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Hydrogeology of the Karst Area of the Grassano and Telese Springs

Idrogeologia dell'Area Carsica delle Sorgenti di Grassano e di Telese

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Riassunto: Il presente lavoro descrive e analizza le condizioni idrauliche delle acque sotterranee nell'area carsica delle sorgenti di Grassano e di Telese (Campania, Italia meridionale), caratterizzata da flussi ascendenti. Lo studio si basa su misure piezometriche, monitoraggio delle portate e delle caratteristiche chimico-fisiche delle sorgenti, nonché su misure dell'attività del radon ^{222}Rn. Nell'area di studio l'ipotesi circa l'esistenza di flussi ascendenti delle acque sotterranee è supportata da numerose e differenti evidenze, quali: l'ubicazione e la posizione topografica delle sorgenti; l'eccezionale densità di sinkhole connessi a processi geomorfologici che si sviluppano al di sotto della superficie topografica e coinvolgono acque ricche in CO_2 e H_2S; la costanza nel tempo della temperatura e della conducibilità elettrica delle acque sorgive; la variazione dell'attività del radon durante l'anno idrologico; l'incremento del carico idraulico con la profondità; la presenza di condizioni artesiane nella piana alluvionale. Anche i risultati delle simulazioni numeriche della circolazione idrica sotterranea supportano le ipotesi sul fenomeno dei flussi ascendenti nell'area sorgiva e rappresentano un utile strumento per interpretare i fenomeni idrologici nell'area di studio. Tali risultati sono in accordo con tutti i processi idrogeologici osservati nell'area delle sorgenti di Grassano e di Telese; queste ultime apparterrebbero al sistema di flusso regionale del massiccio dei Monti del Matese e rappresentano uno dei principali recapiti del complesso delle sorgenti basali.

Keywords: *karst springs; ascendant groundwater flow, sinkholes; H_2S and CO_2; groundwater modelling.*

Parole chiave: sorgenti carsiche; flussi ascendenti; sinkholes; H_2S e CO_2; groundwater modelling.

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Abstract: *This work deals with the hydraulic phenomenon of the ascendant groundwater flow affecting the karst area of the Grassano and Telese springs (Campania, Southern Italy). It has been investigated through piezometric measurements, discharge and chemical-physical monitoring of springs and measurements of the radon ^{222}Rn activity. The presence of ascendant flows is supported by numerous and different types of evidences in the area: location and topographical position of the springs; amazing density of sinkholes connected to geomorphic processes that develop below the topographic surface and involve the rising of CO_2 and H_2S rich waters; constancy of the temperature and the electrical conductivity of the spring waters over the time; fluctuation of the radon activity during the hydrological year; increasing of the hydraulic head with depth; presence of artesian conditions in the alluvial plain. Numerical simulations of the groundwater flow also support the general phenomenon of the ascendant flow in the discharge area and represent a useful background to interpret hydrological phenomena in the study area. The results of the simulations are suitable with all the hydrogeological processes observed in the area of the Grassano and Telese springs; this last is thought to belong to the regional groundwater flow system of the Matese massif and represents its discharge zone.*

Introduction

Geomorphological and hydrological processes are closely interrelated in carbonate karst environments. According to many authors (Palmer 1991; Ford and Williams 2007; Klimchouk 2007) two types of karst systems can be distinguished: epigenic and hypogenic.

Epigenic karst systems form by water infiltrating from overlying recharge surfaces and develop in genetic relation to topographic landscape; hypogenic karst systems form by corrosion and erosion from mineralized waters of deep origin, ascending from lower formations.

Moreover, the first are local systems, and/or parts of recharge segments of intermediate and regional flows systems, whereas the latter are associated with discharge regimes of regional or intermediate flow systems.

Karst systems are able to concentrate the drainage of a wide groundwater catchment area in a restricted zone, the discharge zone, where a single spring or a group of springs are located. Such systems can be characterized by a high transmissivity and a high capability to store large volumes of water; these conditions allow a deep groundwater circulation, involving descendant, horizontal and ascendant flows in the recharge, in the central through-flow and in the discharge zones of the regional groundwater flow system, respectively

(Hubbert 1940; Toth 1960; Domenico and Schwartz 1990). Generally, discharge zones are located in the most depressed zones of the flow systems.

Many sectors of the Apennines show all the geomorphological and hydrological features of the karst systems described above (Galdenzi and Menichetti 2017).

Hypogenic geomorphic processes and ascendant flow phenomena characterize the area of the Grassano and Telese springs. Large fresh karst springs and sulphureous thermal springs are closely located here and an extraordinary density of sinkhole is observed.

Specific hydrogeological and geochemical surveys and groundwater simulations have been carried out in this study. All the acquired groundwater data (spring discharge, hydraulic head, pH, temperature, electrical conductivity, radon ^{222}Rn activity), together with the analyzed karst geomorphological features, support the numerical model results. The latter highlight the ascendant flows phenomenon, which feeds both fresh and thermal springs. This phenomenon is described in the present work for the first time, for Grassano and Telese karst areas; it explains many of the hydrogeological features observed in the abovementioned area, as artesian conditions of the groundwater downstream the Grassano springs and the low slope of the water table upstream the springs.

Study area

The study area falls within the axial sector of the southern Apennine (Figs. 1a and 1b), where carbonate platform and terrigenous sequences are present, together with slope-basin terrains and Quaternary deposits (Ciarcia and Vitale 2018).

The area belongs to the Matese massif, whose main hydrogeological features are described by Fiorillo and Pagnozzi (2015). It constitutes a wide karst aquifer that feeds several basal springs, including the Grassano and Telese springs (Fig. 1c). In particular, the eastern sector of the massif would represent the main recharge area of such springs (Corniello and De Riso 1986) and would be hydraulically connected to them by buried karst terrains and outcropping karst reliefs.

The Grassano-Telese area is a peculiar karst area characterized by both bicarbonate-calcium and sulphureous thermal springs. The main outlets are located between 54-64 m a.s.l., along the southern margin of the Montepugliano Mt. and constitute the lowest basal springs group of the Matese karst system.

South of Montepugliano Mt. there is the Telese Plain, where a thick Quaternary sedimentary cover overlies the carbonate bedrock. This sedimentary complex is formed by alluvial, pyroclastic and travertine deposits and it constitutes an aquitard with respect to the underlying karst medium.

As observed in figure 1c, numerous sinkholes are present in the area under study.

Materials and methods

The hydrogeological karst features of the area have been investigated by using different methods.

First of all, digital elevation model, digital orthophotos and topographic maps have been analyzed with the aid of Geographical Information Systems tools for the identification and characterization of the sinkholes, whose morphometry is the result of subsurface hydrological processes. Sinkhole analysis methods are described in details by different authors (e.g. Šegina et al. 2018).

The discharge and the chemical-physical features of the Grassano springs have been detected by monthly measurements: discharge measurements have been performed by a hydrometric boat equipped with an acoustic Doppler profiler, whereas chemical-physical properties of waters and radon activity have been measured by using a Horiba U-50 multiparametric probe and an AlphaGUARD radon monitor, respectively.

Other data have been provided by literature and technical reports. These data regard the characteristics of fresh and thermal springs and well waters (pH, temperature, electrical conductivity and dissolved ions concentrations) and piezometric levels of the groundwater.

Finally, the finite-difference code MODFLOW (McDonald and Harbaugh, 1988) has been employed to simulate the flow along a section across the middle-final path of the Matese groundwater karst system.

Hydrogeological data and numerical model development

A numerical model has been developed based on the geological features of the area and the available boreholes data. These data allow to define the boundary conditions of the model and, in particular, to reconstruct the aquifer geometry and the water table level.

The model considers a 12 km long section between the Monaco di Gioia Mt. and the Telese Plain (Fig. 2a). Karst terrains are the aquifer and flysch sequences are the aquiclude, i.e. the flow zone and the no-flow zone of the model, respectively; Quaternary deposits of the Telese Plain have been considered as an aquitard.

To fix some hydraulic features of the model, the hydraulic head of 65 m a.s.l., observed in boreholes 10 km upstream Grassano springs (54 m a.s.l.), has been considered; as a consequence, the water table level has been imposed between these boreholes and the Grassano springs (Fig. 1b), according to a water table slope of 0.001.

Downstream the Grassano springs, no other conditions have been assigned to the model in correspondence of the Telese Plain, with the exception of the hydraulic conductivity of the Quaternary complex.

The numerical model considers a cell grid of 100x100 m^2 along the 12 km section (Figs. 2b, c, d); since the aquifer depth is unknown, three distinct thicknesses, H, have been considered (500, 1000 and 2000 m).

The model runs under steady-state conditions; in particular, hydraulic heads have been fixed upstream spring outlet by borehole data, as described before. Then, the hydraulic heads have been computed for the other cells of the model, including those of the discharge zone. In such way cells with fixed hydraulic head act as a constant source of water entering

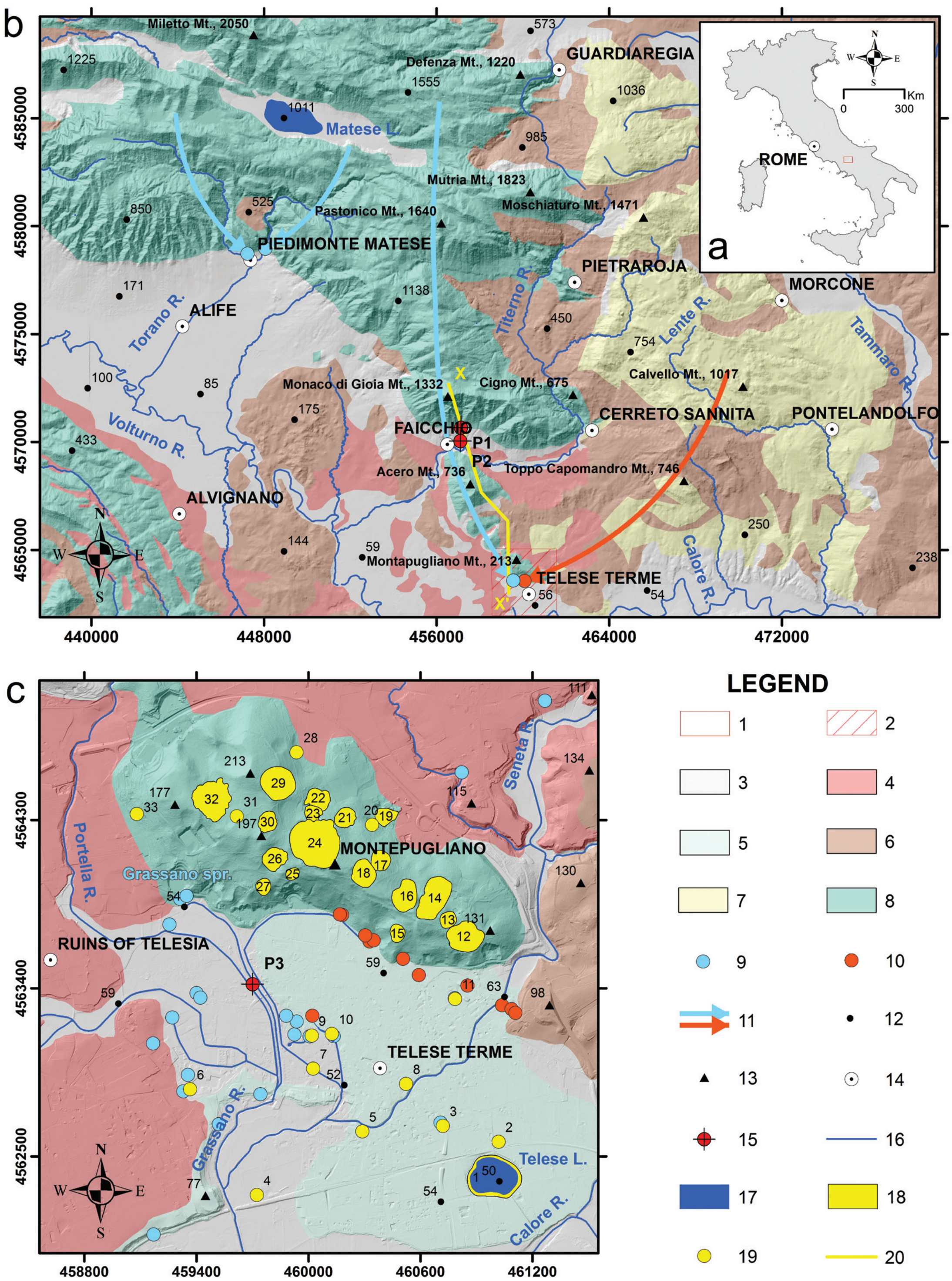

Fig. 1 - Location of the Matese massif (a). Geological sketches of the Matese massif (b) and Telese-Grassano area (c), with some hydrogeological features. 1. Matese massif area; 2. Grassano-Telese area; 3. slope, alluvial, lacustrine and travertine deposits (Quaternary); 4. pyroclastic deposits (Quaternary); 5. travertine deposits (Quaternary); 6. argillaceous and flysch sequences (Paleocene-Miocene); 7. slope-basin deposits (Cretaceous-Miocene); 8. carbonate platform limestones and dolostones (Jurassic-Miocene); 9. fresh springs; 10. thermal springs; 11. schematic supposed paths of the groundwater; 12 elevation points (in m a.s.l.); 13. peaks (with elevation); 14. villages; 15. boreholes; 16. rivers; 17. lakes; 18. major sinkholes; 19. minor sinkholes; 20. trace of hydrogeological cross-sections (XX') of figure 2.

Fig. 1 - Ubicazione geografica del massiccio dei Monti del Matese (a). Schemi geologici semplificati del massiccio del Matese (b) e dell'area di Grassano-Telese, con alcuni elementi idrogeologici. 1. area del massiccio del Matese; 2. area di Grassano-Telese. 3. depositi di versante, alluvionali e lacustri e travertini (Quaternario); 4. depositi piroclastici (Quaternario); 5. travertini (Quaternario); 6. depositi argillosi e sequenze flyschoidi (Paleocene-Miocene); 7. depositi di scarpata-bacino (Cretacico-Miocene); 8. calcari e dolomie di piattaforma (Giurassico-Miocene); 9. sorgenti fredde; 10. sorgenti termali; 11. percorsi ipotetici schematici delle acque sotterranee; 12. punti quotati (in m. s.l.m.); 13. vette (con elevazione); 14. città; 15. pozzi; 16. fiumi; 17. laghi; 18. sinkhole maggiori; 19. sinkhole minori; 10. traccia della sezione idrogeologica (XX') riportata in figura 2.

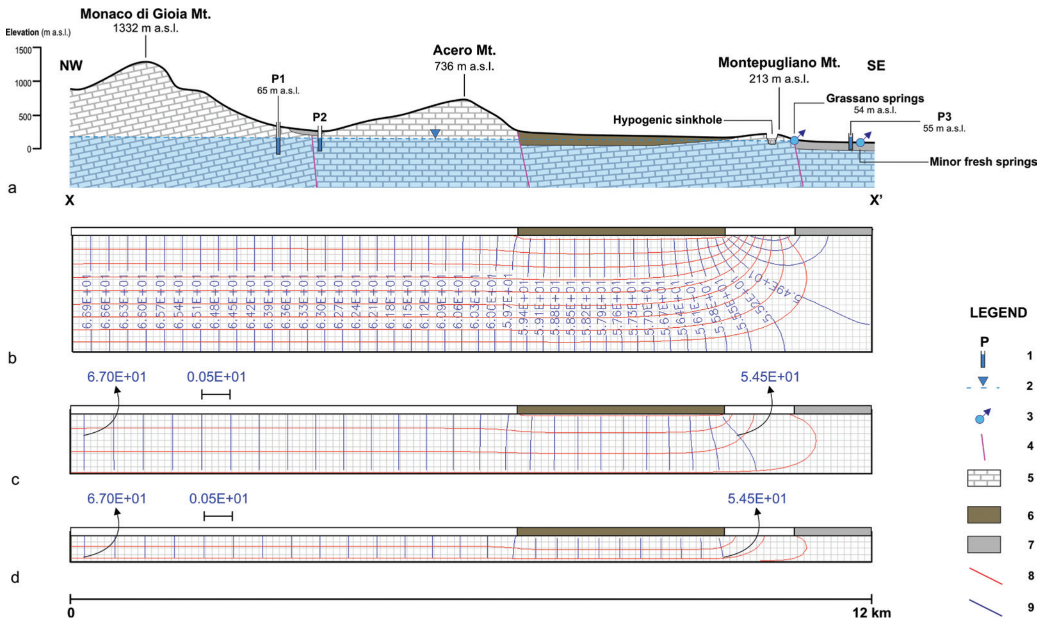

Fig. 2 - Hydrogeological section (a) and graphical results of the numerical simulations (b, c and d). Model depths are 500 m (b), 1000 m (c) and 2000 m (d). The section trace XX' is shown in figure 1.1. boreholes; 2. water table; 3. springs; 4. faults; 5. karst aquifer (carbonate terrains); 6. aquiclude (flysch); 7. aquitard (alluvial, pyroclastic and travertine deposits); 8. flow paths; 9. equipotential lines (meters a.s.l.).

Fig. 2 - Sezione idrogeologica (a) e risultati grafici delle simulazioni numeriche (b, c e d). Le profondità del modello sono 500 m (b), 1000 m (c) e 2000 m (d). La traccia di sezione XX' è mostrata in figura 1. 1. pozzi; 2. tavola d'acqua; 3. sorgenti; 4. faglie; 5. acquifero carsico (terreni carbonatici); 6. aquiclude (flysch); 7. aquitard (depositi alluvionali, piroclastici e travertini); 8. linee di flusso; 9. linee equipotenziali (metri s.l.m.).

this portion of the aquifer and the recharge amount doesn't need to be assigned.

The hydraulic head computed by the model for the cells of the discharge zone has been used for calibration, by varying the hydraulic conductivity of the karst medium, K_K.

According to these conditions, groundwater comes in from NW (left side in figures 2b, c, d) and comes out in correspondence of the Grassano springs discharge area. The distribution of the hydraulic heads has been estimated by an iterative method for different values of the hydraulic conductivity (Fig. 3): the numerical code was run many times by changing the hydraulic conductivity of the karst aquifer, for each different assigned thickness, until similar values of simulated and observed springs elevation were found. In all cases, a hydraulic conductivity with one order lower magnitude than that of the karst medium has been assigned to the deposits of the Telese Plain.

Artesian condition was observed during the drilling of boreholes located 1 km downstream the spring outlets (Fig. 1c); based on local technical reports, a hydraulic head of at least 55 m a.s.l. can be fixed here. Such value is few meters higher than the local ground level. Aquifer confined conditions are widespread in the Telese Plain, as observed in other local boreholes

Results

Montepugliano Mt. sinkholes are sub-cylindrical closed depression in carbonate terrains (up to 99 m deep and 290 m wide), with steep walls and a debris floor. They form by failure of the roofs of hypogenic caves within the carbonate bedrock associated to rising of CO_2 and H_2S rich deep waters, as suggested by: the presence of thermal springs at the base of the relief; the position of the Montepugliano Mt. with respect to the regional flow system; the short distance between the bottom of the sinkholes and the water table; the high concentration of such landforms.

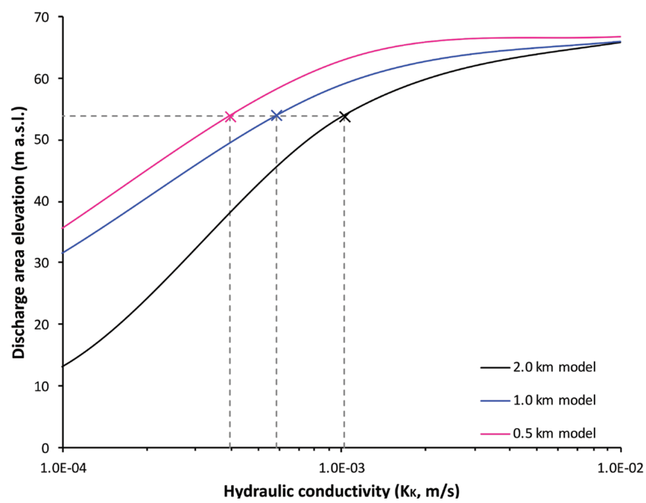

Fig. 3 - Steady-state calibration. Model depth ranges from 500 up to 2000 m. Simulated springs elevation matches the measured one for hydraulic conductivity values of 0.0004 (H = 500 m), 0.0006 (H = 1000 m) and 0.001 m/s (H = 20000 m) circa.

Fig. 3 - Calibrazione sotto condizioni stazionarie di flusso. La profondità del modello varia da 500 a 2000 m. La quota topografica simulata delle sorgenti eguaglia quella misurata per valori della conducibilità idraulica di circa 0.0004 (H = 500 m), 0.0006 (H = 1000 m) e 0.001 m/s (H = 2000 m).

Telese Plain sinkholes form by collapse of the roof of underground cavities within the cover terrains, that generate by aggressive waters rising from lower formations.

Hence, following the genetic classifications of Ford and Williams (2007), Gutiérrez et al. (2008) and Nisio (2008), based on results of the morphometrical analysis and other field evidences, Montepugliano Mt. and Telese Plain sinkholes can be classified as collapse and deep piping sinkholes, respectively.

Both fresh bicarbonate-calcium (Grassano springs) and sulphureous thermal springs (Telese springs) characterize the study area.

Grassano springs represent some of the major outlets of the Matese aquifer and are characterized by the total absence of H_2S. Their temperature and electrical conductivity values are about 11.6 °C and 1150 µS/cm respectively and are almost constant over the hydrological year (Fiorillo et al. 2019). Spring discharge ranges between 2.5-6.0 m^3/s and would control radon activity. The latter varies according to the flow rate, as observed for other karst springs of the Campania region fed by ascendant fluxes (Fiorillo et al. 2018).

Sulphureous springs show higher values of temperature (17-21 °C), electrical conductivity (1669-2650 µS/cm), dissolved ions content, dissolved CO_2 (up to 1268 mg/l) and H_2S (up to 18.3 mg/l) content and lower pH (< 6.5) then the bicarbonate-calcium springs.

The Montepugliano relief can be considered the main discharge area of both kinds of springs.

The steady-state numerical models (Figs. 2b, c, d) show that the general shape of the flow-net does not depend on the depth of the aquifer; in all cases, the groundwater flows horizontally upstream the springs, between Monaco di Gioia and Acero Mts., and comes from the central zone of the Matese massif (Fig. 1b). In correspondence of Montepugliano Mt., which is the drain of the groundwater flow, a general ascendant path takes place and feeds the springs. The geometry of the flow net is also consistent with the artesian conditions observed in the Telese Plain.

The 2D model has been calibrated using different values of the hydraulic conductivity; for each depth of the model, the best match between measured and simulated values of the hydraulic heads of Grassano springs has been found (figure 3). The relationship between model thickness, H, and hydraulic conductivity of the karst medium, K_K, is shown in figure 4 and it is:

$$H = -6.1 \cdot 10^5 + 3.3K_k \cdot 10^3 + 0.69$$

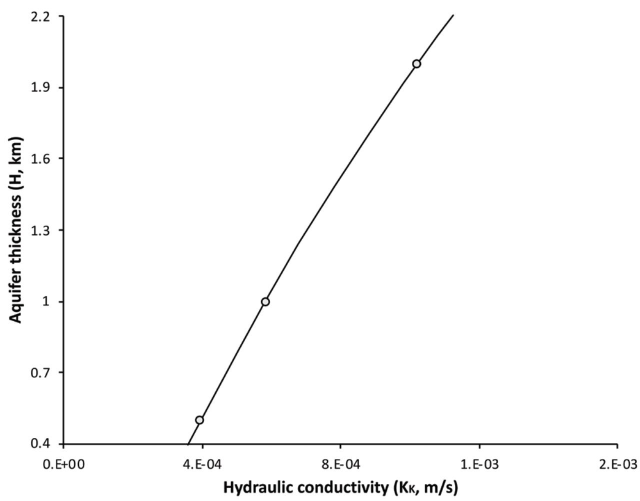

Fig. 4 -Relationship between model thickness and hydraulic conductivity of the karst medium.

Fig. 4 - Relazione tra lo spessore del modello numerico e la conducibilità idraulica del mezzo carsico.

Discussion

The research conducted in the area of Grassano and Telese springs provides a comprehensive description of its main hydrogeological karst features, that are related to ascendant groundwater flow processes.

The model simulations provide a possible scenario of the groundwater circulation mechanisms. Given the scope of the research and the few hydrogeological data available, the developed model does not take into account the heterogeneities of the karst aquifers related to the irregular networks of fissures, fractures and conduits; nevertheless, it provides a reasonable description of the general flow pattern, also considering the scale of the simulated aquifer.

More detailed surveys are needed to ascertain the aquifer depth, which is modelled here by three distinct thicknesses. The model provides the shape of the flow-net under fixed conditions and highlights the ascendant phenomenon that feeds the springs. The model does not consider the spring discharge and thus a direct comparison of the three model sections (Figs. 2b, c, d) can be only partially done. In particular, these aspects need further analyses that consider the discharge as a constrain of the model.

Similar to Grassano springs, thermal springs have to be related to the ascendant fluxes; they would be characterized by deeper paths than fresh springs, and have probably different recharge areas (Fig. 1b). In fact, cold karst springs and thermal springs occur generally in different parts of regional flow systems (Madl Szonyi and Toth 2015). Therefore, the Montepugliano Mt. would constitute the discharge area of aquifers located in different zones of the Matese massif, that are the eastern and the western sectors of the massif for fresh and thermal springs, respectively.

Conclusions

The work describes the hydrogeological features of the Grassano and Telese karst areas, which are characterized by a complex groundwater circulation.

A possible scenario of the groundwater behavior is provided by 2D numerical models which are a useful tool for the understanding of the water circulation. Our model provides a semi-quantitative and practical description of the groundwater circulation affecting the Grassano springs, located along the southern slope of Montepugliano Mt.; it represents the main discharge zone of the Matese massif, where deep ascendant groundwater flow feeds the Grassano and Telese springs and, subordinately, other minor springs in the Telese Plain.

The ascendant characteristic of the groundwater flow feeding the karst springs has been deducted from geological and hydrogeological features; according to worldwide literate concerning regional groundwater flow, it appears a novel concept for this area.

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