DOI 10.7343/as-2022-551

ACQUE SOTTERRANEE
Italian Journal of Groundwater
journal homepage: https://www.acquesotterranee.net/

2022-AS40-551: 27 - 35

New hydrogeological results on the Groundwater Dependent Ecosystem of the Pilato Lake (Sibillini Mts, Central Italy)

Nuovi risultati idrogeologici sull'ecosistema dipendente dalle acque sotterranee del Lago di Pilato (Monti Sibillini, Italia centrale)

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ARTICLE INFO

Ricevuto/*Received*: 4 February 2022
Accettato/*Accepted*: 28 March 2022
Pubblicato online/*Published online*: 30 March 2022

Handling Editor: **Emma Petrella**

Publication note:
This contribution has been selected from Flowpath 2021 congress held in Naples 1-3 December 2021

Citation:
Martarelli L, Gafà RM, La Vigna F, Monti GM, Silvi A (2022) New hydrogeological results on the Groundwater Dependent Ecosystem of the Pilato Lake (Sibillini Mts, Central Italy). Acque Sotterranee - *Italian Journal of Groundwater*, 11(1), 27 - 35
https://doi.org/10.7343/as-2022-551

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Keywords: *Hydrogeology, Groundwater dependent ecosystem (GDE), Pilato Lake, Sibillini Mts, Central Italy.*

Parole chiave: Idrogeologia, Ecosistema acquatico (GDE), Lago di Pilato, Monti Sibillini, Italia centrale.

Riassunto

Ubicato a circa 1950 metri di quota in un circo glaciale del Monte Vettore (Parco Nazionale dei Monti Sibillini - Italia Centrale), il Lago di Pilato è uno dei pochissimi specchi d'acqua glaciali presenti nell'Appennino. Il Lago di Pilato, data la presenza endemica del crostaceo Chirocephalus marchesonii, nel passato è stato studiato prettamente da un punto di vista biologico; scarse sono invece le informazioni idrogeologiche su questo ecosistema acquatico.

Per investigare il prosciugamento totale del lago nelle recenti estati 2017, 2019 e 2020, è stato ricostruito l'abbassamento stagionale dei livelli del lago negli anni 2010, 2012 e 2014-2020. È risultato che, negli anni del pre-sisma, lo svuotamento del lago era avvenuto più lentamente rispetto al periodo post-sisma. È quindi verosimile che lo scuotimento sismico abbia indotto un incremento della permeabilità, e conseguentemente della velocità di infiltrazione delle acque attraverso i depositi superficiali (detritici e glaciali) e/o del substrato calcareo alla base del lago. È pertanto possibile supporre nei prossimi anni più frequenti episodi di essiccamento del bacino lacustre.

Il modello idrogeologico concettuale dell'area di studio mostra che il processo di riempimento del lago è governato dalle precipitazioni nevose e piovose. È stata stimata la temperatura dell'aria nel periodo 2017-2020 ed i suoi effetti sull'evaporazione dallo specchio lacustre e sull'evapotraspirazione reale. Inoltre, è stata anche calcolata l'infiltrazione attraverso i sedimenti di base del bacino del lago. L'area della superficie bagnata e le variazioni di volume idrico nel tempo ed anche la permeabilità d'insieme dei sedimenti di base a sostegno del bacino lacustre sono state calcolate.

Abstract

Located at an altitude of about 1950 m a.s.l. in a glacial cirque of Mount Vettore (Monti Sibillini National Park - Central Italy), Pilato Lake is one of the few glacial lakes existing in the Apennines. Due to the endemic presence of the crustaceous Chirocephalus marchesonii, the Pilato Lake was in the past mainly studied from the biological viewpoint, but hydrogeological information on this groundwater dependent ecosystem is scarce.

Furthermore, for investigating the lake drying in the recent 2017, 2019 and 2020 summers, the seasonal lowering of lake levels during 2010, 2012 and 2014-2020 was reconstructed. It resulted that in the pre-seismic years, the lake emptying was slower than in the post-seismic time. It is then supposed that seismic quaking induced an increase in permeability and, consequently, increased infiltration velocity through the lake sustaining surficial (detrital and glacial) and/or bedrock deposits towards the subsurface. More frequent summer dryings of the lake are then supposed for the next future.

The hydrogeological conceptual model of the study area showed that the refilling process of the lake is driven by snow and rain precipitations. The air temperatures during 2017-2020 and their effects on evaporation from lake and on actual evapotranspiration were estimated. The infiltration through sustaining sediments was calculated and the estimation with time of lake wet surface and lake volume variations, and then bulk permeability of sustaining sediments, were evaluated as well.

Introduction

Mountain regions are of special importance for global environmental and climate change research. Due to the strong altitudinal gradients, many mountain areas provide unique opportunities to detect and analyse global change processes and phenomena (Becker and Bugmann 2001). In this context, mountain lakes are often located in protected natural areas, a feature that leads to their role as guards of global environmental change. Despite variations in latitude, mountain lakes share many features, including their location in catchments with steep topographic gradients, cold temperatures, high incident solar and ultraviolet radiation, and prolonged ice and snow cover (Moser et al. 2019).

Mountain lakes are usually relatively small, located in sparsely vegetated catchments and exposed to extreme climates. Most of them are of glacial origin and range from a few samples in small mountain regions to many thousands in Arctic and sub-Arctic lands. These lakes are not relevant from the water reserve point of view, due to their usual limited water volume and small hydrographic catchments with respect to lake volume. They tend to be sometimes in correspondence of headwaters, far from populated areas, experiencing minimal or no direct human impact in their catchments (Catalán et al. 2009).

Several studies have shown that groundwater can play an important role in the water balances of such lakes (Hauer et al. 1997; Hayashi and Rosenberry 2002; Barnett et al. 2005). However, a number of uncertainties remain, including whether substantial groundwater exchange is common or rare, what types of interactions may occur, and what are the important factors affecting groundwater exchange. This understanding is important for predictions of hydrology, water chemistry and ecology patterns and interactions in the headwaters of mountain watersheds (Roy and Hayashi 2008).

Lakes in mountainous areas are of special interest in environmental studies. Mountain areas often have rocky bedrock, with thin soils and sparse vegetation, which together give rise to surface water with low ionic strength. Such waters are particularly sensitive to inputs of atmospheric pollutants and to changes in climate. Mountain lakes are in general much less influenced by disturbance by local pollution from agriculture and wastewater. Therefore, they are good early warning indicators for monitoring more widespread environmental changes (Brit and Wright 1998).

Located at an altitude of about 1950 meters in a glacial cirque of Mount Vettore (Monti Sibillini National Park - Central Italy), Pilato Lake is one of the few glacial lakes existing in the Apennines. Due to the endemic presence of the crustaceous Chirocephalus marchesonii (Ruffo and Visentini 1957), the Pilato Lake (Fig. 1) was in the past mainly studied from the biological viewpoint, but hydrogeological information on the area of this groundwater dependent ecosystem (GDE) was never collected before Martarelli et al. 2019. The ongoing activities presented in this work are aimed to contribute to fill this gap and to evaluate the causes for the more frequent occurrences of drying out of the lake at the end of summer period in the last years.

Multidisciplinary survey activities were conducted since 2018 in order to evaluate the effects induced on the Pilato Lake GDE by the Central Italy 2016-2017 seismic sequence (Martarelli et al. 2019). In fact, the site has been hit by the earthquakes of the cited seismic sequence, but rockfall landslides from slopes were observed as the only local manifest seismic-induced effect. Geomorphological evidence of surface faulting was not observed in the lake area, while on the external western side of the Mt Vettore range there is a faulting surface recognizable as the cropping out evidence of the fault system of Mt Vettore - Mt Bove (Testa et al. 2019), which has been inferred as responsible for the main shock of the cited seismic events (Gori et al. 2018). Thus, the study site is within the epicentral area of the 2016-2017 seismic sequence.

The importance of hydrogeological surveys for the characterization of GDEs and for raising the awareness on environmental and climate change impacts on such kind of GDEs was experienced and pointed out.

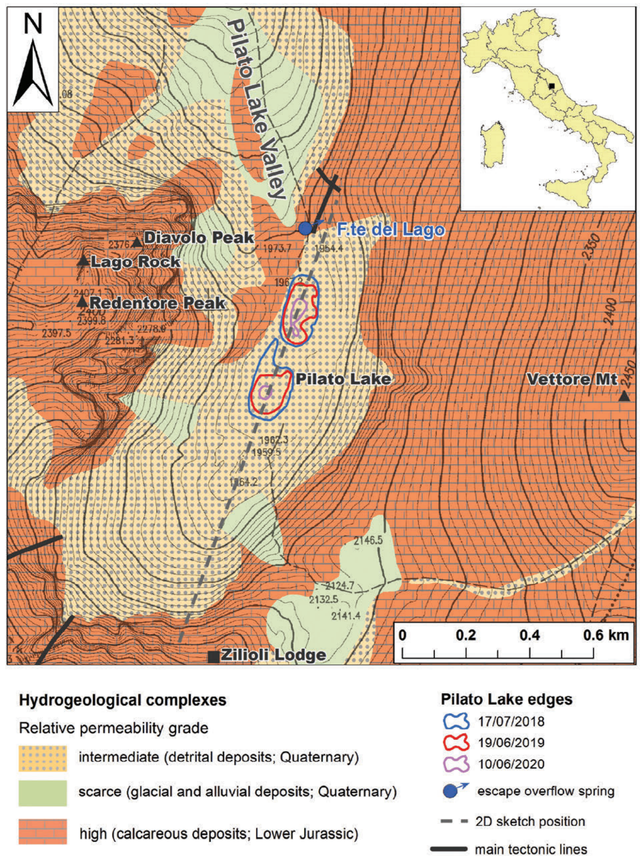

Fig. 1 - Hydrogeological simplified sketch map of the Pilato Lake area (modified from Martarelli et al. 2019). The location of 2D hydrogeological sketch (reported in Fig. 4) is here shown. Inset map shows study area location in the Italian context. Geographical coordinates of the NW and SE edges of the figure are lat.42.830°, long.17.253° and lat.42.817°, long.13.275°, respectively.

Fig. 1 - Carta idrogeologica semplificata dell'area del Lago di Pilato (modificato da Martarelli et al. 2019). È qui riportata anche la traccia dello schema 2D di Figura 4. Nell'inserto a piccola scala è inoltre indicata l'ubicazione dell'area di studio nell'ambito del territorio italiano. Le coordinate geografiche degli spigoli NW e SE della figura sono, rispettivamente, lat.42.830°, long.17.253° e lat.42.817°, long.13.275°.

Geological, structural and hydrogeological settings

The Sibillini Mts area is in the central sector of the Apennine Belt and consists of a Meso-Cenozoic thrust and fold structure formed during Upper Miocene-Quaternary. It is composed of a Triassic-Miocene pre-orogenic sedimentary succession thrust on Mio-Pliocene syn-orogenic sediments featured by variable facies typologies and thickness values. 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; Pierantoni et al. 2013; Viaroli et al. 2021).

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; Fronzi et al. 2020, Di Matteo et al. 2020). The Mio-Pliocene syn-orogenic silico-clastic sediments act as an aquitard (Petitta et al. 2011; Barberio et al. 2017; Petitta et al. 2018). The calcareous fissured and karstified lithotypes display a high effective infiltration grade (from 500 to 700 and up to 900 mm/yr) and in total feed a groundwater yield of about 300 m^3/s (Boni et al. 1986, 2010; Barberio et al. 2017; Petitta et al. 2018).

The complex tectonic processes occurred in the study area induced the differentiation of the Sibillini Mts ridge in several hydrogeological units (Boni et al. 2010; Mastrorillo and Petitta 2014; Fronzi et al. 2020; Nanni et al. 2020; Viaroli et al. 2021); in particular, the Pilato Lake area (Fig.1) has been included within the Vettore-Sibilla-Castel Manardo Mts Unit. According to the previously cited literature and to the outcomes of the present study, the terrains cropping out in the Pilato Lake area 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.

Detrital and glacial deposits constitute the sediments sustaining the Pilato Lake ponds (Martarelli et al. 2019).

Methods

The survey methods used during the 2018-2020 monitoring activities for verifying the effects induced by the Central Italy 2016-2017 seismic sequence on the Pilato Lake GDE (Martarelli et al. 2019) are briefly described as follows. Hydrogeological surveys were performed for about two hydrological years on monthly or bimonthly steps and included assessment of variations of the lake level by lake edge differential GPS surveys (by a station equipped with a controller/receiver geosystem adopting rapid-static coordinate acquisition and post-processing methods) and chemical-physical parameters of the lake's waters (temperature; specific electrical conductivity, EC; pH; obtained in situ by a multi-parametric analysis device).

Climatic characterization by analysis of available meteoclimatic long-term datasets (from 2002 to 2020) at selected stations located at Montemonaco, Monte Prata and Monte Bove Sud (precipitation - also snow, at the stations equipped with snow-gauges - and temperature; data after Regione Marche 2021) and estimation of water loss through evaporation from lake surface (according to Visentini 1937; Dragoni and Valigi 1994) were performed. Among the former meteoclimatic stations, Monte Prata is the best representing station with respect to Pilato Lake area geo-orographical features (e.g., site elevation and exposition). Unfortunately, the meteoric annual mean precipitation data calculated at Monte Prata station (but the same is for other local stations located at high elevation) appear to be underestimated (about 900 mm/yr) when compared with the realistic expected meteoric precipitation corresponding to its altitude and with respect to other local meteoclimatic stations distributed from about 400 to 1400 m a.s.l.. This is likely due to instrumental measurement errors induced by the heated rain gauges used in these stations for snowfall evaluation, which may cause up to 66% of unmeasured snow amounts, due to strong wind and other accidents during measurements (Lendvai et al. 2015). To obtain a whole rain and snow more realistic mean value at Pilato Lake area, the local elevation-precipitation correlation line was drawn on the basis of local meteoclimatic stations data (the obtained reference equation is $P=0.48 \cdot EL+790$, where P is precipitation and EL is elevation) and the local precipitation value was estimated (about 1700 mm/yr during 2017-2020). The accuracy problems with snowfall data are further emphasized when considering the monthly scale. Then, a combined discussion of air temperature (that are featured by quite good time series) and precipitation data at monthly scale was considered as inappropriate. Furthermore, the Monte Prata station (data from 2002 to 2020) was selected for carrying out a non-parametric Mann-Kendall test (Kendall et al. 1983; Sneyers 1990), to evidence any possible statistical trend only for air temperature time series.

Drone photogrammetry, obtained by Martarelli et al. 2019 using a Phantom 4 drone (according to Niedzielski 2019 method) allowed the reconstruction of the bathymetry of the basin for water volume calculation.

Geophysical surveys performed by Martarelli et al. 2019 consisted in active seismic surface-waves and ground probing radar methods (according to Dal Moro 2015 and Lin and Ashlok 2016 approach) and were finalized to subsoil characterization in terms of estimate of thickness of loose debris deposits over the bedrock.

Historical time series of the lake levels are not available. Therefore, for investigating the lake drying out events occurred in the recent 2017, 2019 and 2020 summers, the lake level lowering sequences during 2010, 2012 and 2014-2020 seasons were reconstructed by collection and interpretation of historical pictures available at different websites in the internet. The water level positions taken from those pictures

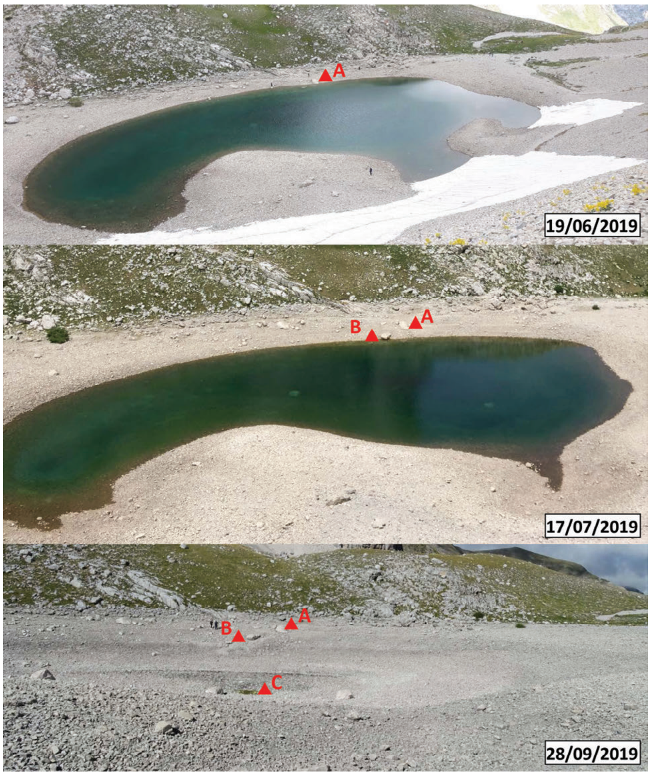

Fig. 2 - Example of reconstruction of lake levels with time from pictures in different dates of 2019. The lake level positions were referred to control points with quoted elevation values a.s.l. (red triangles marked with capital letters: A = 1947 m; B = 1946 m; C = 1940 m).

Fig. 2 - Esempio di ricostruzione dei livelli del lago nel tempo da foto scattate in differenti date del 2019. Le posizioni dei livelli del lago sono state riferite alle quote s.l.m. rilevate in alcuni punti di controllo (triangoli rossi contrassegnati da lettere maiuscole: A = 1947 m; B = 1946 m; C = 1940 m).

were referred to the elevation values quoted according to selected control points (Fig. 2). Yearly plots of these level variations were obtained and discussed.

The bulk permeability (K) of sustaining sediments was as well valuated by the application of equation $K=\Delta V/(A\cdot\Delta t)$, considering the estimation with time (Δt) of wet lake surface (A) and water lake volume variations (ΔV). The two latter parameters were calculated using GIS spatial analyst tools (DEM elaboration with 0.1 m resolution and volumetric and area calculations), considering the performed reconstruction of the bathymetry of the lake basin.

Results and discussion

Drone flight, elevation contour lines of topographic maps and GPS surveys of elevation of lake borders with time allowed a reconstruction of the lake basin bathymetry (Fig. 3) that supported, in turn, the calculation of the sizes and volumes of the water basin at different hydrological conditions and the estimate of evaporation from the lake surface.

Geophysical surveys previously performed in the Pilato Lake area (Martarelli et al. 2019) lead to infer a maximum estimated thickness of debris deposits (detrital and glacial sediments on top of calcareous bedrock is about 10-15 m in correspondence of topographical highs and 25-30 m at the middle points of minimum elevation of the two main ponds featuring the lake bathymetry).

The physical-chemical characteristics of the lake waters are here reported as reference ranges (T=12-13°C, with a very marked seasonal variation; pH=8-9; EC=60-125 µS/cm) and

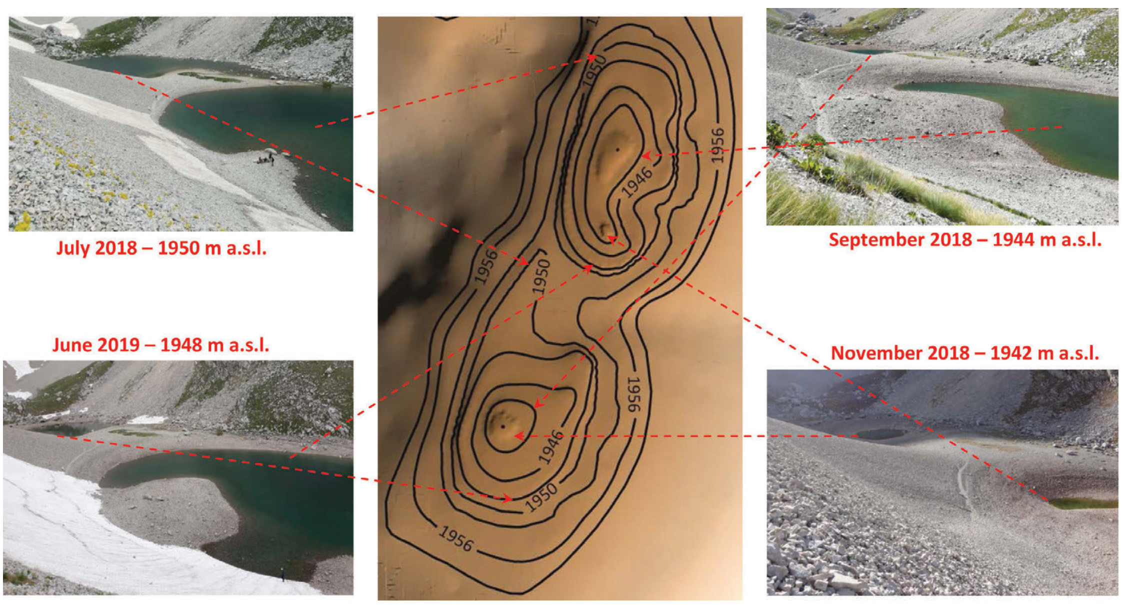

Fig. 3 - Reconstruction of the Pilato Lake basin bathymetry (central picture) drawn by combined information obtained from drone flight, elevation contour lines of topographic maps and GPS surveys of elevation of lake borders with time and implemented by DEM elaboration (resolution 0.1 m). Some lake pictures and the reference water level elevation a.s.l. are also reported. In all pictures, the basin shown in the right-bottom corners is the northern pond of the Lake, while that in the left-top corners is the southern one.

Fig. 3 - Ricostruzione della batimetria del bacino del Lago di Pilato tracciata da informazioni comparate ottenute da volo di droni, traccia di isoipse di mappe topografiche e rilievo GPS della quota del livello del lago nel tempo e realizzata tramite elaborazione di un DEM (risoluzione 0,1 m). Sono riportate anche alcune foto del lago e le relative quote del livello idrico. In tutte le foto, il bacino visibile nell'angolo a destra in basso è la depressione settentrionale del lago, mentre il bacino nell'angolo a sinistra in alto è quella meridionale.

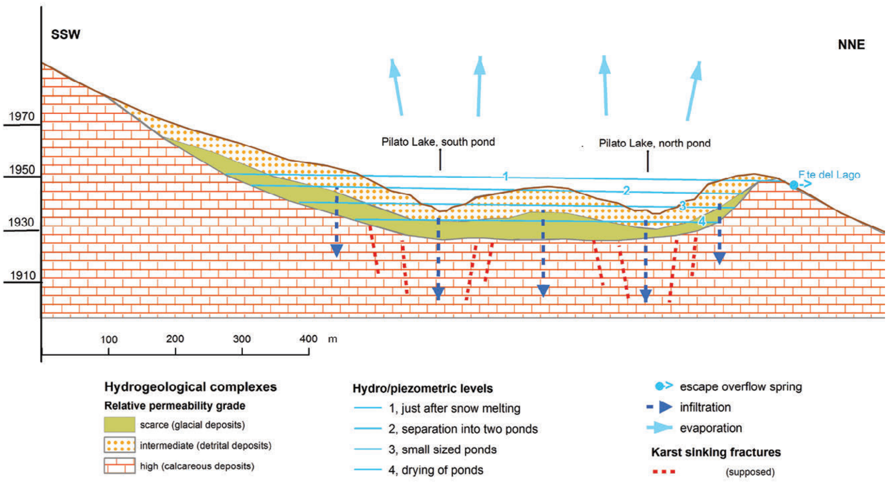

Fig. 4 - 2D sketch of the hydrogeological asset of the Pilato Lake area (modified from Martarelli et al. 2019). Thickness of detrital and glacial deposits (about 15-25 m in total) and hydro/piezometric level variations (about 20 m in total from 1. to 4. position) are shown. Sketch location is displayed in Figure 1.

Fig. 4 - Schema idrogeologico 2D dell'area del Lago di Pilato (modificato da Martarelli et al. 2019). Gli spessori dei depositi detritici e glaciali (circa 15-25 m in totale) e le variazioni dei livelli idro/piezometrici (circa 20 m in totale dalla posizione 1. alla 4.) sono stati riportati. La traccia dello schema è presente in Figura 1.

are consistent with those of stagnant and slightly oxygenated waters during summer-autumn low water conditions (during the winter-spring season it is not possible to approach the lake due to presence of snow and related avalanche hazard) and with prevailing provenance of the lake's recharge by snow melting and precipitation (Martarelli et al. 2019). A complete dataset of these data will be available in the future.

The surveys of the lake margins evidenced that the maximum potential lake water levels, when the lake basin is potentially totally filled after the complete melting of snow, is about 1960 m a.s.l. Furthermore, the minimum value of elevation of the lake bathymetry is about 1940 m a.s.l.. In particularly dry years, as occurred in 2017, 2019 and 2020, the two ponds in which the lake separated in late summer dried out (Fig. 4; Martarelli et al. 2019).

The whole of the surveyed hydrogeological results achieved in this research and in a related previous study (Martarelli et al. 2019) allowed confirming the reconstruction of the hydrogeological conceptual model for the Pilato Lake area (Fig. 4). The initial water overflow through the Fonte del Lago spring (elevation about 1948 m a.s.l.), the evaporation from the lake surface and the drainage process through the scarce permeability glacial deposits towards the Basal Calcareous Aquifer hosted at lower elevations within the calcareous deposits are responsible for the progressive lowering of the lake level.

On the other side, as concerns the refilling process of the lake, the hydrogeological conceptual model of the study area showed that the stock up of lake water is driven by snow and rain precipitations (P; annual estimated average is 1700 mm/yr). From the meteoclimatic point of view, the non-parametric Mann-Kendall test (Kendall et al. 1983; Sneyers 1990) carried out on the mean air temperature time series of the Monte Prata gauging station evidenced major trends of general time tendency to temperature increase in February (trend value of Mann-Kendall Test Z = 2.05; Sen's slope estimate = 0.213), April (Test Z = 2.05; Sen's slope = 0.151) and August (Test Z = 1.89; Sen's slope = 0.161), also shown on the annual mean temperature values (Test Z = 2.38; Sen's slope = 0.060), as is evidenced by the regression line in Fig. 5.

The persistence of the snowpack, especially in the spring and early-summer seasons, ensures a continuous recharge of the lake's waters which assures that the waters do not drain completely at the end of the summer season. Therefore, this circumstance is crucial to avoid the complete disappearance of the lake (Martarelli et al. 2019). The mean air temperatures in the years 2017, 2019 and 2020 (about 7 °C) were higher than the annual mean value (about 6°C) and the highest within the 2002-2020 period (Fig. 5), thus likely leading to early melting of the snowpack and a high evaporation rate from the lake surface, both contributing to the complete drainage of Pilato Lake.

More in detail, the air temperatures during 2017-2020 (mean value within these four years is about 7°C) and their effects on evaporation from the lake (E, range of values obtained for the former four years is about 910-1080 mm/yr; Visentini 1937 method; annual base equation $E=90 \cdot Ta+300$, for elevations >500 m a.s.l.) and on actual evapotranspiration (ET, corresponding range of values is about 450-480 mm/yr; Turc 1961 method) were estimated. Finally, the mean value

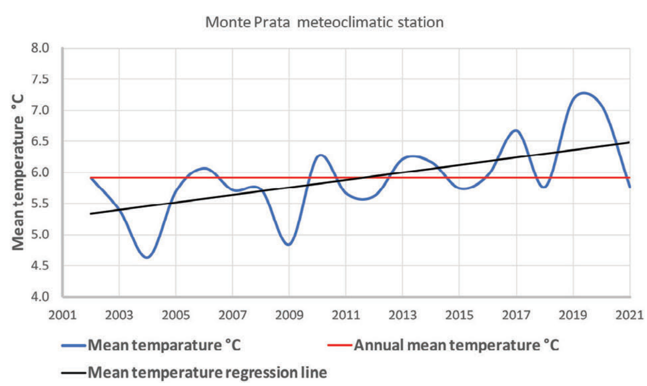

Fig. 5 - Plot of mean air temperature with time at the Monte Prata meteoclimatic station. Annual mean temperature and annual mean temperature trend are also shown. In 2017, 2019 and 2020, the mean temperatures were the highest among the values calculated during 2002-2020.

Fig. 5 - Diagramma delle temperature medie dell'aria rispetto al tempo nella stazione meteoclimatica di Monte Prata. Sono state anche riportate la media annua delle temperature ed il trend delle temperature medie. Negli anni 2017, 2019 e 2020 le temperature medie sono state le più elevate tra i valori calcolati nel periodo 2002-2020.

of infiltration (I) through sustaining sediments within the same period was calculated using the hydrogeological budget equation I=P-R-ET-E and, considering the former estimated values and the negligible runoff value (R; e.g. Boni et al. 1986) in the relatively permeable calcareous deposits around the lake area, it resulted in a range of values obtained for the former four years of about 140-340 mm/yr (Tab. 1).

The contours of bathymetric isolines of the lake area, obtained by drone flights, elevation contour lines of topographic maps and monthly/bimonthly GPS surveys of elevation of lake borders were recently refined and allowed the estimation with time (Δt) of lake wet surface (A) and lake volume variations (ΔV), and then bulk permeability (K=ΔV/A·Δt) of sustaining sediments was as well valuated (10^{-6}÷10^{-7} m/s; Tab. 2). This is substantially in accordance with a grain size lab test carried out within the present study on a sample of the sediment beneath the lake. The test certified that the terrain is gravelly-silty sand (sand 44.5%, gravel 25.8%, silt 25.5, clay 4.2%), then likely ascribable to a similar expected permeability value range (e.g. Tomlinson 2015).

Tab. 1 - Range of values of the parameters of hydrogeological budget in the Pilato Lake GDE area within the 2017-2020 period.

Tab. 1 - Intervallo dei valori degli elementi del bilancio idrogeologico nell'area del GDE del Lago di Pilato nel periodo 2017-2020.

Parameter		Value (mm/yr)
Rainfall and snowfall	(P)	1700
Evaporation (Visentini method)	(E)	910÷1080
Actual evapotranspiration {1} (Turc method)	(ET)	450÷480
Runoff	(R)	negligible
Net effective infiltration	(I=P-E-ET-R)	140÷340

{1} Mean temperature within the 2017-2020 period is about 7°C

During the surveys at the Pilato Lake area, geomorphological evidence of co-seismic ruptures was not observed, but only boulders detached from the surrounding slopes were found throughout the study area (Martarelli et al. 2019). In any case, for investigating the lake drying in the recent 2017, 2019 and 2020 summers, the seasonal lowering of lake levels during 2010, 2012 and 2014-2020 was reconstructed (Fig. 6). It resulted (Tab. 3) that in the pre-seismic years 2010-2016 the lake emptying was slower (mean value 0.044 m/d) than in the post-seismic time 2017-2020 (mean 0.066 m/d).

Tab. 2 - Evaluation of bulk permeability of Pilato Lake sustaining sediments.

Tab. 2 - Stima della permeabilità d'insieme dei sedimenti che sostengono il Lago di Pilato.

Parameter		Value (mm/yr)
Lake volume variations	(ΔV)	17.000-37.000 m^3
Reference lake wet surface	(A)	10.000-28.000 m^2
Time span	(Δt)	50-70 days (4.320.000-6.048.000 s)
Bulk permeability	(K=ΔV/(A·Δt))	$8.6 \cdot 10^{-7} \div 1.0 \cdot 10^{-7}$ m/s

Tab. 3 - Yearly values of regression line slope of lake level lowering measurements (see Fig. 6).

Tab. 3 - Valori annuali della pendenza della retta di regressione dei livelli del lago (vedi Fig. 6).

Year	Slope	R^2	Reference period	Statistics		
2010	-0.054	0.985	Jun-Aug	Period 2010-2016		
2012	-0.032	0.997	Jun-Dec	mean	min	max
2014	-0.048	0.954	Jun-Oct	-0.044	-0.054	-0.032
2015	-0.040	0.971	Jun-Nov			
2016	-0.045	0.999	Jul-Nov			
2017	-0.081	0.802	Jun-Aug	Period 2017-2021		
2018	-0.057	0.957	Jun-Nov	mean	min	max
2019	-0.073	0.965	Jun-Sep	-0.066	-0.081	-0.051
2020	-0.051	0.879	May-Jul			

This is also true for the 2018, year with relatively abundant precipitation and moderate temperature, demonstrating that the only meteoclimatic issues may not fully explain the process. Probably, the acquisition of data in the next years may be crucial for improving the understanding of the process itself. The quite insignificant overlapping of minimum and maximum ranges of slope values for both the 2010-2016 and 2017-2020 periods and the good R2 coefficient values of regression lines (varying from 0.802 and 0.999) support the previous reported considerations (Tab. 3). It is then likely that seismic quaking induced increasing permeability and, consequently, infiltration velocity through the lake sustaining surficial (detrital and glacial) and/or bedrock deposits towards the subsurface. More frequent summer dryings of the lake are then conceivable for next years. After an accurate reading of Fig. 6 it is also possible to stress that a lake level elevation value lower than about 1947 m a.s.l. on the May-June period of each reference year represents a warning threshold for a probable late summer drying of the lake.

Conclusions

The research activities are still in progress and to date we can propose the results of this new step of discussion.

The lake level from its maximum flooded elevation in May-June (completion of snow melting; the maximum potential morphological level at 1960 m a.s.l.) fell down with time due to evaporation and infiltration through the glacial deposits in the subsoil, reaching down a seasonal low level in late summer. Finally, in particularly arid years, the lake may dry out (the minimum possible level at ponds bottom about 1940 m a.s.l.).

For investigating the lake drying in the recent 2017, 2019 and 2020 summers, the seasonal lowering of lake levels during 2010, 2012 and 2014-2020 was reconstructed. It is then supposed that seismic quaking induced an increase in permeability and, consequently, infiltration velocity through the lake sustaining detrital and glacial and/or bedrock deposits towards the subsurface. More frequent summer dryings of the

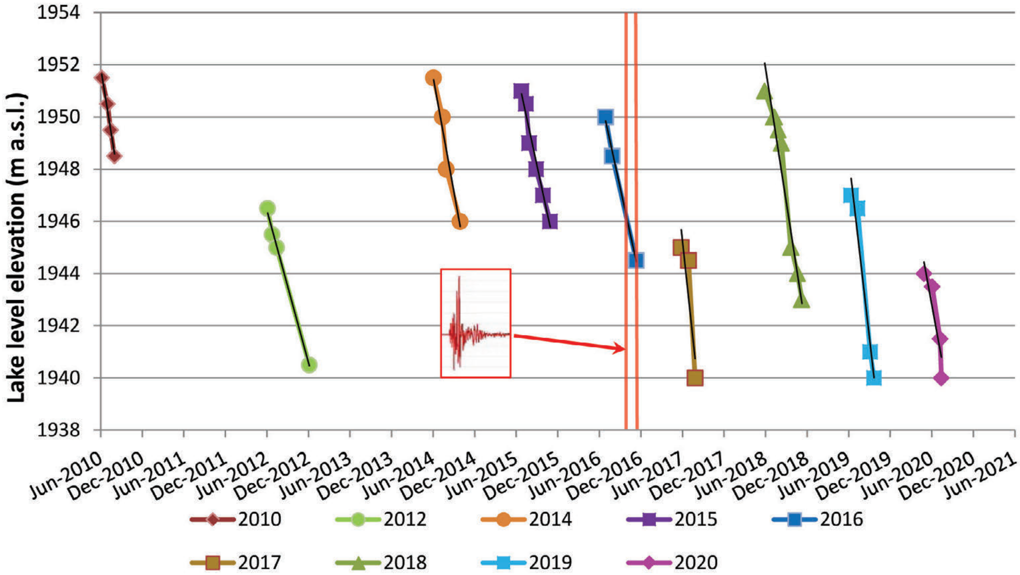

Fig. 6 - Yearly lake level lowering during 2010, 2012 and 2014-2020. The regression line equations of each annual series are shown. A lake level elevation value lower than about 1947 m a.s.l. on the May-June period of each reference year represents a warning threshold for a probable late summer drying of the lake. The vertical red lines represent the main events of the 2016 seismic sequence.

Fig. 6 - Diminuzione dei livelli del lago negli anni 2010, 2012 e 2014-2020. Sono riportate le equazioni delle rette di regressione di ciascuna serie annuale. Quote del livello del lago minori di circa 1947 m s.l.m. nei mesi di maggio-giugno di ogni anno di riferimento rappresentano il livello di allerta per il probabile essiccamento del lago durante la stagione estiva. Le linee rosse verticali rappresentano i principali eventi della sequenza sismica 2016.

lake are then conceivable in next years. A lake level elevation value lower than about 1947 m a.s.l. on May-June period of each reference year represents a warning threshold for the probable late summer drying of the lake.

Further investigation in the study area will include: i) installation of data-loggers for surveying over time water levels in the two ponds of the lake, ii) in depth analyses of long-term meteoclimatic data and estimate of evaporation from the lake surface, iii) a more detailed drone photogrammetric survey, iv) a more accurate calculation of the hydrogeological budget of the Pilato Lake basin, v) the implementation of a numerical model.

Even if at a preliminary stage, the activities presented in this work contributed not only to a better comprehension of the Pilato Lake GDE, but they could also be a contribution for implementing the limited literature on the topic of mountain lakes and the knowledge of the hydrogeological processes involving them.

Competing interest

The authors declare no competing interest.

Acknowledgements

The Ente Parco Nazionale dei Monti Sibillini is warmly thanked for the support and provided authorization to field surveys at the Pilato Lake. Two anonymous referees are kindly acknowledged for their useful comments and suggestions.

Author contributions

All authors contributed to data collection, data processing, results interpretation, writing, review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Additional information

Supplementary information is available for this paper at https://doi.org/10.7343/as-2022-551

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