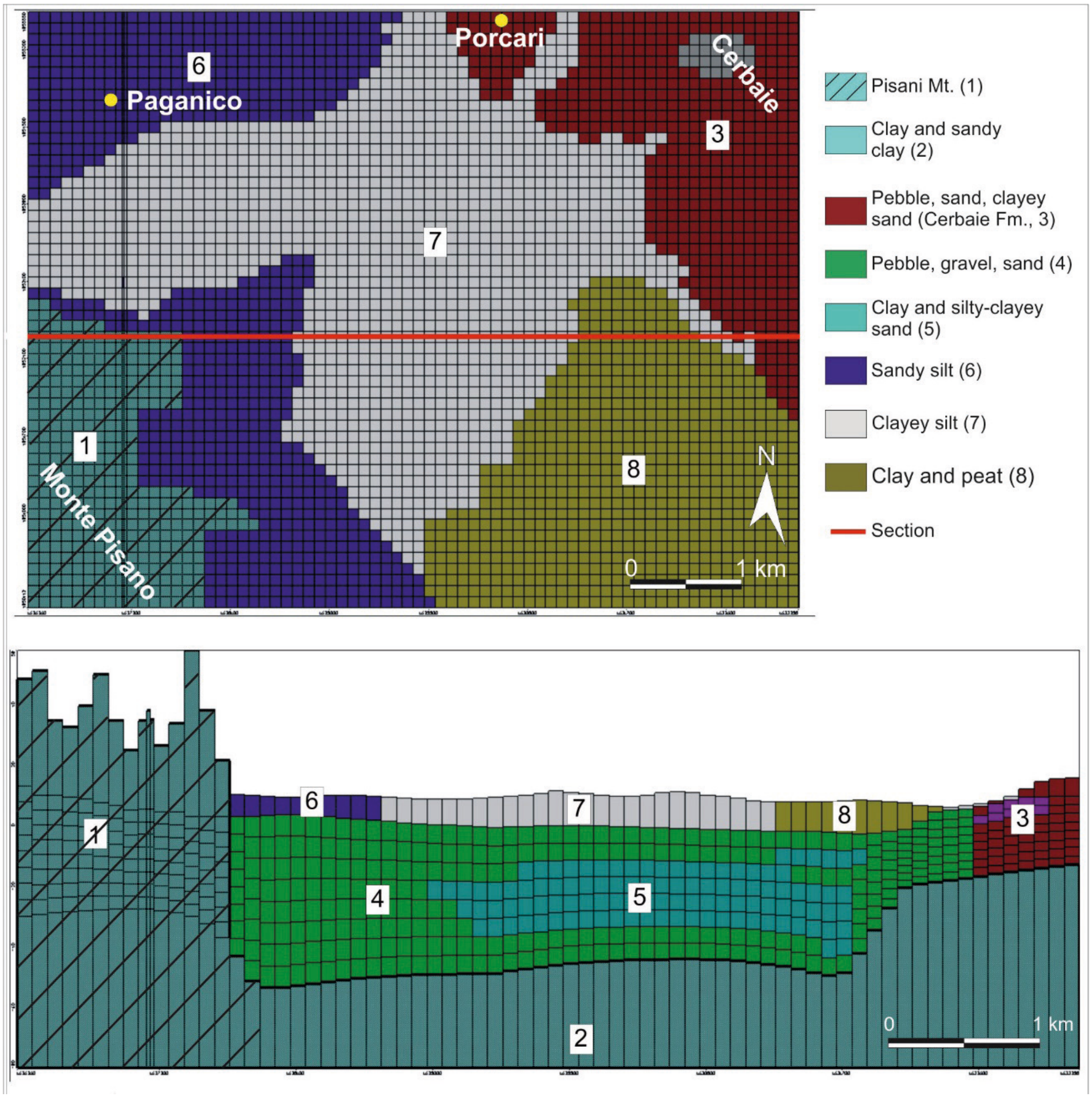

Figure 7. Hydraulic properties distribution (in plan and section, see Tab. 2) reproduced in the numerical model (vertical scale overemphasized).

The numerical model creates a three-dimensional matrix of the potentiometric head values cell by cell, by means of technique of iterative calculation. This simultaneously solves the continuity equation (in respect to the Darcy law) for all the couples of adjacent cells and for every interval of time set up. The matrix allows to draw virtual piezometric maps, to calculate the water amount which moves between different portions of the modelled volume, and to evaluate the influence of the various terms of the hydrogeological budget, either for the whole model domain or for selected parts of it.

In order to analyze the time evolution of groundwater (transient modeling), several modeling “run” are calculated in sequence carrying out, manually or automatically, adjustments to the parameters varied in time, assuming as starting situation of every run the results of the previous one. The agreement between the implemented model result and the physical reality is verified by the calibration process, namely comparing the potentiometric head values calculated by the model with the measured ones. Therefore, the calibration allows to refine the initial numerical model until it can simulate efficiently the real, physical system. As a consequence, it is possible to produce forecast scenarios and also obtaining indirect information (and eventual correction) for uncertain input data (e.g. pumping rate).

Numerical model implementation

The implementation of a finite difference model requires: definition of the modeling domain; space discretization; time discretization; individuation of domain volumes characterized by homogeneous hydraulic properties; assignation of the hydraulic properties to every homogenous domain volume; quantification of the water fluxes (natural and artificial) between the volume modeled and the external areas.
The modeling domain of the study area was individuated on the Tuscany Region technical map (1:10.000 scale) and imported in Visual MODFLOW as background map. The domain limits are: X min 1626260 m, X max 1633258 m, Y min 4850143 m, Y max 4855550 m (Monte Mario/Italy zone 1 coordinate system), Z min –80 m, Z max 100 m. The altimetry was obtained from the same topographic map and imposed as upper limit of the modeling domain.
The hydrogeological conceptual model suggested a vertical discretization by means of three layers: the first one represents the cover material of the aquifer; the second layer is the aquifer; the third one is the impermeable clayey basement of the aquifer. Then, the second layer was further subdivided into eight layers, in order to represent horizons and lens of inside the aquifer characterized by different hydraulic conductivity (e.g. sandy-clayey lens).
The horizontal discretization was got by a square grid with 100 m wide cells (54 rows and 70 columns). Finally, the time discretization was based on the piezometric survey time intervals. However, a further stress period of 60 days prior the first survey was included as starting and stabilization time of the numerical engine (Tab. 1).
The hydraulic parameterization (hydraulic conductivity *Kx*, *Ky*, *Kz*, total porosity *nt*, effective porosity *nu*, specific yield *Sy*, specific storage *Ss*) was then assigned to the hydrogeological bodies individuated of the conceptual model. Data were obtained by literature (for the impermeable basement), by hydraulic conductivity tests and literature for the aquifer confining layer, by pumping tests for the aquifer (Tab. 2 and Fig. 7).
Owing to the lack of specific quantitative data and considering the probable vertical anisotropy of the aquifer, due to its natural stratified structure, *Kz* was considered lower (one order of magnitude, approximately) than *Kx* and *Ky*. The Macigno Fm., cropping out in portion of Pisani Mountains included in the modeling area, was considered essentially impermeable.

Boundary conditions (constant heads - CH)

The water fluxes at the boundary of the modeling domain were implemented through the "constant heads" technique, namely the piezometric values really measured were imposed at the limit of domain. This implies the loss of some calibration points (those delimiting the modeling area), because a piezometric value used as constant head cannot afterwards used in the comparison between calculated and observed data. This loss is however compensated by the possibility of verifying, with real values, the water fluxes between the modeling area and neighborhood, also considering that the modeling domain is only a little portion of a wider aquifer.

Canals and drainage ditches

The water fluxes between aquifer and canals and drainage ditches were implemented by specific Visual MODFLOW functions, namely "River" and "Drain". The difference is that hydrographic bodies when implemented by the "River" function could both withdraw from and recharge the aquifer, where when implemented by the "Drain" function they could only withdraw

Table 1. Discretization of the calibration time by means of stress periods.

Month (mm/yy)	12/07	01/08	02/08	03/08	04/08	05/08	06/08	07/08	08/08	09/08	10/08
Stress period (days)	0-60	60-111	111-138	138-160	160-187	187-214	214-243	243-271	271-302	302-341	341-375

Table 2. Values of hydraulic conductivity (*Kx*, *Ky*, *Kz*), specific storage (*Ss*), specific yield (*Sy*), total (*nt*) and effective (*nu*) porosity put into the numerical model.

Soil	***Kx* (m/s)**	***Ky* (m/s)**	***Kz* (m/s)**	***Ss***	***Sy***	***nt* (%)**	***nu* (%)**
Clay and peat	5×10^{-8}	5×10^{-8}	5×10^{-9}	3×10^{-2}	2	50	2
Faintly clayey silt	5×10^{-6}	5×10^{-6}	5×10^{-7}	1×10^{-4}	3	30	5
Sandy silt	5×10^{-5}	5×10^{-5}	5×10^{-6}	1×10^{-5}	10	40	10
Pebble and gravel in sandy-silty matrix	2×10^{-5}	2×10^{-5}	$2\cdot10^{-6}$	2×10^{-3}	25	35	25
Clay and clayey-silty sand	5×10^{-8}	5×10^{-8}	$5\cdot10^{-9}$	1×10^{-5}	7	40	5
Pebble in clayey-sandy matrix	5×10^{-5}	5×10^{-5}	5×10^{-6}	1×10^{-5}	20	30	15
Clay and sandy clay	5×10^{-10}	5×10^{-10}	5×10^{-11}	N/D	3	45	4

from the aquifer. However, the first condition occurs only in the northern portion of the modeling domain, where mainly sandy-silty sediments cover the aquifer. The implementation of "River" and "Drain" functions needs of the absolute elevation of the water surface and of the canal bed, length and width of the canal, thickness and hydraulic conductivity of the sediments lying on the bed. The latter is certainly the most uncertain parameter, because the hydraulic network management agencies often did not know it. In such cases, this parameter was obtained by literature considering the grain size of the materials. On the other hand, this approximation did not influence the modeling results. The bed elevation of all the canals and ditches was directly measured close to the several bridges whose elevation is usually indicated in the Tuscany Region technical map.

Recharge and evapotranspiration

Recharge and evapotranspiration were obtained using the thermo-pluviometric data registered by three monitoring stations of the area and its surroundings. The daily rainfall for the whole modeling time was uniformly assigned to the first layer of the modeling domain (for every stress period), with a 20% effective infiltration rate (according to Nardi *et al.*, 1987). The potential evapotranspiration rate was calculated by the Thornthwaite approach (Thornthwaite, 1948; Thornthwaite & Mather, 1955; 1957) for every stress period. The extinction depth of this phenomenon was obviously considered; on the basis of literature (Shah *et al.*, 2007), an extinction depth of 3 and 1 m was assigned to the woodland and to the arable land, respectively. The distinction between such areas was obtained by aerial photo analysis and on-site surveys.

Pumping rate

The estimation of the pumping rate is one of the most difficult parameters to obtain for hydrogeological numerical modeling purposes. On the other hand, the initial input can be afterwards varied during calibration, on the basis of the real (measured) hydraulic head trend, obtaining a pumping rate closer to the real value, in a kind of back-analysis. The pumping rate is considered as external stress by the numerical engine. Information about the pumping rate (well-fields, irrigation, industrial and domestic wells) of the study area

Table 3. Pumping rate (in m^3/day) related to the main well-fields of the modeling domain (see Fig. 8 for location).

ID well	**Pumping rate (m^3/day)**	**ID well**	**Pumping rate (m^3/day)**
1	1,000	103	860
2	250	Paganico 1	1,000
3	400	Paganico 5	1,000
4	400	Paganico 6	1,000
19	15	Pollino 1	1,040
27	250	Pollino 1A bis	2,070
34	50	Pollino 2	800
40	600	Pollino 3 bis	2,020
41	100	Pollino 6	1,900
102	570	Tazzera 11	1,000
Total: 16,325 m^3/day			

Table 4. Calibrated values of the hydraulic parameters of the soils.

Soil	***Kx* (m/s)**	***Ky* (m/s)**	***Kz* (m/s)**	***Ss***	***nt* (%)**	***nu* (%)**	**Sy**
Clay and peat	9.3×10^{-12}	9.3×10^{-12}	7.1×10^{-13}	0.03	0.50	0.10	0.09
Faintly clayey silt	1.2×10^{-8}	1.2×10^{-8}	6.3×10^{-10}	1×10^{-4}	0.30	0.08	0.05
Sandy silt	9.9×10^{-6}	9.9×10^{-6}	9.7×10^{-7}	1×10^{-5}	0.25	0.15	0.10
Pebble and gravel in sandy-silty matrix	3.5×10^{-4}	3.5×10^{-4}	5.3×10^{-6}	3×10^{-4}	0.25	0.20	0.10
Clay and clayey-silty sand	8.0×10^{-6}	8.0×10^{-6}	9.9×10^{-8}	$\times10^{-5}$	0.30	0.05	0.01
Pebble and gravel in silty-sandy matrix	9.7×10^{-6}	9.7×10^{-6}	1.0×10^{-7}	1×10^{-5}	0.30	0.12	0.06
Pebble in clayey-sandy matrix	1.0×10^{-7}	1.0×10^{-7}	7.5×10^{-9}	1×10^{-5}	0.35	0.08	0.06
Pebble and gravel in clayey-silty matrix	1.0×10^{-8}	1.0×10^{-8}	9.5×10^{-9}	1×10^{-5}	0.40	0.05	0.06

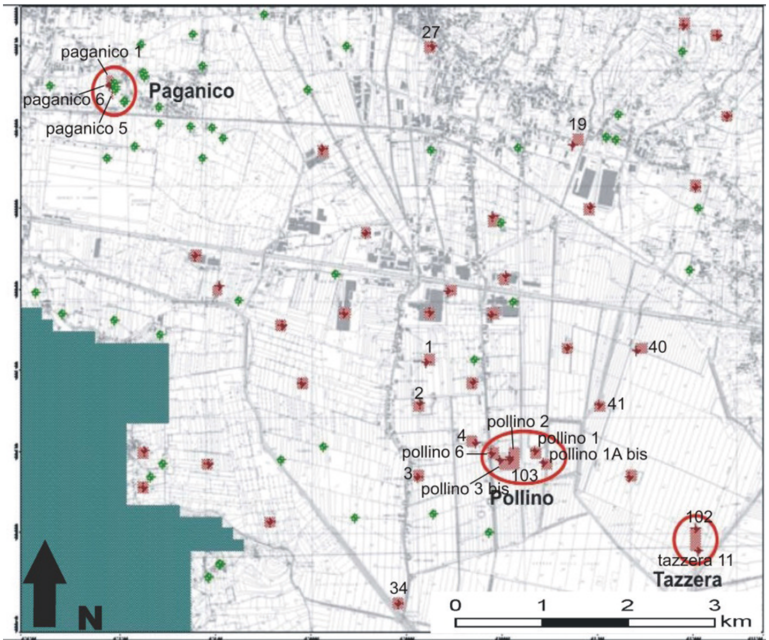

Figure 8. Modeling area with location of the head observation wells (green), used in the calibration process, and of the pumping wells (red).

was provided by the Lucca Province Administration and by the local aqueduct managing company. Nevertheless, the last provided only generic information about the well-fields (pumps theoretical output, pumping about 16 hours/day; Tab. 3 and Fig. 8), but not the real pumping rate attributable to the several well-fields of the area.

The Lucca Province Administration and the local aqueduct managing company also provided the well-screens depth of agricultural/industrial wells and well-fields, respectively, while the screen depth of domestic wells was provided by the owners. Obviously, if the pumping rate associated to the well-field and industrial wells may be consider (theoretically) sufficiently reliable and time constant, pumping rate of agricultural and domestic wells is more variable, depending on season and demand.

Model "run"

Due to the pronounced temporal anisotropy of the main elements of the groundwater budget and to better understand the water crisis of the LP, the transient state approach was used. In order to start the model calculation, a theoretical and uniform water table depth of 0.75 m was assigned. In fact, during the first iteration the numerical engine needs for a water table within the first horizon. To avoid the initial distortion deriving from such an unreal input, the calculation started 60 days before the first calibration date. Obviously, the modeling output produced for this period has not physical significance.

Calibration

The calibration phase is very important in order to verify the agreement between the measured physical reality and the computed virtual reality. This step implies the correction and adjustment of the input data until the degree of real-virtual correspondence fulfils the modeling purposes. This process can be also automated, but in this case a manual variation of the input data (e.g. pumping rate) was preferred. The manual refinement was made by trial, error quantification, new corrected trial and so on, in order to obtain a modeling result as close as possible to the measured data. This approach gives the opportunity to match input values nearer to the real values, initially introduced with large uncertainty. From this point of view, particularly interesting is the possibility of using this approach to achieve semi-quantitative information about hydrogeological data that commonly result difficult or impossible to collect (e.g. pumping rate).

In Fig. 8 the modeling area and the head observation wells used for the calibration process are shown. At the end of the calibration process, Visual MODFLOW provides some calibration graphs, including calculated vs. observed head diagram, calibration residuals histogram, calculated and measured head vs. time, normalized Root Mean Square (RMS) error vs. time. Fig. 9 shows, as example, the first two graphs. The calibration diagrams allow to verify the quality of the numerical processing. The results showed by the diagrams come from the optimization of the hydraulic parameters produced in a semi-automatic approach by means of the function PEST (parameter estimation), included in Visual Mod Flow. The

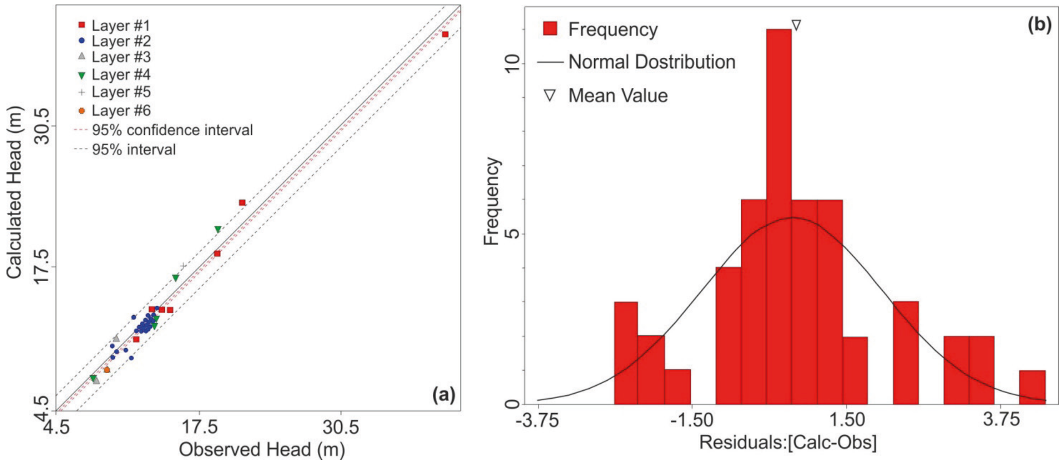

Figure 9. Calibration diagrams: a) calculated vs. observed head diagram; b) calibration residual histogram.

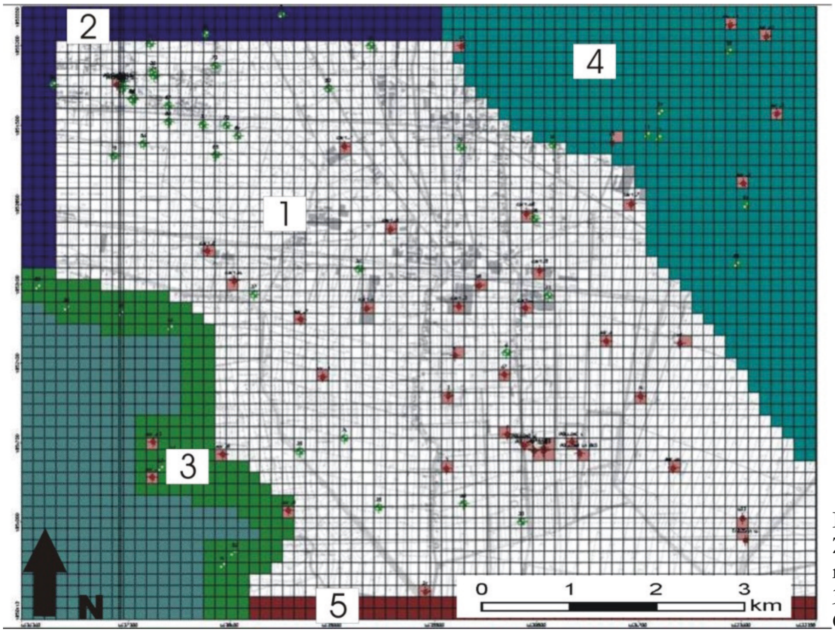

Figure 10. Location of the water budget zones. Zone 1: plain between Paganico and Porcari marsh; Zone 2: NW portion of the aquifer; Zone 3: areas close to the Pisano Mountains; Zone 4: Cerbaie Hills; Zone 5: SE portion of the aquifer.

hydraulic parameters optimized by PEST (Tab. 4) are quite different from those introduced in the first implementation.

A sensibility analysis was carried out in order to individuate the more critical input data as regard the modeling output. As expected, the more sensible input values are represented by rainfall recharge and pumping rate, namely little variation of these factors induces significant modification of the model output. On the contrary, little influence seems to have all the others input data, included the interaction between groundwater and drains/rivers. The last is because the superficial waters are in hydraulic connection with the aquifer only in northern portion of the study area.

As regards the pumping rate, considering the uncertainty of the number and volume of withdrawal, in order to calibrate the model an increase of such data was necessary, according to the following criterion: for each industrial pole individuated by satellite images for which no information was available about the presence of pumping well, a "virtual well" was created. To these "virtual wells" a pumping rate obtained by the average of all the known industrial wells was arbitrarily assigned. Afterword, the pumping rate of every well was corrected by the attempt and error approach, in order to obtain the better agreement between the piezometric level calculated by the numerical model and that measured in the survey. At the end of the calibration process, the normalized RMS, a statistical parameter that provides an estimation quality of the calibration itself, ranges from 1.90% to 4.98% (a good calibration generally includes a RMS minor to 5-10%).

The water budget

The calibrated numerical model allows to quantify the water zone budget. With this purpose, the modeling domain was divided into five areas (Fig. 10):

– Zone 1: flat area included between Paganico village and Porcari marsh and delimited by Cerbaie Hills to the East and Pisano Mountains to the West;
– Zone 2: groundwater flow coming from the northwestern area delimiting the modeling domain;
– Zone 3: areas bounding the Pisano Mountains and mainly represented by alluvial fan;
– Zone 4: Cerbaie Hills;
– Zone 5: southwestern portion of the aquifer characterized by groundwater flow towards the Bientina valley.

In Tabs 5 and 6 the main data resulting from the water budget estimated by the numerical model is shown. The analysis of the water budget suggests that drains, rivers, and evapotranspiration exert a marginal influence on the modeling domain (actually an expected result after the sensibility analysis). On the contrary, the Constant Heads (CH), representing the water exchange with the surrounding areas, assume a certain importance in the water budget. Slightly significant is the water contribution coming from the Cer-

Table 5. In and out groundwater volume (m^3/day) for the modeling domain at the end of every stress period. Day: no. of days in each stress period; Storage: water reserve; CH: constant heads; Wells: pumping wells; Drain: draining canals; River: water volume associated to the rivers; EVP: evapotranspiration; R: rainfall recharge.

Day	Storage		CH		Wells	Drain	River		EVP	R	Total		In-Out
	In	Out	In	Out	Out	Out	In	Out	Out	In	In	Out	
60	1713477	936730	260218	58562	1666802	20531	106	68	175220	884571	2858372	2857913	459
111	642941	1147543	286886	20896	1386181	18775	83	73	30179	1674019	2603929	2603647	282
138	480018	121645	168977	8153	704160	10414	42	45	36770	233735	882772	881187	1585
160	312404	231577	149020	5381	578148	8510	35	39	26876	390418	851877	850531	1346
187	351262	307253	193265	6296	716730	10634	42	53	62345	560355	1104924	1103311	1613
214	357574	286934	202269	6057	748195	10821	37	59	116727	610400	1170280	1168793	1487
243	389410	365247	226400	5649	868802	11923	34	72	184738	822820	1438664	1436431	2233
271	495095	70844	226918	5757	861200	11593	46	69	216707	445890	1167949	1166170	1779
302	950079	431	262149	8143	961224	12258	68	68	285286	58243	1270539	1267410	3129
341	1264004	315	350483	13776	1267780	14382	29	92	309247	207	1614723	1605592	9131
375	478552	65343	330241	15753	904886	11898	10	86	167862	360755	1169558	1165828	3730
Tot	7434816	3533862	2656826	154423	10664108	141739	532	724	1611957	6041413	16133587	16106813	26774

Table 6. In and out groundwater volume (m^3/day) related to the Zone 1 referring to the Constant Heads, pumping wells, draining canals, and to the water exchange with the zones 2, 3, 4 e 5.

Day	Zone 1						Zone 2		Zone 3		Zone 4		Zone 5	
	Storage		CH		Wells	Drain								
	In	Out	In	Out	Out	Out	In	Out	In	Out	In	Out	In	Out
60	11945	5584	0	55	27682	331	4246	0	7028	159	3236	366	298	1
111	8454	17151	0	47	27082	372	4425	0	6167	48	3424	270	513	0
138	11073	3290	0	28	25982	369	4437	0	5972	107	3209	198	467	0
160	9668	8318	0	34	26192	374	4609	0	6055	2	3180	187	465	0
187	9098	9058	0	36	26443	382	4854	0	6149	46	3177	165	507	0
214	9111	8436	0	29	27603	389	4952	0	6813	40	3183	128	559	0
243	10103	9928	0	34	29849	401	4994	0	7068	25	3212	116	598	0
271	12679	1967	0	32	30649	398	4973	0	7103	48	3085	103	628	0
302	22330	4	0	34	30763	372	4618	0	7049	72	2891	93	605	0
341	23342	6	0	37	32263	344	4553	0	7137	106	2684	106	591	0
375	14845	14	0	34	26363	334	4967	0	6503	86	2505	117	450	0

baie Hills (Zone 4), while more important is the water volume coming from the Pisano Mountains alluvial fans (Zone 3) and from the northern portion of the aquifer (Zone 2). The groundwater flow through the southern portion (Zone 5), which should represent the natural direction, is very little and mainly directed to the NW rather than SE, due to the influence of the Pollino well-field.

However, the principal recharge of the modeling domain is represented by rainfall, while the main out groundwater volume is associated to pumping wells. The pumping rate significantly exceeds the recharge, and the water budget closing implies a marked contribution coming from the storage (in the monitored period at least). This confirms the heavy hydrogeological stress characterizing the study area.

As regards the initial implementation of the input data, the pumping rate that allowed a good calibration was increased by 11,700 m^3/day, from 16,300 m^3/day (declared) to 28,000 m^3/day (estimated by the numerical modeling), while the number of wells raised from 22 to 44. Such "new wells" implemented are only virtual and do not have a precise position in the area, but rather represent points having a high probability of concentration of the aquifer exploitation not declared. From this point of view, the numerical modeling, if effectively calibrated, can operate in back-analysis in order to estimate the real pumping rate of a certain area.

Conclusions

The Lucca Plain (LP), subject to water crisis and well known in its geological and hydrogeological structure, provided an interesting test area in order to evaluate the potential of the integrated calibration technique as a tool of individuation and quantification of water stress referable to human activity. The main limit of this methodology is related to the necessity of many geological, stratigraphic and hydrogeological data, and to the availability of detailed and repeated piezometric surveys.

The analysis of a portion of a wider aquifer was compensated by means of the transfer of part of the calibration data to the function "boundary". An extension of this approach on the whole LP aquifer should be desirable in order to test its capacity in the sustainable groundwater management. In fact, a complete and reliable hydrogeological numerical modeling allows the simulation of anticipatory scenarios, varying recharge, pumping rate, well-field location, relation between groundwater and superficial water, etc., allowing at knowing, with consistent advance, the consequence of eventual managing decisions.

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