

Sustainable yield of the Colle Quartara carbonate aquifer in the Southern Lepini Mountains (Central Italy)

Uso sostenibile dell'acquifero carbonatico di Colle Quartara nei Monti Lepini meridionali (Italia Centrale)

Giovanni Conte, Pio Di Manna, Rossella Maria Gafà, Lucio Martarelli, Gennaro Maria Monti, Marco Amanti

Riassunto: Il presente studio è finalizzato a contribuire alla gestione sostenibile delle risorse idriche sotterranee di uno dei più utilizzati acquiferi carbonatici dell'Appennino Centrale, presente in un'area campione dei Monti Lepini (Italia Centrale). Le caratteristiche idrogeologiche a scala regionale dell'idrostruttura dei Monti Lepini sono descritte in letteratura, pertanto, lo studio è stato finalizzato a caratterizzare in modo più dettagliato la porzione meridionale dell'acquifero, settore interessato da campi pozzi che emungono ingenti quantità di acque sotterranee (circa 1,2 m³/s) per approvvigionamento idrico a scopo potabile. Per l'intera area campione è stato eseguito un dettagliato rilevamento geologico, in scala 1:10.000, con criterio litostratigrafico e strutturale, integrato da stazioni geo-meccaniche, analisi della fatturazione e della distribuzione delle principali strutture carsiche. L'acquifero è stato poi caratterizzato attraverso analisi meteo-climatiche, elaborazione di dati da serie idrometriche e di portata sorgiva, interpretazione dei risultati di prove di pompaggio.

Parole chiave: acquifero carbonatico, sfruttamento sostenibile, gestione delle risorse idriche sotterranee Monti Lepini Appennino Centrale.

Keywords: carbonate aquifer, sustainable yield, groundwater resource management, Lepini Mountains, Central Apennines.

Rossella Maria GAFÀ 

Soil Department/Geological Survey of Italy
Applied Geology and Hydrogeology Survey
Italian National Institute for Environmental Protection and Research (ISPRA),
via Vitaliano Brancati 48, 00144 Rome, Italy
Tel: +39.06.50071 - Fax: +39.06.50072916.
E-mail: rossella.gafa@isprambiente.it

**Marco AMANTI, Giovanni CONTE,
Gennaro Maria MONTI, Pio DI MANNA,
Lucio MARTARELLI**

Soil Department/Geological Survey of Italy
Applied Geology and Hydrogeology Survey
Italian National Institute for Environmental Protection and Research (ISPRA), via Vitaliano Brancati 48, 00144 Rome, Italy

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L'attività distensiva plio-pleistocenica ha ribassato il settore tirrenico della successione carbonatica, successivamente ricoperto dai depositi della Piana Pontina, dando luogo ad un acquifero carbonatico in pressione.

Le informazioni raccolte hanno permesso la ricostruzione del modello concettuale idrogeologico del settore in studio. In considerazione della scala operativa delle indagini effettuate e dei risultati ottenuti, l'acquifero carbonatico può essere assimilato ad un mezzo poroso equivalente ed è quindi stato possibile elaborare un modello numerico semplificato dell'acquifero tramite il codice MODFLOW-2005.

Il modello numerico, tuttora oggetto di aggiornamento, ha consentito alcune considerazioni preliminari riguardo alla gestione sostenibile della risorsa idrica sotterranea, permettendo la ricostruzione di possibili scenari alternativi a carico dell'acquifero carbonatico, anche in considerazione dei probabili non significativi scambi idrici con l'acquifero della Piana Pontina.

Abstract: *The present research is aimed to contribute to the groundwater resource sustainable management of a carbonate aquifer in a test area of the Lepini Mountains (Central Italy). This aquifer constitutes a major exploited groundwater body of central Apennines.*

At regional scale, the hydrogeological features of the Lepini hydrostructure are well known. The present study focuses on a portion of the Lepini Mountains where important tapping-works for drinking water supply are in activity (about 1.2 m³/s). New investigations were carried out including: meteo-climatic analysis, spring discharge and hydrometric time series processing, pumping test result interpretation. In addition, a detailed lithostratigraphical and structural survey of a portion of the Lepini hydrostructure at 1:10,000 scale was performed also examining the dense network of discontinuities affecting the carbonate aquifer.

Extensional Plio-Pleistocene tectonic activity displaced the carbonate rock sequence under the Pontina Plain, where the carbonate aquifer is confined. The investigation results have allowed the reconstruction of the hydrogeological conceptual model of the studied portion of carbonate massif. Given the scale of the study and the results of the investigation, the carbonate aquifer can be treated as an equivalent porous medium, and the simplified numerical model of the aquifer was constructed with the code MODFLOW-2005.

The numerical model, still now under continuous implementation, produced first results on the current withdrawal sustainability, allowing evaluation of possible alternative exploitation scenarios of the carbonate aquifer also considering the probably not significant flow exchanges with the Pontina Plain aquifer.

Introduction

This work is aimed to define groundwater resource sustainable management of a carbonate aquifer in a test area of the Lepini Mountains (Central Italy), which constitutes one of the main exploited carbonate aquifers of central Apennines (extension about 535 km²).

Better understanding of karst aquifers and assessment of store groundwater reserves are particularly important where the negative impact of climate variations on the more vulnerable sources is envisaged (Fiorillo and Guadagno 2012, Stevanovic et al. 2015).

To evaluate the effects of different climate scenarios and analyze the sustainability of pumping, aquifer numerical modeling is a useful tool. However, the numerical modeling of a fractured aquifer is rather complicated because of the need for a detailed characterization of the object of investigation system (Kiraly 2003). Recently, this problem is approached by using an equivalent porous medium to represent a fractured aquifer (Romanazzi et al. 2015); this happens especially when the aquifer is densely fractured and has a good stability of the discharge regimen of the main springs, little affected by karstic systems (Boni and Petitta 1994, Lotti et al. 2012).

In recent decades the Pontina area was characterized by a significant increase in human activity, agriculture, tourism and industry. Considering the ongoing climate change (IPCC 2007), this may have consequences in terms of groundwater resources exploitation (Sappa et al. 2005).

The Lepini Mts are part of the Volsci Chain along with Ausoni and Aurunci Mts; they cover an area of about 535 km² and have an average altitude of 612 m with a maximum altitude of 1536 m at Semprevisa Mount. The outcropping terrains belong to the Mesozoic Latium-Abruzzi Succession, made up of limestone and dolostone in carbonate platform

facies, with a thickness of about 4000 m. Previous studies (Boni and Petitta 1994, Celico 2002, Teoli et al. 2014) have already defined an hydrological conceptual scheme of the area. Under the Pontina plain, the carbonate structure was lowered by Plio-Pleistocene tectonics and the hosted carbonate aquifer is confined and feeds the adjacent aquifers of the Pontina plain.

The Lepini Mts were affected by numerous studies (Mouton 1977, Boni et al. 1980, 1986, Celico 1983, Sappa et al. 2005), which concerned the quantitative hydrogeology of the Lepini ridge and flat. Previous studies had developed finite difference numerical models related to the whole carbonate ridge (Boni and Petitta 1994, Celico 2002) and its relations with the flat (Teoli et al. 2014).

The present study, as regards the realization of the hydrogeological field surveys, focuses on a small portion of the Lepini Mountains, Colle Quartara (4.65 km²), where both a significant hydrogeological parameters control network and an important tapping-work for drinking water supply (about 1.2 m³/s) (Fig. 1) for a great part of the Latina town (120,000 inhabitants) are present. Furthermore, the realized detailed lithostratigraphical survey interested a larger area including the Sezze town at NW (Fig. 2). Moreover, for the finalization of a reliable hydrogeological budget calculation, the considered recharge area has been duly extended to the whole Lepini Ridge.

Groundwater resources of the Lepini Mts are as well used for domestic, industrial, agricultural and breeding purposes approximately for the 34-35% of the aquifer capability (Alimonti et al. 2010).

The present work contributed to local hydrogeological knowledge with new investigations including meteo-climatic analysis, spring discharge and hydrometric time series processing and pumping test result interpretation.

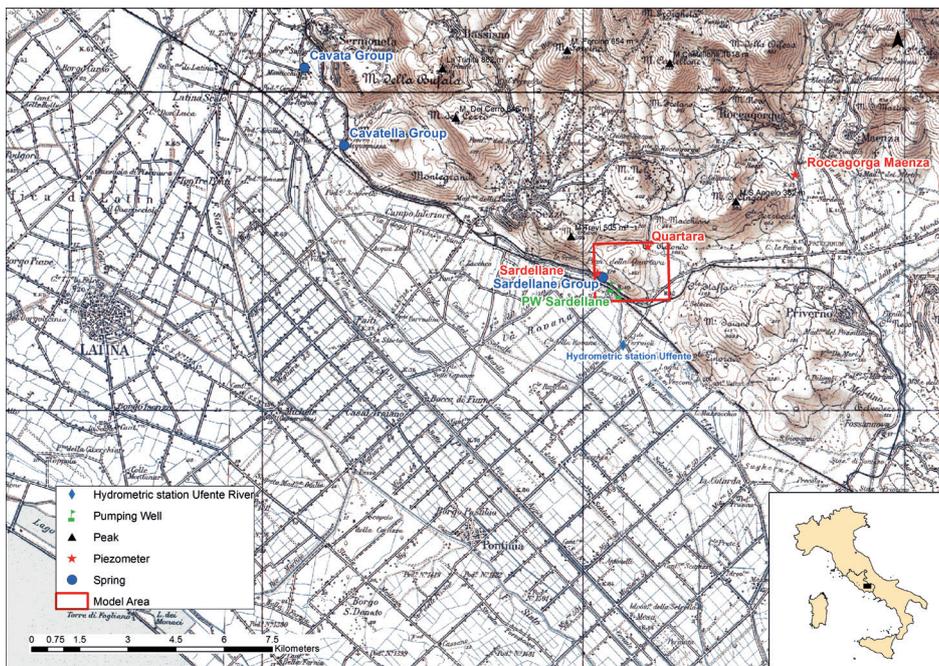


Fig. 1 - Sketch map of the study area, located in the SW slope of the Lepini Mts (southern Latium) near the town of Latina. Inset map shows study area in the context of Italy.

Fig. 1 - Schema dell'area di studio, collocata nel versante sud-ovest del Lepini Mts (Lazio meridionale), vicino alla città di Latina. L'insero nella mappa mostra l'area di studio nel contesto d'Italia.

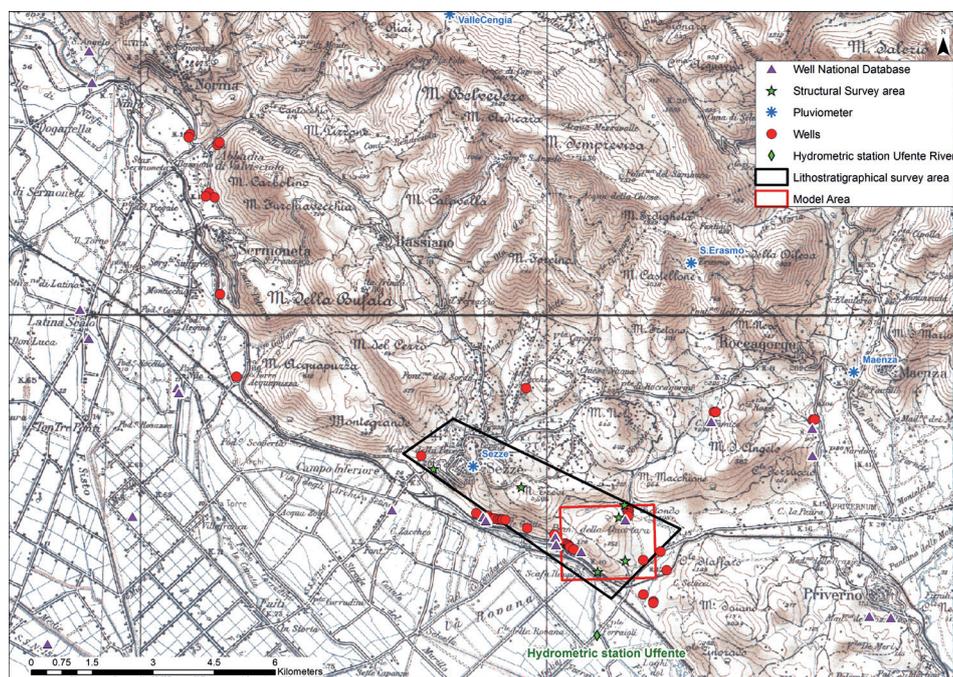


Fig. 2 - Measurement stations location map (structural survey areas and hydrometric, meteorological and hydrogeological control points have been reported). Lithostratigraphical survey area and study area (this latter corresponds to the numerical model area) are also shown.

Fig. 2 - Mappa dell'ubicazione delle stazioni di misura (sono state riportate le aree interessate dai rilievi strutturali e i punti di controllo idrometrici, meteorologici ed idrogeologici). Sono anche visibili sia l'area in cui è stato effettuato il rilevamento litostratigrafico sia l'area di studio (quest'ultima corrisponde all'area in cui è stato sviluppato il modello numerico).

Furthermore, the survey scale (less than 1:25,000) of the geological maps available for the study area is not adequate to the expected detailed survey scale of the present study. Therefore, the new geological survey realized during this work, and still ongoing in surrounding areas, produced a greater descriptive detail of the area; it also improved the results previously obtained through indirect investigation by aerial photographs analysis and field measurement of geological-structural discontinuity (and other structural elements) in the vicinity of the well fields. Identification of useful anomalous geological contacts for stratigraphical differentiation of the carbonate succession, otherwise undetectable by aerophotogrammetry, was achieved, also contributing to a decisive definition of conceptual model hydrostructural boundaries.

Geological and hydrogeological setting

The Lepini Mountains constitute the NW termination of the Volsci Range and represent a portion of the innermost Latium-Abruzzi neritic domain. The Lepini succession is represented by Upper Triassic- Cenomanian inner shelf deposits to the base, and by biotrititic sediments (saccaroidi limestones, Cenomanian – Turonian), followed by Upper Turonian – Santonian bioclastic limestones (wakestone and floatstone) with Rudistae. Bioclastic calcarenites with Echinids and mudstones with Globotruncana levels (Campanian-Mastrichtian) ended the Mesozoic succession and outline the sinking of the Lepini sector into a ramp system during the Upper Cretaceous. (Centamore et al. 2007 and references therein). After a Paleogene gap, the paraconcordant contact between the Upper Cretaceous deposits and Miocene formations, composed of organogenic limestone, marly limestone and clay sandstone turbiditic deposits, marks the

transition from the foreland basin to the foredeep; then, an overthrust tectonics led the Lepini Chain to overlap northeastward on the Latina Valley Tortonian flysch (Fig. 3).

During Upper Messinian-Lower Pliocene, the area was subject to extensional tectonics that produces a horst and graben system throughout entire sectors of the chain. Plio-Pleistocene marine deposits, consisting of clayey-sandy and sandy-clayey sequences with occurrence of Alban Hills volcanics in the northern sector of the plain, almost fill up the extensive Pontina Plain graben, mainly set on the carbonate platform sequences. A very differentiated Quaternary continental facies covers the study area.

The Lepini Mountains show a typical fold and thrust belt structural setting, crossed by relevant normal faults (Fig. 3). The structural setting is characterized by a main thrust on the NE side and by minor compressive structures in the central sectors of the chain. This structural pattern is complicated by the presence and the activity of relevant extensive Apennine trend faults that cross and disarticulate the compressive structures with a total cumulative offset up to 2.000 meters in the SW sector. These faults downthrow the carbonate ridge toward West producing a staircase morphology and are responsible for the graben structure of the Pontina Plain, filled by Quaternary deposits.

The Lepini Chain is an important carbonate regional aquifer affected by showy karst process. It is bordered at northeast by the said overthrust on terrigenous deposits of the Latina Valley and at southwest by the Pontina Plain deposits that limit the tectonically lowered carbonate rocks creating confined aquifers (Boni et al 1980, Celico 2002). This asset favoured the occurrence of the four major spring-fed areas (out of which only three are visible in Fig. 1) at the contact between the carbonate ridge and the impermeable sediments of the Pontina Plain.

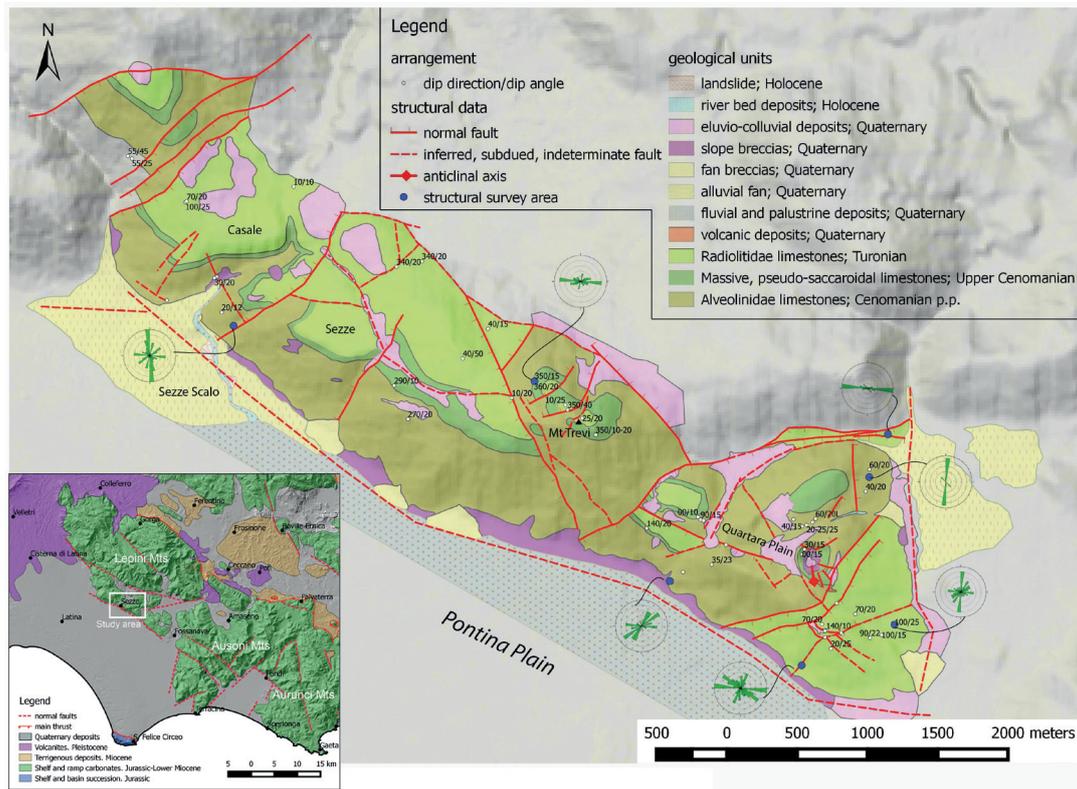


Fig. 3 - Geological map and results of structural surveys in Sezze ridge. The rose diagrams (in green with black circles outside) represent discontinuity plane orientations. Inset map shows regional geological sketch.

Fig. 3 - Schema geologico e risultati delle indagini strutturali sulla dorsale di Sezze. I diagrammi a rosa (in verde con cerchi neri esterni) rappresentano gli orientamenti dei piani di discontinuità. La mappa nell'inserto mostra lo schema geologico regionale.

Materials and Methods

New investigations including meteo-climatic analysis, spring discharge and hydrometric time series processing and pumping test result interpretation, this latter for the estimation of hydraulic conductivity data, have been carried out. Rainfall and air temperature on a daily basis were obtained from the web site of the Hydrographic and Mareographic Service of Regione Lazio (Regione Lazio - U.I.M., 1931-2015). For the meteo-climatic analysis 20 rainfall stations and a thermometer station (Latina) were considered (Fig. 4). The stations were selected according to the requirements of homogeneity and completeness of the data and the length of the recordings. The missing data have been reconstructed only where recordings of stations nearby were available, with strongly ($R^2=0.8$) correlated values, applying multivariate linear regression. The spatial interpolation of climate parameters has been developed in a GIS environment, using the geostatistic method of kriging (Matheron 1962). Thermopluviometric data at the Latina control station, which provides continuous recordings from 1931, have been considered for trend analysis. For detecting trends in the time series, tests of significance with the widely used non-parametric method of Mann-Kendall (MK; Kendall et al. 1983, Sneyers 1990) have been conducted. In MK test the null hypothesis, H_0 , is that the time series does not contain a significant trend; this test

is applicable to the detection of a monotonic trend of a time series with no seasonal or other cycle (Von Storch 1995, Zhang et al. 2001). Finally, for estimating the linear trend slope (the rate change), the Sen's method (Sen 1968) was applied.

Time series of continuous water monitoring network recording and pumping test data conducted at the Sardellane, Sezze, Quartara, Roccagorga and Roccagorga-Maenza well pumping stations were kindly provided again by Lazio Region.

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The Lepini carbonate ridge is affected by karst with the presence of well-developed caves and large sinkholes (as in the case of Colle Quartara) (Boni et al. 1980, Celico 2002) and the absence of perennial streams. These terms allow to

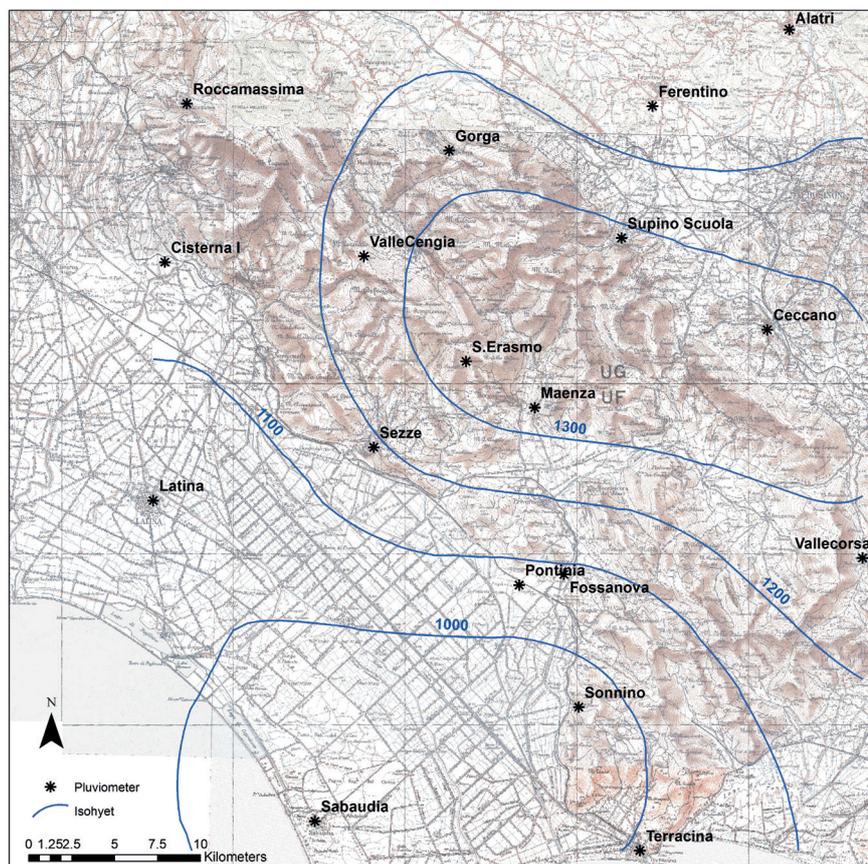


Fig. 4 - Isobetal map of cumulative annual mean rainfall, calculated from 1993 to 2013 in 20 measuring station located in the study area.

Fig. 4 - Mappa delle isoiete di precipitazione media annua cumulata, calcolato fra il 1993 ed il 2013 in 20 stazioni di misurazione situate intorno all'area di studio.

consider runoff negligible (Bono 2010). That said, in the ridge and in particular in the study area, the effective rainfall is comparable to the effective infiltration.

In addition, a detailed lithostratigraphical and structural survey of a portion of the Lepini hydrostructure at 1:10,000 scale was performed, also examining the dense discontinuities network affecting the carbonate aquifer. The survey campaigns were prepared by analyzing aerial photographs taken in 1954 and 1980. The lithostratigraphical survey area (Fig. 2) has an extension of about 10 km², lies entirely in the Sezze municipality and is included in the Sheet n. 159 Frosinone of the Geological Map of Italy at 1:100,000 scale. The survey scale of this sheet (1:25,000) is not adequate to the detailed survey scale of the present study, since it reports a single undifferentiated lithostratigraphic unit of the outcropping substrate, referred to Late Cretaceous, and does not define satisfactorily the local tectonic framework.

The rock discontinuity survey included the examination of 14 differently oriented outcrops in order to have an overall view of the fracture network (Fig. 2). The collected data include about 1,500 between direction, tilt, spacing and fractures aperture measurements. To process these data the calculation program DPS 6.1 (Rocscience Inc., Toronto, ON, Canada) was used that allowed to represent the orientations of the discontinuity planes. The Clu-Star32 software (Geo&Soft International, Turin, Italy) defined the orientation of the middle plane of the main groups of discontinuities in terms of immersion and inclination, based on the density of the

projected poles. This calculation was performed by cluster analysis (using at first hierarchical and then non-hierarchical clustering).

Finally, during 2014-2015 a hydrogeological survey was conducted: 33 wells around the study area were measured to have a greater number of data to define the model boundary conditions (Fig. 2).

The Well National Database [Geological Survey of Italy – Italian National Institute for Environmental Protection and Research (ISPRA), in implementation of the Italian governmental law N.464/84], the well and spring database of the Latium Region and other databases from public and private institutions provided the stratigraphical and hydrogeological information here processed. A geo-referenced database of this information has been realized with the purpose of carrying out the data exportation toward GIS environment or specialized software. A codification of standard criteria for classification and description of lithological and stratigraphical data and terms coming from very different documentary sources has been adopted (Fig. 2).

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All hydrological data and geological-structural and hydrogeological surveys and evaluations have been used to improve the numerical model within the MODFLOW-2005 software

Results

Lithostratigraphic and structural analysis

The results of the lithostratigraphic and structural surveys in the SW portion of the Lepini hydrostructure (Sezze Ridge) at 1:10,000 scale are reported in Fig. 3. The analysis

of the results shows an extremely fractured medium, with a consistent dispersion of fracture orientation.

The rose diagrams in Fig. 3 have been produced in order to represent the discontinuity plane orientations. Based on the density of the projected poles, the orientation of the middle plane of the four groups of discontinuities has been defined in terms of immersion and inclination (Tab. 1).

The discontinuities survey results have been used for determination of hydraulic conductivity of the rock, considered as an equivalent porous medium (this assumption is justified by the significant dispersion of the fracture orientation).

Tab. 1 - Parameters of the main families of discontinuities. Despite a substantial dispersion of the orientations, there are four systems of discontinuities including the layer joints (St) and three fracture systems (F1, F2, F3), with orientation consistent with the main local tectonic deformations (E-W, NW-SE and NE-SW).

Tab. 1 - Parametri delle principali famiglie di discontinuità. Nonostante una notevole dispersione degli orientamenti, ci sono quattro sistemi di discontinuità compresi i giunti di strato (ST) e tre sistemi di frattura (F1, F2, F3), con orientamento coerente con le principali deformazioni tettoniche locali (EW, NW-SE e NE-SW).

N.Fam.	Dip direction (°)	Dip (°)	Aperture (mm)	Frequency (1/mm)
F1	191.0	86.0	1.3	10.54
F2	314.0	85.0	1.1	7.38
F3	355.0	30.0	0.5	0.79
St	79.0	24.0	0.5	2.00

Hydrostratigraphical setting

A preliminary simplified 3D sketch has been prepared (for instance, the many systems of tectonic lines were not still elaborated and included) to improve the understanding of the main stratigraphical and hydrogeological features of the study area.

The local simplified geological lithostratigraphical succession is as follows:

- a basal calcareous unit having a good spatial continuity and thickness (greater than 300 m), extensively cropping out in the Lepini Mts relief and covered by the upper units in the Pontina Plain sector, where it acts as a bed-rock;
- a sandy-gravelly unit generally up to some tenth of meters thick and showing a good spatial continuity, especially in the subsoil of the Pontina Plain sector;
- a clayey unit generally thick up to few tenth of meters and having a good spatial continuity; it mainly occurs in subsoil in the Pontina Plain sector or covers, also as alluvial deposits, the calcareous unit in structural troughs of the Lepini Mts relief;
- a volcanic units constituted by deposits coming from the Alban Hills magmatic district with thickness up to few tenth of meters and a quite good spatial continuity in the NW sector of the study area and mainly drilled in the subsoil in the plain area at the SW;
- a travertine unit with local thickness up to 10 m and occurring discontinuously throughout the plain;

- a peat unit with local thickness up to 10 m and occurring discontinuously throughout the plain as well;
- a covering unit of variable thickness and occurring throughout the study area.

As concerns the delineation of the groundwater bodies hosted in the hydrostratigraphical units, the available hydrogeological data allow to reconstruct the following representative piezometric surfaces:

- a calcareous aquifer piezometric surface showing a good spatial continuity mainly in the Lepini Mts relief; it was possible to evidence its emergence by spring occurrences (most of them gathered to the Ufente River) as a shallow phreatic equipotential surface at the Lepini relief-Pontina plain margin;
- a sandy-gravelly-clayey-volcanic undifferentiated aquifer piezometric surface (single piezometric surfaces of gravelly, clayey and volcanic aquifers were not defined for lack of data continuity) with a whole good spatial continuity in the Pontina Plain sector and often showing confined or semiconfined conditions.

Based on the hydrogeological features of the distinguished stratigraphical units (other typologies of units have not significant continuity at the whole study area scale) the study area hydrostratigraphical unit outlines have been defined. From bottom to top it was possible to define (Fig. 5):

- a calcareous very productive unit occurring in both the Lepini Mts relief, as a phreatic aquifer, and the Pontina Plain sector, as a confined aquifer; it is exploited by wells for some tenths to hundreds meters and has a null depth to water at the Lepini relief-Pontina plain margin, where the aquifer crops out give rise to many spring groups. Depth to water progressively increases (maximum 100-150 m in the study area; groundwater table elevation $5 \div 30$ m a.s.l.) towards the highest altitude of the relief;
- a sandy-gravelly-clayey unit, mainly present in the Pontina Plain subsoil as a phreatic or partially confined aquifer, hosted in the interconnected coarse grain layers; maximum drilled thickness is about some tenths of meters and depth to water is about 10-70 m (groundwater table elevation $-10 \div 30$ m a.s.l.);
- a volcanic unit, generally about 10 m-thick and having a significant hydrogeological role in the NW sector of the study area; its depth to water is variable and up to 50-100 m (groundwater table elevation $10 \div 30$ m a.s.l.).

Meteo-climatic analysis

The long time pluviometric series collected at Latina (from 1931 to present) and other 19 control stations have been analyzed in order to define the rainfall spatial distribution (reference period 1993-2013; Fig. 4) and to identify possible trends, useful for assessing the sustainability of pumping implemented at the Sardellane water supply plant (Fig. 6). However, Mann-Kendall (Mann 1945, Kendall 1975) test does not confirm the significance of a linear trend because of the high dispersion of values.

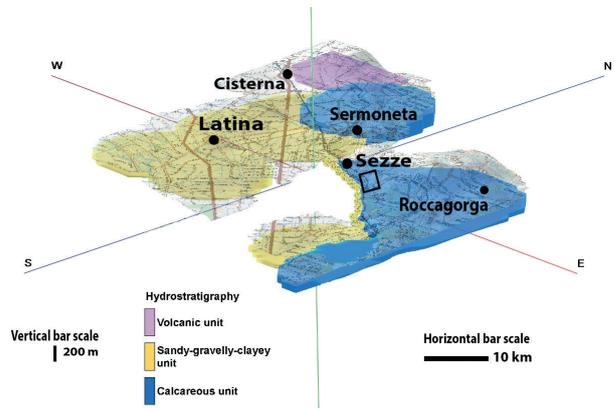


Fig. 5 - Preliminary 3D hydrostratigraphical sketch of the SW Lepini area (vertical exaggeration $\times 10$). The study area is evidenced with a black box.

Fig. 5 - Schema idrostratigrafico preliminare in 3D dell'area SW dei Monti Lepini (esagerazione verticale $\times 10$). L'area di studio è evidenziata con un rettangolo nero.

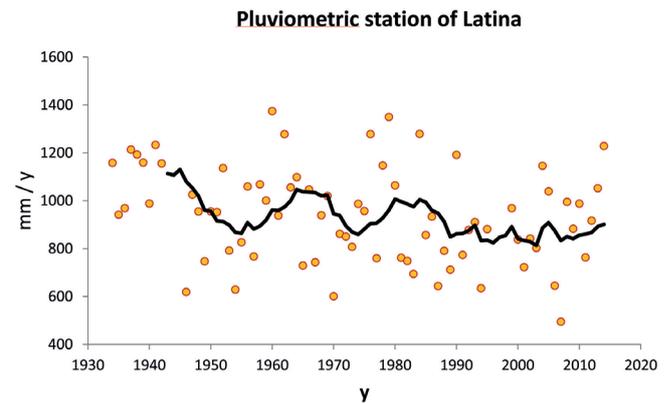


Fig. 6 - Cumulative annual mean rainfall recorded at Latina during 1934-2014. The 10-year moving average curve shows a slight negative slope.

Fig. 6 - Precipitazione cumulata media annua registrata a Latina nel periodo 1934-2014. La curva della media mobile a 10 anni mostra una lieve pendenza negativa.

As regards air temperatures, the time series of monthly and annual temperatures from 1951 to 2015 has been submitted to the Mann Kendall test: the winter months (December, January and February) do not record any trend, while the spring, summer and autumn, as well as the average annual temperature, show a marked upward trend (Tab. 2). Furthermore, Fig. 7 shows the deviation from the mean annual temperature value.

Roccaporga-Maenza hydraulic heads (not affected by withdrawals) have been compared with rainfall and effective rainfall data; the evapotranspiration value have been calculated by Thornthwaite method. As a whole, the trend of piezometric level after a certain delay exhibited a good correspondence with effective precipitation (Fig. 8).

Hydrogeological balance analysis

Tab. 3 shows that Colle Quartara zone outflow accounted about 26 to 90% of effective rainfall in the whole Lepini structure from 2007 to 2010. In agreement with this, some attempts to close the hydrogeological budget of the study area

Tab. 2 - Man Kendall test result with Sen's slope estimate.

Tab. 2 - Risultati del test di Mann Kendall con la stima della pendenza di Sen.

Time series	First year	Last Year	n	Mann-Kendall trend		Sen's slope estimate
				Test Z	Signific.	Q
Jan	1951	2015	61	1.33		0.013
Feb	1951	2015	61	-0.15		0.000
Mar	1951	2015	61	2.88	**	0.021
Apr	1951	2015	61	2.75	**	0.026
May	1951	2015	61	3.98	***	0.037
Jun	1951	2015	61	3.50	***	0.034
July	1951	2015	61	3.76	***	0.039
Aug	1951	2015	61	4.79	***	0.043
Sept	1951	2015	61	2.25	*	0.019
Oct	1951	2015	61	3.42		0.031
Nov	1951	2015	61	2.57	*	0.024
Dec	1951	2015	61	0.65		0.006
Tot	1951	2015	61	4.31	***	0.026

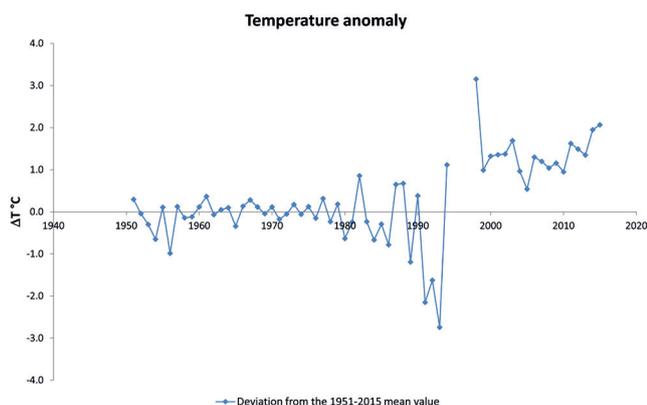


Fig. 7 - Annual temperature anomaly trend. Reference period 1951-2015.

Fig. 7 - Tendenza delle anomalie della temperature medie annue. Periodo di riferimento 1951-2015.

considering only the Colle Quartara recharge surface failed. In fact, the Colle Quartara zone outflow is really compensated only supposing a recharge area at least 10 times higher than the actual values. This means that it is not possible to consider the study area of Colle Quartara as a real hydrogeological budget unit and therefore the budget calculation area has been extended to the whole of Lepini Ridge.

The Colle Quartara outflow amounts have been assumed in any case as reference values for the estimation of the ratio between them and the water recharge of the whole ridge, in order to evidence a potential overexploitation of the groundwater resources at the ridge scale due to the Sardellane water plant activity.

The boundaries conditions of the Lepini hydrogeological karst provide that the regional karst aquifer is hydraulically isolated (Celico 1983, Boni et al. 1980). This interpretation excludes that the karst aquifer receives external contributions. Considering the Lepini ridge, the average annual amount of rainfall is 1160 mm/y, out of which 36% is lost by

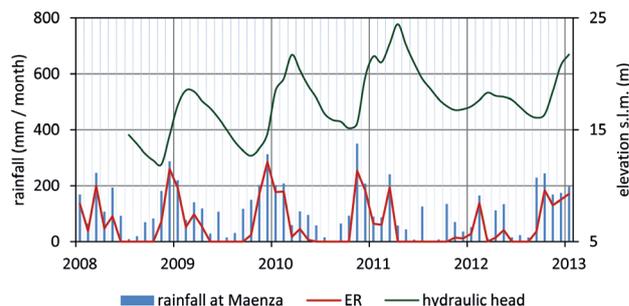


Fig. 8 - Distribution of effective rainfall (ER) obtained by Thornthwaite method compared with the distribution of monthly precipitation recorded at Maenza and hydraulic heads at Rocca-gorga-Maenza.

Fig. 8 - Distribuzione delle precipitazioni efficaci (ER) ottenute con il metodo Thornthwaite a confronto con la distribuzione delle precipitazioni mensili registrate a Maenza e le altezze piezometriche del pozzo Rocca-gorga-Maenza.

evapotranspiration (415 mm/y), and the infiltration consists of 600 mm/y and represents the 52% of annual rainfall (Alimonti et al. 2010); total spring yield is about 10 m³/s, so about the whole of annual infiltration is returned to the surface as springs and spring-fed areas (Alimonti et al. 2010). As mentioned, the runoff is negligible (Bono 2010) or consists in few m³/s (Alimonti et al. 2010) and then corresponds to 5-10% of annual rainfall. The estimated exploited water amounts are about 5% of annual rainfall.

As regards the elements involved in the hydrogeological balance analysis of the study area (Fig. 1), Sardellane water supply plant is located on the edge of the Lepini ridge (sector from Sezze to Priverno) and intercepts at shallow depths the basal carbonate aquifer. The withdrawals analysis showed a seasonal variation (Fig. 9). Since July 2009, it may be noted (Fig. 10) an increasing trend of amounts of pumped water from Sardellane plant on July of later years.

Quantitative relationships between groundwater output (Colle Quartara zone springs and volume removed from

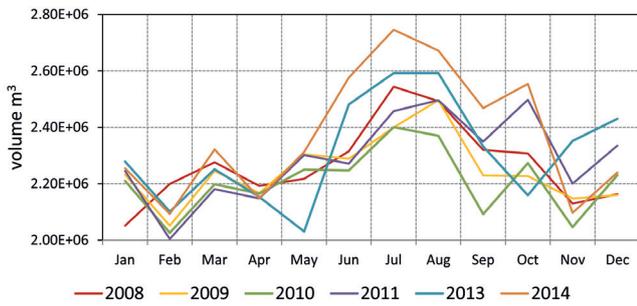


Fig. 9 - Monthly values of the water volumes taken from the Sardellane water supply plant. From the diagram it is evident the marked seasonality of withdrawals. Data provided by the managing authority.

Fig. 9 - Valori mensili dei volumi di acqua prelevati dalla centrale di approvvigionamento idrico Sardellane. Dal diagramma è evidente la marcata stagionalità dei prelievi. Dati forniti dall'autorità di gestione.

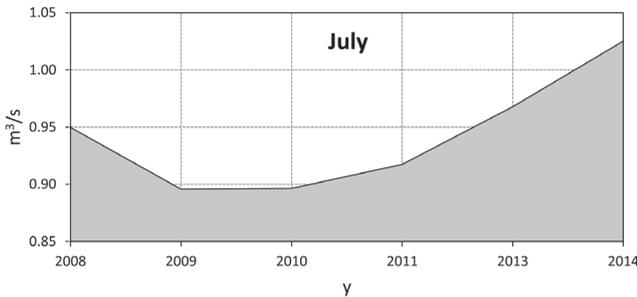


Fig. 10 - Trend of amounts of pumped water from Sardellane plant on July of later years. Data provided by the managing authority (Acqua Latina 2004-2015).

Fig. 10 - Andamento della quantità di acqua pompata nei mesi di luglio dall'impianto di Sardellane. Dati forniti dall'autorità di gestione (Acqua Latina 2004-2015).

the Sardellane pumping wells) and estimated total volume entering the Lepini carbonate structure were compared to results obtained considering the effective rainfall calculated by Thornthwaite method (Thornthwaite 1948).

As a whole, it is possible to accomplish a hydrogeological balance estimation only taking into account the total Lepini Mts hydrostructure, as already estimated in literature (e.g., Bono 2010). Tab. 3 shows that in the particularly dry year 2007, the volume output from study area (linear springs of Ufente system and withdrawals from Sardellane wells) corresponds to 90% of effective rainfall of the whole Lepini hydrostructure.

Fig. 11 compares the hydrograph of Sardellane and Quartara piezometers, whose distance from each other is about 1.5 km. The first is located about 200 m from the well field: baseline groundwater pumping activities are discontinuous during the year with a capacity of about 1 m³/s. The effects of disturbance by the plant activity are evident in the serrated line representing the piezometric curve of Sardellane, unlike that of Quartara.

The influence of pumping is also evident in the Ufente river hydrograph (Fig. 12) showing water discharge coming from springs located along the foothill stretched near the Sardellane plant.

The data processing in Fig. 13 has been performed by the radial basis function method (Broomhead and Lowe 1988). The thick black dotted line divides the area of Lepini Mts relief from the alluvial deposits of Pontina plain. The piezometric surface is obviously influenced by the Sardellane pumping wells.

Tab. 3 - Water balance data: inputs refer to the entire Lepini ridge while outputs refer to the study area only. The runoff is considered negligible.

Tab. 3 - Dati di bilancio idrico: gli input sono relativi all'intera dorsale dei Lepini mentre gli output sono relativi all'area di studio. Il ruscellamento è considerato trascurabile.

		A	B	C	(B+C)/A*100
Lepini rainfall		Lepini effective rainfall (ET by Thornthwaite)	Out flow study area		Balance study area
y	(m ³ /y)	(m ³ /y)	Linear springs of Ufente system (m ³ /y)	Withdrawals from Sardellane wells (m ³ /y)	%
2004	887,351,000	567,742,000	N.A.	N.A.	N.A.
2005	758,523,000	434,527,000	N.A.	N.A.	N.A.
2006	624,452,000	247,865,000	N.A.	N.A.	N.A.
2007	403,497,000	126,367,000	87,620,459	27,000,000	90.7
2008	811,595,000	449,988,500	89,326,851	27,207,333	25.9
2009	812,772,000	467,001,500	102,615,291	26,946,397	27.7
2010	780,886,000	461,116,500	116,098,119	26,507,540	30.9
2011	479,574,000	183,719,000	118,890,000	27,485,657	80.0
2012	718,291,000	386,858,500	N.A.	N.A.	N.A.
2013	795,866,000	362,516,000	N.A.	27,752,522	N.A.
2014	781,207,000	373,804,500	N.A.	28,482,894	N.A.

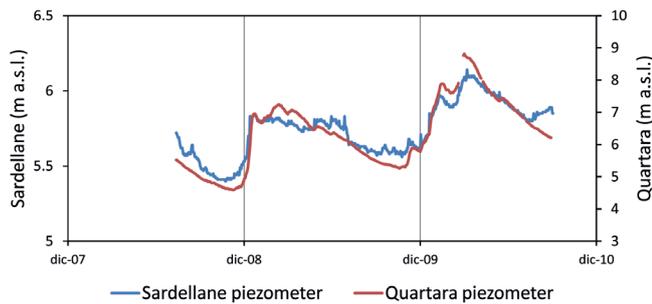


Fig. 11 - Comparison of hydrograph of Sardellane and Quartara piezometers. For a best comparison, different vertical scales have been adopted.

Fig. 11 - Confronto fra gli idrogrammi dei piezometri di Sardellane e Quartara. Per un migliore confronto, sono state utilizzate due diverse scale verticali.

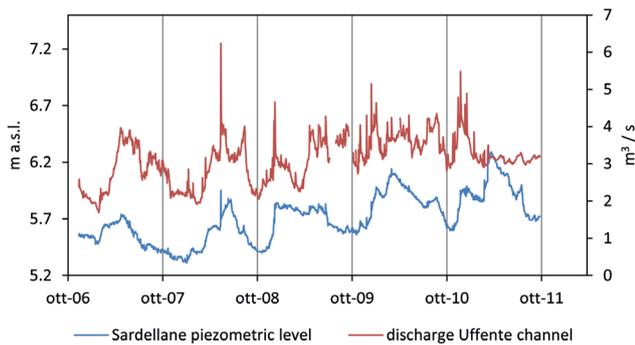


Fig. 12 - Discharge hydrograph of Uffente River, collecting foothill spring system contributions close to the well field of Sardellane. It presents a very irregular trend also due to the activity of water withdrawal from the aquifer.

Fig. 12 - Idrogramma di esaurimento del fiume Uffente, che raccoglie le acque delle sorgenti basali nei pressi del campo pozzi di Sardellane. L'idrogramma presenta un andamento molto irregolare anche per l'attività di prelievo di acqua dalla falda.

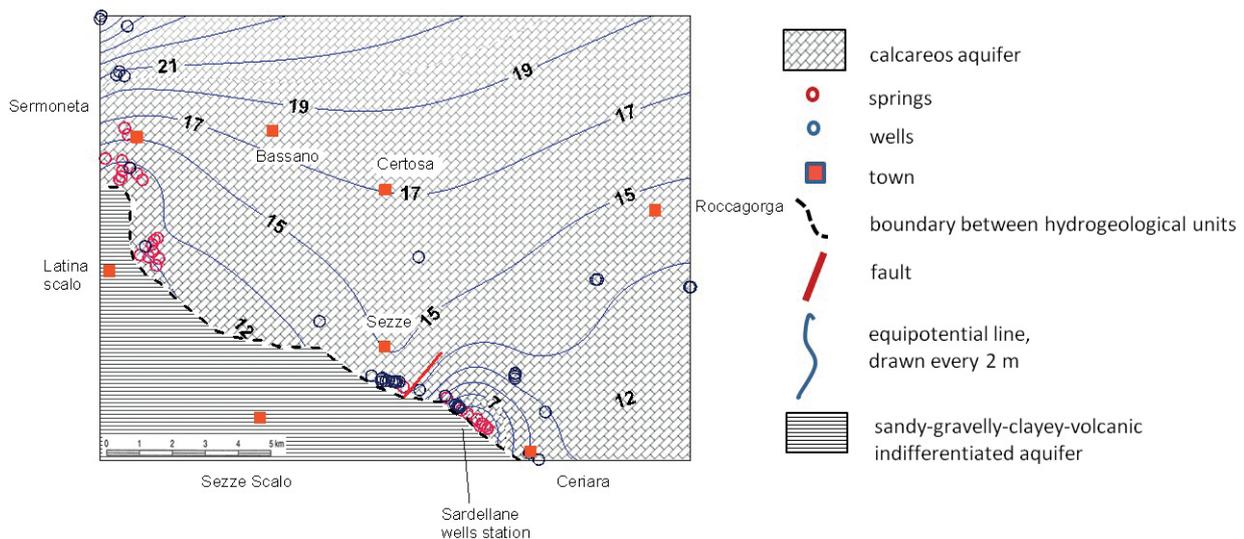


Fig. 13 - Piezometric contour map of the southwestern part of the Lepini carbonate ridge prepared from wells and springs data (values expressed in m). Data were collected during the winter-spring of 2015.

Fig. 13 - Mappa delle isopieze della parte sud-occidentale della dorsale carbonatica dei Lepini, elaborata dai dati dei pozzi e delle sorgenti (valori espressi in metri). I dati sono stati raccolti durante l'inverno-primavera del 2015.

Numerical model

Though based on the available still not fully exhaustive data, a preliminary numerical model has been elaborated, as a first attempt for the definition of a next suitable updated model for a sustainable exploitation management of the local groundwater resources.

The investigation results have allowed the reconstruction of the hydrogeological conceptual model of the studied portion of carbonate massif described in paragraph hydrostratigraphical setting. Given the study scale and the obtained results, the carbonate aquifer can be treated as an equivalent porous medium, and the simplified numerical model of the aquifer have been constructed with the code MODFLOW-2005 (McDonald and Harbaugh 1988). The model area includes the area around the springs and the well field of Sardellane (Fig. 2).

The model domain has been divided into two layers (Fig. 14), each with a top and bottom, which represent the roof and the bed of the hydrostratigraphical unit schematized by the layers. The top of layer 1 corresponds to topography (DEM of the Lazio Region with 20 m cells) and the top of layer 2 corresponds to the roof of limestone under the Quaternary deposits. The bottom of the first layer corresponds to the roof of layer 2 while the bottom of the second layer corresponds to a plane surface at a depth of - 250 m. The size of the cells is 30 m sides, for a number of rows and columns of 268 and 385, respectively.

The top of layer 2 is partly a fictitious surface, because it is real only in the part corresponding to the Pontina Plain, while, compared with the dorsal surface, this one has fictitious elevations so as not to create intersections with the top of layer 1 (topography) and so as not to have zero thicknesses in layer 1.

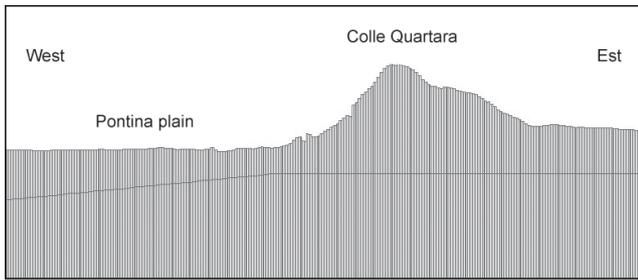


Fig. 14 - West-East Section along a row of the model.

Fig. 14 - Sezione ovest-est lungo una riga del modello.

The boundary conditions are represented by:

- at the North, East and West boundaries Constant Head. This head has been set based on the values of the piezometric surface, developed in the survey campaign 2014-2015 (Fig. 13);
- at the South-Western edge, flow head dependent (General Head Boundary), taking as reference the head imposed to 0 m due to the existence of the Tyrrhenian Sea, about 17 km away from the study area.

Groundwater recharge (effective infiltration) is estimated to be 600 mm/y. The Ufente river is modeled as a drain (rate: 2.5-4.5 m³/s). The Sardellane pumping wells is represented as a single well of withdrawal (average rate: 0.9 m³/s); the flow condition is imposed by the package Well.

The simulated model is in steady-state conditions, therefore, the only hydrogeological parameters used is the hydraulic conductivity. This value has been assigned on the basis of literature data (Regione Lazio 1931-2015). Assessorato Ambiente. Relazioni su prove di portata e analisi (Pumping test and analysis reports), unpublished data and new data estimated after interpretation of pumping tests.

Two areas with different homogeneous hydraulic conductivity have been defined and correspond to carbonate aquifer (2.5*10⁻² m/s) and to alluvial deposits (0.5*10⁻⁵ m/s) respectively. A very low permeability has been attributed to the alluvial deposits, in order to simulate the absence of water interchange between the plain and the limestone structure. The calibration step has been performed using the hydraulic heads of two groups of wells (each composed of four wells) measured during the campaign 2014-2015. The calibration was performed with manual method trial and error adjustment, which consists of a procedure which provides for the manual adjustment of the parameters and the comparison between simulated and experimental data to reach the best solution. The procedure provided the change of hydraulic conductivity as it is found to be the most sensitive parameter.

The steady state numerical model, still now under continuous implementation, produced first results on the current withdrawal sustainability. The preliminary model showed that the hydrodynamic equilibrium of the natural drainage of waters in the study area is not extensively affected by the pumping activities (Figs. 15 and 16); the model output showed that the pumping activity subtracts from the Ufente river (about 2.5-3.0 m³/s in the low flow) about 0.6-0.7 m³/s of water (Kalf and Woolley 2005).

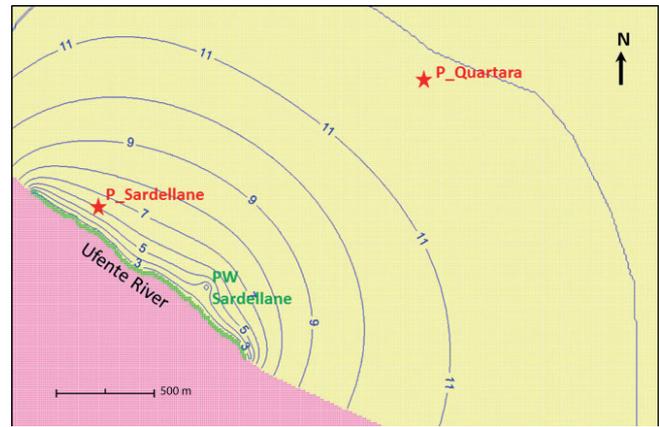


Fig. 15 - Model output with well pumping.

Fig. 15 - Output del modello con attività di pompaggio.

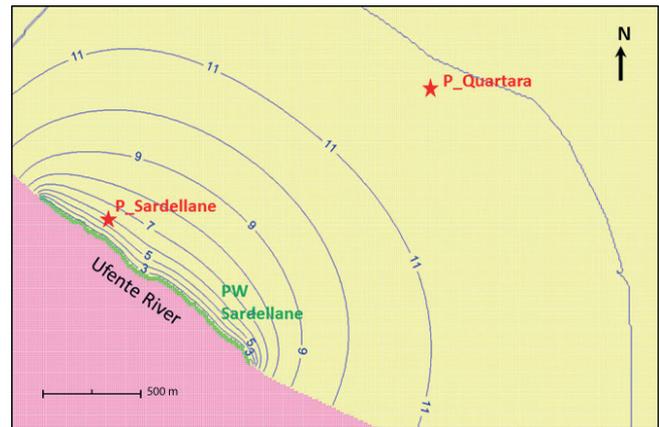


Fig. 16 - Model output without well pumping.

Fig. 15 - Output del modello senza attività di pompaggio.

Discussion

The results of geological and hydrogeological investigations and the numerical model outputs were used to assess whether the Colle Quartara aquifer portion is over-exploited by Sardellane pumping wells.

The water balance calculation compared the whole Lepini Ridge input to the main output in the study area, to evaluate the possible overexploitation by the Sardellane well field. Tab. 3 shows that in 2007 and 2011 the natural and artificial outputs of Colle Quartara area is almost equal to the whole Ridge input. This suggests that in particularly dry years the aquifer naturally exploits the resource stored in the wettest years. Although now the well field withdrawal does not contribute to reducing the aquifer reserves, it must be taken into consideration the over-exploitation risk due to occurrence of repeated particularly dry years.

The results of lithostratigraphic and structural analysis have highlighted that the reservoir medium is extremely fractured along differently oriented planes. This evidence made it possible to assimilate, at the study area scale, the fractured carbonate aquifer to an equivalent porous aquifer. This assessment was also supported by extremely stable regimen of basal springs (Boni et al. 1980, Boni and Petitta, 1994, Celico 2002).

It was possible to process a numerical model through the MODFLOW-2005 computer code. The model was found to be sufficiently representative of the aquifer system in the studio. The lack of information, such as the actual quantities of pumped water from the wells and the few measures of the piezometric levels, has unfortunately allowed only making some estimates on the data used in the model. However, the model can be considered a first attempt for contributing to the management and planning of exploitation of water resources. This numerical model shows that the Colle Quartara aquifer sector shows no signs of overexploitation. However, climate changes consisting of a significant temperature increase (Fig. 7) reduce the effective precipitations and therefore the effective infiltration. The progressive increase of the amount of water extracted in the warmer months (Fig. 10) must warn of future output increase that, whenever happened together with a possible reduction of inputs, may generate overexploitation situations. The developed numerical model can be as well further implemented to assess future scenarios including the sustainability of pumping activities.

Conclusions

This work aimed at defining groundwater resource sustainable management of one of the main exploited carbonate aquifers of central Apennines, in a test area of the Lepini Mountains (Central Italy).

The outcropping terrains belong to the Mesozoic Latium-Abruzzi Succession, made up of limestone and dolostone in carbonate platform facies, with a thickness of about 4000 m. From the structural point of view, the Lepini Chain exhibits Mesozoic carbonates overlapping on Miocene terrigenous deposits of Latina Valley on the north-eastern limit, while on the south-western limit, the chain structure was lowered by Plio-Pleistocene direct faults towards the Tyrrhenian Sea. The Lepini Chain hosts an important carbonate regional aquifer affected by showy karst process and, beneath the Pontina Plain, the carbonate aquifer is confined and feeds some groups of spring and the adjacent aquifers of the Plain.

New investigations including meteo-climatic analysis, spring discharge and hydrometric time series processing and pumping test result interpretation have been carried out. For detecting trends in the time series and for estimating the linear trend slope, tests of significance with Mann-Kendall method and Sen's method, respectively, have been applied. In addition, detailed lithostratigraphical and structural surveys of a portion of the Lepini hydrostructure at 1:10,000 scale have been performed, also investigating the dense network of discontinuities throughout carbonate rocks. Therefore, useful elements for the stratigraphical differentiation of the carbonate succession and for the improvement of a numerical model with the code MODFLOW-2005 have been identified.

Mann-Kendall test does not evidence significant trends in the pluviometric time series, because of the high dispersion of values. As regards air temperatures, the time series of monthly and annual temperatures submitted to the Mann-Kendall test display a marked upward trend during spring,

summer, autumn and as well concerning the average annual temperature values.

The structural analysis results revealed an extremely fractured medium, with consistent dispersion of fracture orientations. The orientation of the middle plane of four groups of discontinuity has been defined in terms of immersion and inclination.

Based on the local hydrogeological features of the lithostratigraphical units, study area hydrostratigraphical unit outlines have been proposed. From bottom to top it was possible to define: i) a calcareous very productive unit occurring in both the Lepini Mts relief, as a phreatic aquifer, and the Pontina Plain sector, as a confined aquifer; at the Lepini relief-Pontina plain margin it give rise to many spring groups; ii) a sandy-gravelly-clayey unit, mainly occurring in the Pontina Plain subsoil as a phreatic or partially confined aquifer, hosted in the interconnected coarse grain layers; iii) a volcanic unit showing a significant hydrogeological role in the NW sector of the study area. It is worth noting to evidence that the study area shows a general regional hydraulic continuity throughout the hydrogeological structure of the Lepini ridge.

The meteo-climatic analysis showed a substantial constancy of the values of precipitation heights, but also a strong trend to temperature rising with consequent increase of real evapotranspiration and then reduction of effective precipitation. In this perspective, it is appropriate to make a careful and appropriate sustainable yield assessment of groundwater resource.

The volumes of water coming out from the hydrogeological system between Sezze and Priverno are on average around 25-30% of total inflows of the whole Lepini Ridge. In particularly dry years, however, the fraction of yielded water can exceed 90% of total effective rainfall and therefore, from the sustainability of groundwater exploitation point of view, the aquifer groundwater reserves were likely exploited.

The developed preliminary steady state numerical model shows that the pumping activities marginally affect the hydrodynamic balance of the natural drainage of groundwater in the study area; on the contrary, the surface water flow of the Ufente River is actually decreased by about 25% due to pumping.

Future developments of the research involve the completion of the collection and processing of geological and structural data useful calculating the permeability tensor. This will provide useful information for a best definition of the numerical model grid. Depending on the numerical flow model results, a spatial extension of the model is expected to assess the response of the aquifer on a larger volume and the definition of future scenarios, assuming changes in both the annual extracted amounts and allowing valuation of alternative exploitation scenarios of the carbonate aquifer, also considering the probably not significant flow exchanges with the Pontina Plain aquifer.

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