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The Pilato Lake (Sibillini Mts., Central Italy): first results of a study on the supposed variations of its hydrogeological conditions induced by the seismic sequence 2016-2017

Il Lago di Pilato (Monti Sibillini, Italia centrale): primi risultati di uno studio sulle presunte variazioni delle condizioni idrogeologiche indotte dalla sequenza sismica 2016-2017

Lucio Martarelli, Rossella Maria Gafà, Paolo Maria Guarino, Gennaro Maria Monti, Luca Maria Puzzilli, Angelantonio Silvi

Riassunto: Il Lago di Pilato è situato nei Monti Sibillini (Italia Centrale), ha origine glaciale ed ospita l'endemismo del piccolo crostaceo Chirocephalus marchesonii. Nell'ambito di una collaborazione di ricerca con il Parco Nazionale dei Monti Sibillini, il Servizio Geologico d'Italia dell'ISPRA sta eseguendo alcuni studi finalizzati alla valutazione dei presunti effetti della sequenza sismica dell'Italia Centrale del 2016–2017 sulle condizioni idrogeologiche che controllano l'evoluzione del lago.

Lo studio, iniziato nel luglio 2018, è stato preliminarmente finalizzato alla ricostruzione dell'assetto geologico ed idrogeologico del sottosuolo nell'area della valle che ospita il lago. Sono state eseguite indagini idrogeologiche e geofisiche per poter definire un modello concettuale della circolazione idrica sotterranea e per valutare i cicli stagionali di svuotamento e riempimento del lago. Il programma delle ricerche è tuttora in corso ed al momento saranno presentati solo alcuni risultati preliminari.

I rilievi idrogeologici hanno dimostrato l'assenza di evidenze geomorfologiche di fratture sismiche e quindi il completo essiccamento del lago avvenuto nell'estate 2017 è stato probabilmente dovuto a ragioni meteoclimatiche e/o ad una non ancora verificata variazione di permeabilità dei depositi superficiali e/o del basamento causate dallo scuotimento sismico, che potrebbe avere influenzato l'infiltrazione verso il sottosuolo. I bassi valori di conducibilità elettrica delle acque del lago sono in accordo con la prevalente provenienza della ricarica del lago dallo scioglimento della neve e dalle precipitazioni. Per quanto concerne le prime indagini geofisiche nell'area del lago, i rilievi sismici eseguiti con il metodo delle onde superficiali hanno permesso di stimare che il massimo spessore dei detriti è di circa 12.5-14 m.

In conclusione, lo sfioro delle acque attraverso la Fonte del Lago, l'evaporazione dalla superficie del lago ed il processo di drenance attraverso i depositi glaciali scarsamente permeabili verso l'Acquifero calcareo basale, che si trova nei depositi carbonatici a quote inferiori, sono responsabili della progressiva diminuzione dei livelli del lago nel tempo.

Abstract: *The Pilato Lake has glacial origin, is located in the Sibillini Mountains, Central Italy, and is characterized by the endemism of the small crustaceous Chirocephalus marchesonii. In the context of a research agreement with the Monti Sibillini National Park, the ISPRA Geological Survey of Italy is carrying on some studies aimed to evaluate the supposed effects of the 2016–2017 Central Italy earthquakes on the hydrogeological conditions controlling the lake's evolution.*

The study, started in July 2018, aims primarily at the reconstruction of the geological and hydrogeological subsoil setting, beneath the valley hosting the lake. In order to define the conceptual model of groundwater circulation and, thus, to evaluate the emptying and recharge seasonal cycle of the lake, hydrogeological surveys and geophysical investigations were performed. The research program is still in progress and only preliminary results may be proposed.

The hydrogeological surveys demonstrate the absence of geomorphological evidence of seismic-induced surface fractures generated by the seismic sequence 2016-2017. Consequently, the complete drying of the lake, occurred in summer 2017, was probably due to meteoclimatic reasons and/or to not yet verified variations in the permeability characteristics of the surficial deposits and/or bedrock affecting the infiltration towards the subsoil, caused by the severe seismic shaking. The low electrical conductivity values of the lake's waters are in accordance with the prevailing origin of the lake's recharge by snow melting and direct rainfall. As concerns the first geophysical surveys in the Pilato Lake area, seismic surveys by surface wave method assessed that the maximum thickness of debris here estimated is about 12.5-14 m.

As a whole, the factors responsible for the progressive lowering of the lake level are: i) the water overflow through the Fonte del Lago spring, ii) the evaporation from the lake surface and iii) the drainage through the scarcely permeable glacial deposits towards the Basal Calcareous Aquifer, hosted within the limestone at lower altitude.

Keywords: *hydrogeology, hydrogeological conceptual model, Pilato Lake, Sibillini Mts., Central Italy.*

Parole chiave: idrogeologia, modello idrogeologico concettuale, Lago di Pilato, Monti Sibillini, Italia centrale.

Lucio MARTARELLI ✉
Servizio Geologico d'Italia - ISPRA
Via V. Brancati, 48 - 00154 - Roma, Italia
lucio.martarelli@isprambiente.it

Rossella Maria GAFÀ, Paolo Maria GUARINO, Gennaro Maria MONTI, Luca Maria PUZZILLI, Angelantonio SILVI
Servizio Geologico d'Italia - ISPRA
Via V. Brancati, 48 - 00154 - Roma, Italia
rossella.gafa@isprambiente.it - paolomaria.guarino@isprambiente.it
gennaro.monti@isprambiente.it - lucamaria.puzzilli@isprambiente.it
angelo.silvi@isprambiente.it

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Introduction

In the context of a research agreement with the Monti Sibillini National Park, the Geological Survey of Italy of ISPRA is carrying on a study aimed to evaluate the supposed effects of the 2016–2017 Central Italy earthquakes on the hydrogeological conditions controlling the Pilato Lake's evolution. This lake has glacial origin; it is located in the Sibillini Mountains (Central Italy; Fig. 1) and houses a particular endemism unique in the world: the small crustaceous Chirocephalus marchesonii (Ruffo and Visentini 1957). Due to the former endemism, the Pilato Lake was in the past mainly studied from the biological point of view. Contrarily, probably as a result of the not easy to reach high altitude site and of the small amounts of water resource involved within the lake basin area, hydrogeological studies are still lacking. The Geological Survey of Italy activities within this research agreement programme are contributing to fill this gap.

This study, started in July 2018, aims primarily at the reconstruction of the geological and hydrogeological boundaries beneath the valley hosting the lake. In order to define the conceptual model of groundwater circulation and to evaluate the emptying and recharge seasonal cycle of the lake, hydrogeological surveys and geophysical investigations were performed. A drone survey allowed a preliminary reconstruction of the morphological scenery of the lake area.

Further hydrogeological surveys will be performed for about two hydrological years (monthly/bimonthly) of course excluding winter-spring seasons during which the Lake area is covered by snow. In depth analyses of long-term meteoclimatic data (air temperature, rainfall and snowfall; e.g. Regione Marche 2002-2018) and estimate of evaporation from the lake surface (e.g. Visentini 1937; Dragoni and Valigi 1994) will be conducted. Further geophysical investigations, including seismic and ground probing radar (GPR) surveys, will be carried out, probably at the end of 2019, to better define the geological boundaries in the subsoil along the whole area. Finally, a more detailed drone photogrammetric survey will be executed for allowing the reconstruction of the bathymetry of the lake area.

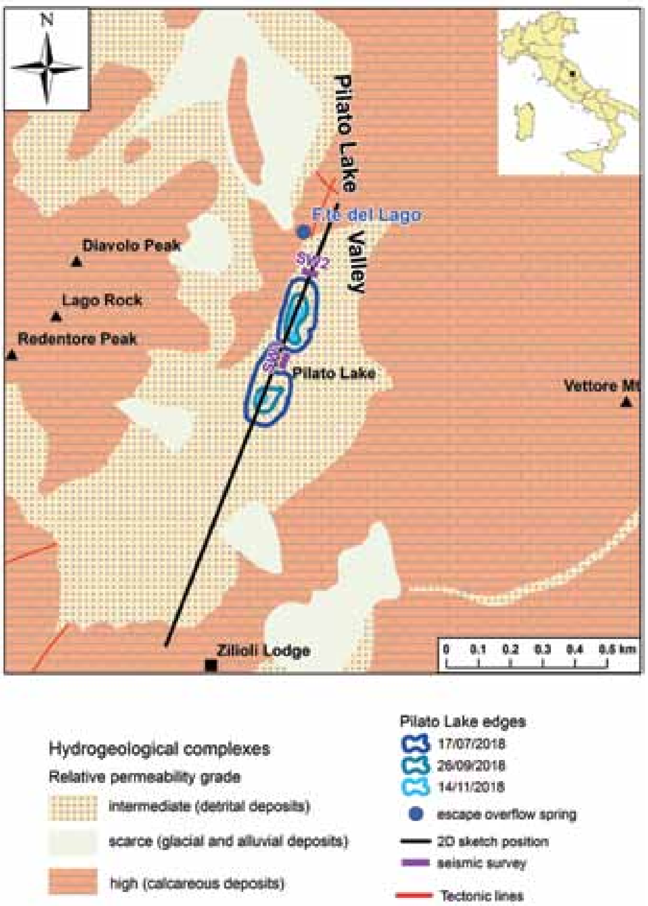

Fig. 1 - Hydrogeological simplified sketch map of the Pilato Lake area. The locations of 2D hydrogeological sketch (reported in Fig. 6) and of seismic surveys are both here shown. Inset map shows study area location in the Italian context.

Fig. 1 - Carta idrogeologica semplificata dell'area del Lago di Pilato. Sono qui riportate anche la traccia dello schema 2D di Fig. 6 e la posizione dei rilievi geofisici effettuati. Nell'inserto a piccola scala è anche indicata l'ubicazione dell'area di studio nell'ambito del territorio italiano.

Materials and methods

Geological, structural and hydrogeological settings

The Sibillini Mts. area is located in the central sector of the Apennine Belt and consists of a Meso-Cenozoic thrust and fold structure formed during Upper Miocene-Quaternary (e.g. Boni et al. 2010; Amoruso et al. 2014). It is composed of a Triassic-Miocene pre-orogenic sedimentary succession thrust on Mio-Pliocene syn-orogenic sediments having variable facies typologies and thickness. The pre-orogenic succession occurring in the study area is included in the Umbro-Marchean Apennine and is characterized by a marine carbonate shelf domain of Lower Jurassic age thrust on Middle Liassic-Lower Miocene stratified marine pelagic sediments (2500-3000 m of total thickness) (Boni et al. 2010).

As concerns the groundwater resource scenario, the Sibillini Mts. fissured and subordinately karstified carbonate ridge hosts main aquifers feeding perennial springs having in general a constant flow rate and located at the margins of those aquifers (e.g., Amoruso et al. 2014; Fiorillo et al. 2015). The Mio-Pliocene syn-orogenic silico-clastic sediments act as an aquitard (Petitta et al. 2011). The calcareous fissured and karstified lithotypes display a high effective infiltration grade (from 500 to 700 and up to 900 mm/a) and in total feed a groundwater yield of about 300 m^3/s (Boni et al. 1986, 2010).

The complex tectonic processes occurred in the study area induced the differentiation of the Sibillini Mts. ridge in diverse hydrogeological units. In particular, the Pilato Lake area (Fig.1) is located in the Vettore-Sibilla-Castel Manardo Mts. Unit.

In the Pilato Lake area, this unit is composed by terrains which may be grouped in the following hydrogeological complexes (from bottom to top; Fig. 1): i) basal calcareous complex, high relative permeability grade, Lower Jurassic, it hosts the Basal Calcareous Aquifer; ii) alluvial deposit complex, scarce relative permeability grade, Quaternary; iii) glacial deposit complex, scarce relative permeability grade, Quaternary, it generally acts as an aquiclude/aquitard; iv) detrital deposit complex, intermediate relative permeability grade, Quaternary, it may host subordinate aquifers.

Methods

Hydrogeological surveys, which will be performed for about two hydrological years on monthly or bimonthly steps starting from July 2018, consisted in the measurement of in situ chemical-physical parameters of the lake's waters (temperature, T; specific electrical conductivity, EC; pH) and spring flow rate. The data collected from July to November 2018 refer to the development of a summer-autumn low water condition. From December to May 2018, the Lake area could not be reached since it was covered by snow.

The geographical coordinate of lake edges were surveyed for the assessment of the variations of the lake level with time.

A drone photogrammetric survey was performed, using a Phantom 4 drone. The survey, carried out according to the standards known in the literature (Niedzielski 2019), involved an area of over 4 hectares with a flight height of 70 m. Image processing allowed to obtain a high resolution 3D model, textured in real colors.

Aim of the drone survey was also to allow the reconstruction of the bathymetry of the basin for water volume calculation and a first detailed reconstruction of the morphological setting of the lake area. Moreover, it was possible to verify the absence of deformations induced by seismicity on the ground, which on the contrary are evident along the external western slope of Monte Vettore (Testa et al. 2019).

The local meteoclimatic features were delineated by the analysis of available datasets from Regione Marche (2002-2018). Selected meteo-climatic stations are located at Montemonaco, Monte Prata and Monte Bove Sud and provided precipitation (snow, where available) and temperature data over a period of about twenty years (where possible). Long-term averages and average values of individual years were evaluated and the resulting deviations were compared. The statistical analysis of time series allowed the assessment of long-term trends and cycles, in addition to the seasonal component. Water loss through evaporation from the lake surface will be also estimated (e.g. Visentini 1937; Dragoni and Valigi 1994).

Geophysical investigations consisting in two active seismic surveys aimed at subsoil characterization in terms of shear-waves velocity (Vs), a parameter directly related to the stiffness of the materials, were conducted. Accordingly, a preliminary estimate of thickness of loose debris deposits over the bedrock was realized. The seismic surveys were performed in the Pilato Lake area in November 2018. Two lines (SW1 and SW2; Fig.1) were investigated by using the surface-waves method (e.g. Dal Moro 2015) aiming to possibly infer a constrain to the maximum thickness of debris deposits (detrital and glacial sediments on top of calcareous bedrock) by differentiating layers in terms of shear-waves velocity values. In both sites a multichannel simulation (e.g. Lin and Ashlok 2016) was performed by using a single three-component receiver and ten shot-positions, equally spaced of 2.5 m, aligned along a straight line to simulate two 30m-long seismic lines. The energy source was a falling-down mass (>20 kg) at a minimum offset of 5 m from the first receiver. The seismograms were registered by a 1s length and a sampling interval of 1ms. The commercial software winMASW by Eliosoft (www.winmasw.com) was used for analyzing the surface wave dispersion and retrieving vertical shear-waves profiles.

Results and discussion

The physical-chemical characteristics of the waters (T=12-13°C; pH=8-9) are consistent with those of stagnant and slightly oxygenated waters. The low values of EC (60-125 µS/cm) of the lake's waters with respect to those collected from the carbonate aquifer springs of the Sibillini Mts. area (180-640 µS/cm; e.g. Boni et al. 1986) is in accordance with the prevailing provenance of the lake's recharge by snow melting and precipitation. The Fonte del Lago temporary spring stopped to yield water in July 2018 and then, only a single measure of the hydrochemical features of its emitted water was collected (EC = 133 µS/cm; T = 4 °C; pH = 8.3).

The drone photogrammetric survey allowed the preliminary reconstruction of the bathymetry of the basin for water volume calculation and a first detailed reconstruction of the morphological setting of the lake area. In the Pilato Lake area, there are no morphological evidences of tectonic ruptures induced by the 2016-2017 seismic sequence potentially responsible for the complete drying of the lake during summer 2017. Then, the drying out was likely due to meteoclimatic reasons and/or to not yet verified variations in the permeability characteristics of the surficial deposits and/or bedrock affecting the infiltration towards the subsoil, caused by the severe seismic shaking.

The most representative meteorological station for climatic conditions of Pilato Lake is at Monte Prata, due to similar exposure and altitude. The analysis of the data showed that the estimated annual average of temperature is 6°C, rainfall is 900 mm/y and snowfall is 1500 mm/y. The available snowfall amounts are not yet officially validated and then they need further verification. A general time tendency to temperature increase emerged, along with a substantial constancy of liquid precipitation and a reduction in snowfall, which is above all concentrated in April. These trends are confirmed by the non-parametric Mann-Kendall test (Kendall et al. 1983; Sneyers 1990). The persistence of the snowpack in the spring season ensures a constant recharge to the lake's waters and in turn assures, despite of the relatively slow drainage through the deposits within the lake bed, a not complete drying before the following winter season. This circumstance is therefore crucial to avoid the periodic complete disappearance of the lake. Probably, the complete drying of Pilato Lake in the year 2017 was mainly due to air temperatures higher than the long-term annual average, which led to early melting of the snowpack, and subordinately to particularly reduced Spring rainfall (Fig. 2).

According to the results obtained from the multichannel

Fig. 2 - Plots of April cumulative monthly snow (left axis) and of deviation of average annual temperature (right axis) with time. A clear negative trend of cumulative monthly snow with time, also confirmed by the Mann-Kendall test, is evident. In the year, 2017 the average annual temperature was the highest among the average values calculated during 2002-2018.

Fig. 2 - Diagrammi della neve cumulata nei mesi di aprile (asse di sinistra) e della deviazione delle temperature dalla media annua (asse di destra) rispetto al tempo. È evidente il trend negativo, confermato anche dal test di Mann-Kendall, della neve cumulata mensilmente nel tempo. Nell'anno 2017 la temperatura media annua è stata la più elevata tra i valori medi calcolati nel periodo 2002-2018.

analysis of surface waves (see Figs. 3 and 4) shear-waves velocities varied from 310-320 m/s close to the surface to more than 1500 m/s in depth. Due to the lack of a-priori geological information, the Vs profiles are poorly constrained especially for the deepest layers; nonetheless, the depth of the rocky bedrock was inferred by considering Vs values higher than 1000 m/s, thus estimating the maximum thickness of debris equal to about 14 m and 6 m along SW1 and SW2 sites, respectively.

The surveys of the lake margins collected during July-November 2018 (Fig. 1) and evidences from pictures taken by local people show that the lake water levels had a relatively rapid decrease from the maximum elevation of about 1960 m a.s.l. in May-June, after the complete melting of snows, to the elevation of about 1955 m a.s.l. in July. This is due to the presence of the Fonte del Lago spring, acting as an overflow for waters. Then water levels went down more slowly due to evaporation and a still unknown infiltration rate through the bed terrains of the two pond areas (at this moment the lake went to a separation), reaching the minimum values of about 1950 m a.s.l. of elevation surveyed in November. In particularly dry years, as during summer 2017, the two separated ponds (Fig. 5) may dry out (Fig. 6).

The whole of the former results allowed a preliminary reconstruction of the hydrogeological conceptual model for the Pilato Lake area (Fig. 6). The water overflow through the Fonte del Lago spring, the evaporation from the lake surface and the drainage process through the scarce permeability glacial deposits (also evidenced by the performed geophysical surveys) towards the Basal Calcareous Aquifer, hosted at lower elevations within the calcareous deposits, are responsible for the progressive lowering of the lake level. A reliable calculation of the hydrogeological budget of the Pilato Lake basin is not feasible at present, since a validated bathymetry of the lake area is not still available.

Conclusions

The research program is still in progress and to date we can propose only preliminary remarks. The hydrogeological surveys demonstrate the absence of geomorphological evidence of earthquake fractures: therefore, the complete drying of the lake occurred in summer 2017 was probably mainly due to the annual temperature, 0.9°C higher than the average (leading to early snowpack melting), and subordinately to particularly reduced Spring rainfall.

The low values of EC of the lake's waters are in accordance with the prevailing provenance of the lake's recharge by snow melting and direct rainfall.

The drone aero-photogrammetric survey allowed a preliminary reconstruction of the lake basin bathymetry that will allow, in turn, the calculation of the water volumes within the lake in the various observed periods.

As concerns the first geophysical surveys in the Pilato Lake area, according to the geophysical models, the thickness of debris varies from few meters to 14 m.

The lake level from its maximum flooded elevation in May-June 2018 (completion of snow melting; about 1960 m a.s.l.) dropped rather rapidly to the elevation of the Fonte del Lago spring (about 1955 m a.s.l.) which acts as an overflow. Water levels declined more slowly due to evaporation and infiltration through the glacial deposits in the subsoil (also evidenced by the performed geophysical surveys) and furthermore reached down the minimum levels in November (about 1950 m a.s.l.). Finally, in particularly arid years, the lake may dry out.

Further investigation in the study area will include: i) hydrogeological surveys during about two hydrological years on monthly/bimonthly steps, ii) in depth analyses of long-term meteoclimatic data and estimate of evaporation from the lake surface, iii) geophysical investigations, including seismic and GPR surveys, iv) a more detailed drone photogrammetric survey.

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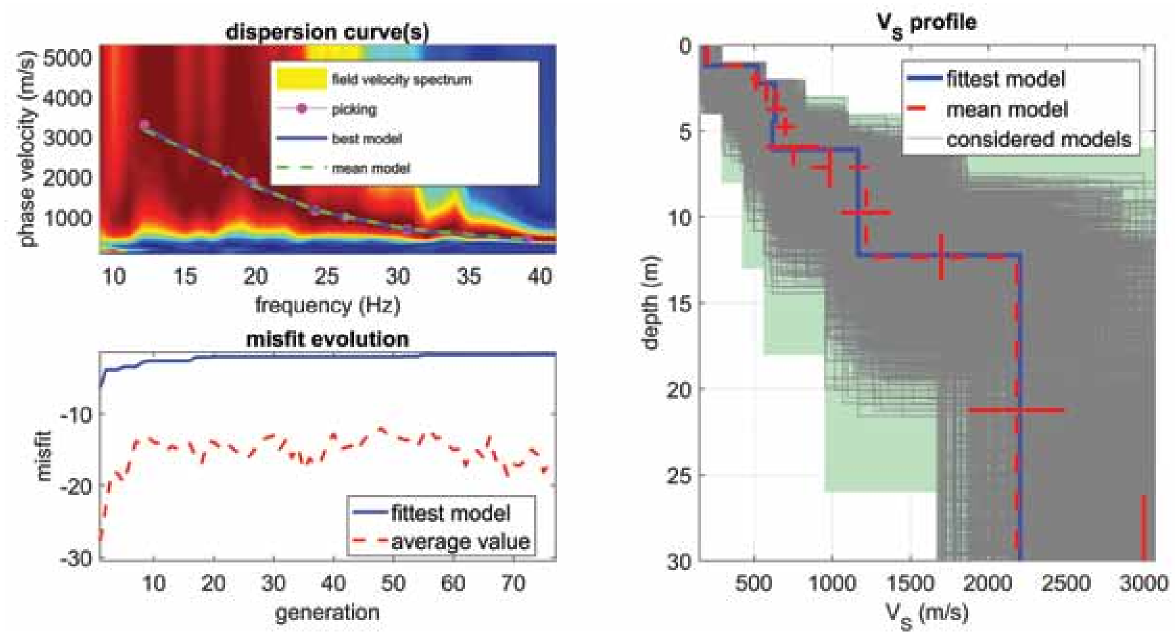

Fig. 3 - Results of the seismic survey at the SW1 site, located between the two already separated small ponds.

Fig. 3 -Risultati dell'indagine sismica nel sito SW1, ubicato tra i due piccoli bacini ormai separati.

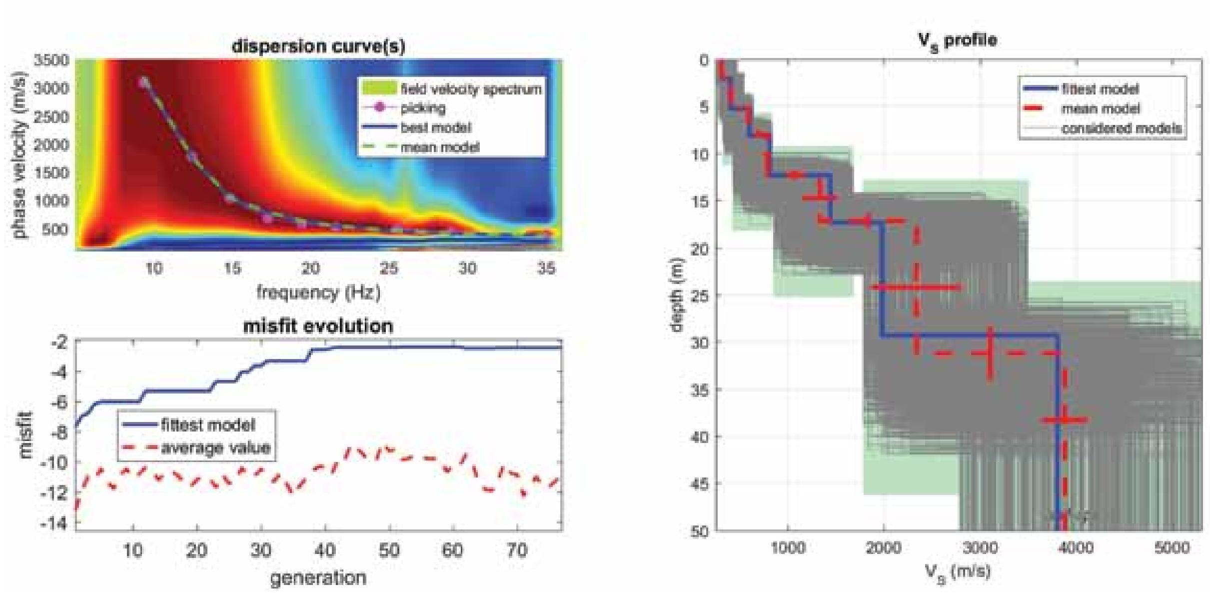

Fig. 4 - Results of the seismic survey at the SW2 site, located at north with respect to the two already separated small ponds.

Fig. 4 -Risultati dell'indagine sismica nel sito SW2, ubicato a nord dei due piccoli bacini ormai separati.

Fig. 5 - Aero-photogrammetric survey taken by drone at the beginning of June 2017 in the Pilato Lake area. View from south to north. The picture field is about 100 m in width x 400 m in perspective depth.

Fig. 5 - Rilievo aerofotogrammetrico da drone nell'inizio del giugno 2017 nell'area del Lago di Pilato. Vista da sud a nord. Il campo immagine copre circa 100 m in larghezza e 400 m in profondità.

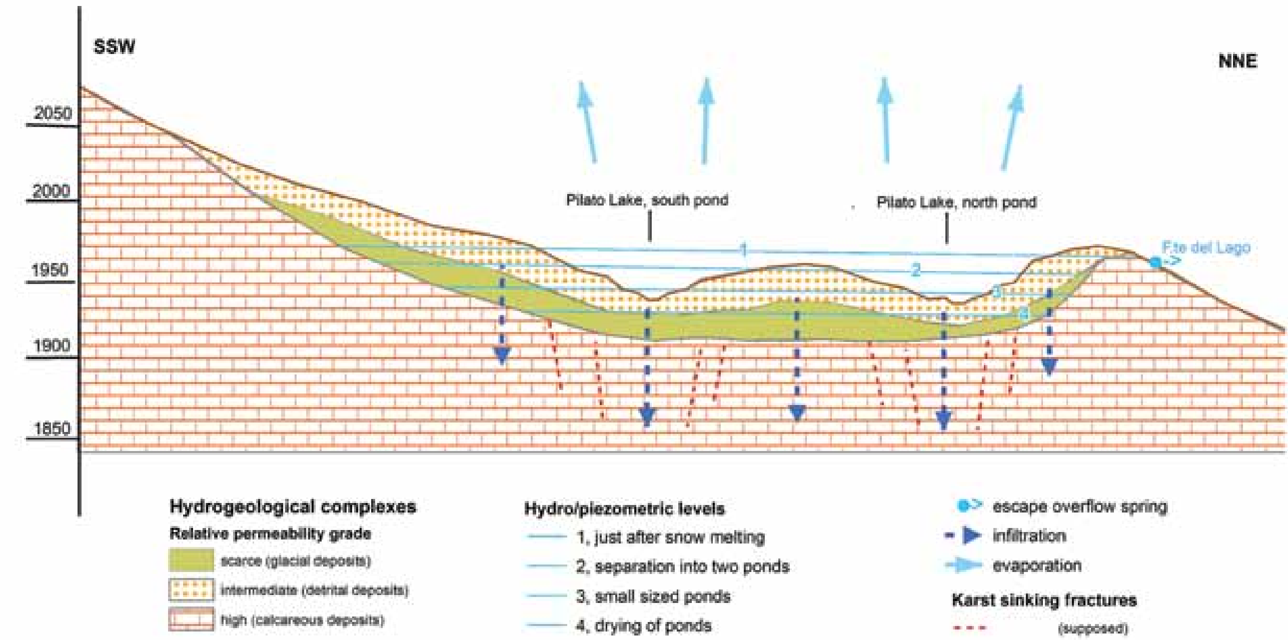

Fig. 6 - 2D sketch of the hydrogeological asset of the Pilato Lake area (horizontal and vertical scales are approximately the same). Thickness of detrital and glacial deposits (about 15 m in total) and hydro/piezometric level variations (about 20 m in total from 1. to 4. position) are exaggerated for a clearer readability. Sketch location is shown in Fig. 1.

Fig. 6 - Schema idrogeologico 2D dell'area del Lago di Pilato (la scala orizzontale è circa la stessa di quella verticale). Gli spessori dei depositi detritici e glaciali (circa 15 m in totale) e le variazioni dei livelli idro/piezometrici (circa 20 m in totale dalla posizione 1. alla 4.) sono stati esagerati per permetterne una migliore visibilità. La traccia dello schema è riportata in Fig. 1.

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