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FORESEEING GROUNDWATER RESOURCES

The present state of Lake Bracciano: hope and despair

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Abstract

In 2017, the surface water resources of central Italy suffered from a combination of dry weather and increased human extraction. Specifically, the water level of the main surface drinking water reservoir supplying the City of Rome (Lake Bracciano) is currently low and the lacustrine ecosystem is in an unstable state. The aim of this study is to describe the current state of Lake Bracciano via a multidisciplinary approach in the light of the climate and hydrological variation over the past decade. The digital reconstruction of the lake cuvette made it possible to quantify the effects of oscillations in the level of the lake on the shoreline, while the potential impact of meteorological forcing on the lake-level oscillations was investigated by monitoring anomalies in precipitation and evaporation rates. The preliminary results indicate that the present Lake Bracciano crisis mainly results from below-average precipitation since 2015, compounded by significant water extraction. Indeed, in the past 3 years, there has been almost no winter recovery phase, resulting in a total water loss of 114 millions of m^3, which has never been observed before. In November 2017, the lake level reached a historic low of − 198 cm with respect to the hydrological zero (corresponding to a 13.5% reduction in the area of the lake bed responsible for self-purification), considerably below the sustainable level of − 150 cm. We conclude that the persistent low precipitation (− 50% in 2017 with respect to the 1961–1990 baseline), intense evaporation (6.7 mm/day during summer 2017), and extraction have brought the ecological state and associated ecosystem services of Lake Bracciano to conditions of serious stress.

Keywords Lake Bracciano · Level changes · Water reserve · Volcanic Lake

1 Introduction

Lakes are important surface freshwater reservoirs for drinking and tourism, as well as cultural, agricultural, and other economic uses (Hadwen et al. 2005; Vilmi et al. 2015). On

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the other hand, lakes play a critical ecosystem role, because they are important nutrient traps and perform ecosystem services such as denitrification (Vitousek et al. 1997; Galloway et al. 2003; Kendall et al. 2007; Xu et al. 2010). Lake Bracciano in particular is of primary importance due to the fact it is one of the most important surface drinking water reservoirs near a European capital (Di Matteo et al. 2010; Calizza et al. 2017). Lakes are large hydrological and hydrogeological basins, whose replenishment is closely related to precipitation and infiltration processes (Ayenew and Becht 2008; Demlie et al. 2007). For these reasons, it is fundamental to ensure the sustainable use (sensu WCED 1987) of freshwater resources, taking into account not only the total available water volume, but also oscillations in rainfall, hydrology and hydrogeology, evaporation processes, and water replenishment mechanisms (Strosnider et al. 2007; Wantzen et al. 2008; Baccetti et al. 2017). On a national level, 2017 saw a thermometric anomaly of + 1.3 °C (reference period: 1971–2000), in addition to a rainfall deficit of more than 50% with respect to the 1961–1990 baseline in the study area. These data were not considered in drinking water extraction management. Thus, as a result of rainfall deficit, evaporation and extraction for human consumption, Lake Bracciano, suffered substantial water-level reduction. The water level is currently low and the entire lacustrine ecosystem is in a very unstable state (Baccetti et al. 2017), with potential important implications for bottom–up and top–down processes that regulate nutrient cycling (Costantini and Rossi 1998; Fazi and Rossi 2000; Mancinelli et al. 2007; Calizza et al. 2013; Costantini et al. 2014; Rossi et al. 2018). Lake Bracciano represents an interesting case study, because it is a regional natural park, it is affected by several human activities, (Dragoni et al. 2006; Fiorentino et al. 2017), and it is the main surface drinking water reservoir for the city of Rome (ACEA 2015). Aware that the value of water resources requires targeted and careful research to better understand the complex mechanisms that regulate and drive these aquatic ecosystems, we hypothesised that knowledge of lake water-level dynamics can help the management of water extraction. We analysed the time variation of rainfall and estimated evaporation in the study area. Comparing variations in meteorological behaviour with the observed oscillations in the lake level allowed us to make some hypotheses on the joint impact of natural and anthropic forcing on lake-level oscillation.

2 Study area

Lake Bracciano is a sub-circular volcanic lake (Shoreline Development, SL = 1.2) located 32 km Northwest of Rome (Lazio, Italy), belonging to the Sabatino Volcanic District, characterised by trachytic and phonolitic products (Mattias and Ventriglia 1970; Buonasorte et al. 1991; De Rita et al. 1983; Karner et al. 2001; Sottili et al. 2004; Peccerillo 2005; Manca et al. 2017). It has a surface area of 57.58 km^2 and a circular perimeter of 31.981 km. It has an elevation of 163.04 m a.s.l. (altitude of the River Arrone emissary, here considered as the hydrometric zero of the lake), with a maximum depth of 165 m and a total volume of 5.13×10^9 m^3. The lake is characterised by a modest catchment area of 147.483 km^2 composed of 24 sub-basins with different shapes and dimensions (Fig. 1). Within the catchment area, there are only a few springs, characterised by very low flow. The high percentage of the lacustrine area (about 30%) with respect to the hydrological and hydrogeological basins makes Lake Bracciano particularly sensitive to climatic variations (Taviani and Henriksen 2015). The lake is oligo-mesotrophic (Rossi et al. 2010; Costantini et al. 2012 a.r.t.) and is used as a drinking water reservoir for the city of Rome and the Vatican. The combination of climate forcing and extraction for human supply (Fig. 3c) produces irregular water-level oscillations that can drastically change the shape of the shoreline and the total water volume.

From a hydrogeological point of view, the Lake Bracciano basin is characterised by volcanic deposits with high heterogeneity at both the local and regional scale. The heterogeneity arises partly from the depositional process, and partly from the presence of multiple volcanic deposits (e.g., tuffs and lavas) subject to syn- or post-volcanic alteration. Alteration of high-permeability and low-permeability geological deposits affects groundwater flow patterns. Several studies have sought to explore the hydrogeology of the Bracciano basin area (Camponeschi and Lombardi 1968; ACQUAITAL SRL 1997; Capelli et al. 2005), making it possible to reconstruct the phreatic surface and main directions of groundwater flows. A substrate of low-permeability deposits acts as a hydraulic barrier to groundwater flow, influencing its direction (Taviani and Henriksen 2015). Based on this reconstruction, the aquifer has an estimated surface area of 202.05 km^2 (Fig. 2).

The elevation of the phreatic surface ranges from 420 m a.s.l. in the north-western part of the basin to 160 m a.s.l. near the lake's southern shoreline. The water table is characterised by a steep hydraulic gradient of approximately 65‰ in the northern part (Fig. 2), with groundwater flowing from the northwest toward the southeast, partly discharging into Bracciano Lake. The northeast and the south sides of the lake are also characterised by inflows of groundwater, with hydraulic gradients of 25 and 5‰, respectively.

The water budget for Lake Bracciano can be summarised as (Mazza et al. 2015):

$$P + \mathrm{SR} + G_\mathrm{i} + S_\mathrm{i} - E - G_\mathrm{o} - S_\mathrm{o} - W = \Delta S, \quad (1)$$

where P is the precipitation on the lake, SR is the surface runoff from the hydrological basin, G_i is the groundwater

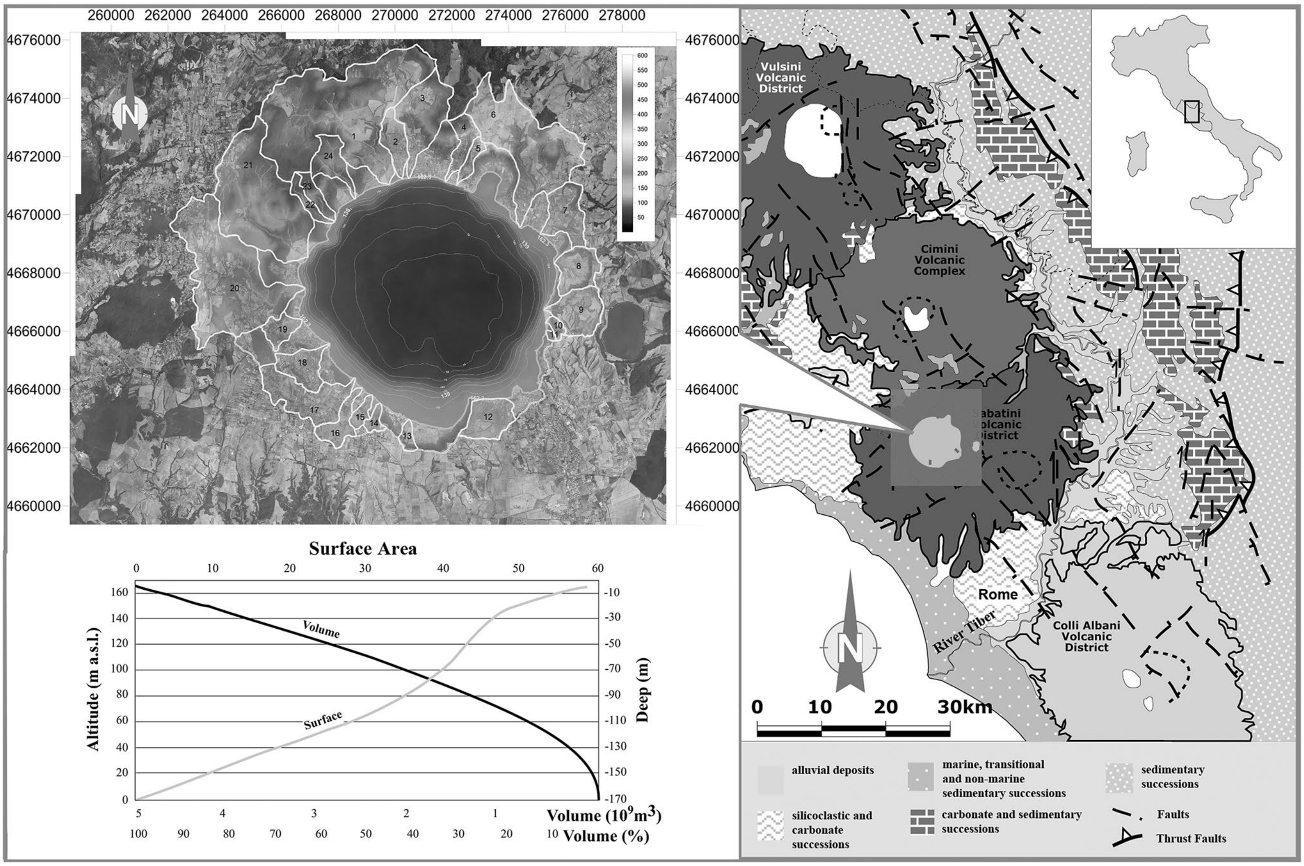

Fig. 1 Superimposed maps of Lake Bracciano with the digital elevation model, bathymetry, catchment basin, and aerial photos (upper left); hypsographic curves for volume and surface area (lower left); and tectonic sketch of the Northern Lazio region in Central Italy (right). The study area is shown in the inset. Volcanic complexes are shown with different grey-scale shades

inflow, S_i is the flow from springs, E is the lake water evaporation, $G_{o\ is}$ the groundwater outflow, S_o is the outflow through the emissary (if present), W is the extraction of water from the lake, and ΔS is the change in the volume of the lake. All the budget terms are expressed in volume per time unit. The terms S_i and S_o are negligible, as stream flows are irregular and the River Arrone is currently dry in its upper reaches.

3 Materials and methods

3.1 Bathymetry and water-table variation

High-resolution aerial photographs were analysed and field campaigns with GPS equipment were conducted to assess movement of the shoreline in relation with changes in the water level. Daily hydrometer field data (Bracciano, Trevignano and Aguilera pier hydrometers) were used to evaluate water-level variation over time (Fig. 2). A detailed digital elevation model was created (Calizza et al. 2016) and the bathymetry was updated to quantify variations of the lake bed. The 3D model was created by digitising the regional technical maps, while the bathymetry was determined by measuring campaigns using echo-sounder and multibeam (Rossi et al. 2006). Kriging interpolation methods were used to obtain contour maps. A GPS survey conducted from January to December 2017 traced in detail (5 cm resolution) the modification of the shoreline corresponding to each drop of 10 cm in the lake surface and evaluated the retreat of the shoreline and loss of surface area. Specific 3D software was used to model the morphology of the lake bed and to evaluate reductions in surface area and volume (Table 1). Specifically, the hypsographic curve of the lacustrine cuvette was drawn to quantify losses in surface area and volume resulting from falls in the water level, with a resolution of 10 cm for the first 25 and 1 m thereafter. Volume and surface area calculations were performed on solids defined by an upper and lower surface. The lake bed was treated as the lower surface, while planar surfaces at various altitudes were used as the upper surface, with the difference then being calculated.

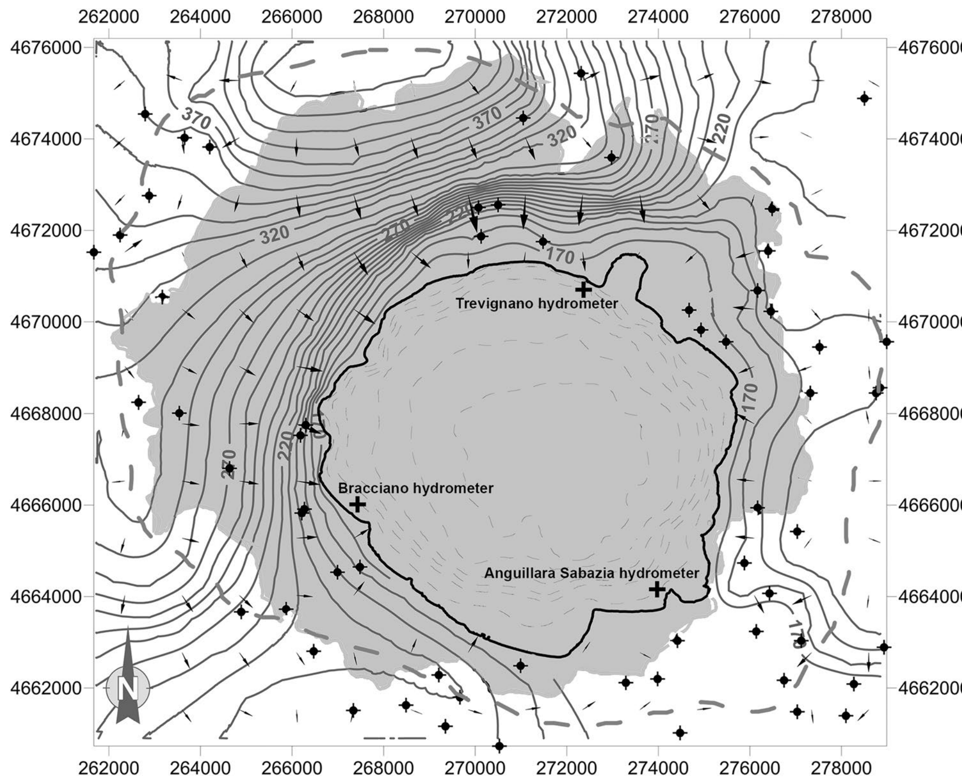

Fig. 2 Piezometric map of the Lake Bracciano hydrogeological basin (bounded by the dashed grey line); arrows indicate the direction and intensity (arrow length) of drainage. Highlighted in grey is the catchment area including the lake itself, with the black line corresponding to the shoreline, while wells are represented by black circles. Thin dashed lines indicate the bathymetry of the lake (isobaths every 25 m)

Table 1 Volume loss at various lake surface levels

Level (m a.s.l)	Drop in level with respect to the reference value (m)	Lake surface area (km^2)	Lake surface area loss (km^2)	Volume (10^9 m^3)	Volume loss with respect to the reference value (10^6 m^3)	Self-purification surface loss (%)
163.04	0	57.58	0	5.13		0
162.04	− 1	56.71	− 0.87	5.07	− 59	− 7.4
161.04	− 2	56.01	− 1.57	5.01	− 115	− 13.5
160.04	− 3	55.33	− 2.25	4.96	− 170	− 19.6
159.04	− 4	54.58	− 3	4.90	− 225	− 26.16

3.2 Climate analyses

To frame the current rainfall regime in a climate perspective, reference was made to regional analyses of precipitation on the western slopes of the Central Apennine mountain chain (Romano et al. 2011, 2017; Romano and Preziosi 2013). Rainfall data for the period 1951–2018 from 102 stations managed by the regional hydrographic surveys (Centro Funzionale of Lazio Region, Servizio Idrografico of Umbria Region and Settore Idrologico Regionale SIR of Toscana Region) were retrieved. To obtain monthly rainfall maps, the observed precipitation data were interpolated using the kriging technique (Cressie 1988). The spatial autocorrelation was modelled by means of a spherical variogram, whose best-fit parameters were calibrated for each month. The kriging interpolation was performed on a regular grid of 5 × 5 km squares and the mean monthly rainfall over Lake Bracciano (hereinafter referred to as P_B^{monthly}) was computed as the average for each square coinciding wholly or partly with the hydrological basin of the lake. Thus, P_B^{monthly} was analysed in terms of: (a) monthly and annual trends over the period 1951–2018, using Mann–Kendall's non-parametric test (Mann 1945; Kendall 1975); (b) periodicity (alternation of dry and wet periods), using a wavelet analysis (Torrence and Compo 1998); and (c) anomalies with respect to the baseline 1960–1990, using the Standardized Precipitation Index (McKee et al. 1993) over 6, 9, and 12 months.

Penman's combined heat balance and aerodynamic equation (Penman 1948, 1956; Romano and Giudici 2007, 2009) was used to estimate evaporation from the open water surface of Lake Bracciano on the basis of the climate data measured at the Vigna di Valle weather station (*"dati/prodotti meteo del Servizio Meteorologico dell'Aeronautica Militare"*) with the exception of downward solar radiation, which was based on ERA data (Dee et al. 2011) using the modified wind function described by Linacre (1993). The short-wave reflectivity and emissivity coefficients of the water surface, as well as long-wave radiation coefficients of clear skies were estimated following Shuttleworth and Maidment (1993). The described analyses made it possible to estimate the terms of precipitation and evaporation appearing in the water budget [Eq. (1)].

4 Results and discussion

The digital model of the lake cuvette made it possible to quantify the effects of oscillations in the lake water level on the shoreline. The changes in the lake water level recorded, since 2000 leave no doubt as to the significant retreat of the shoreline (up to 100 m at the end of 2017 with respect to April of the same year). According to Rossi (2006), the lake's self-purification processes (Ostroumov 2010, 2017 a.r.t.) take place on the lake bed at depths of up to − 25 m with respect to the reference level of the Arrone emissary (19.7% of the total surface area of the lake bed). The minimum sustainable level ensuring the preservation of good ecological status is estimated at − 150 cm. This value corresponds to 10.6% of the area of the lake bed responsible for biotic self-purification, which lies at a depth of 0–25 m.

The current situation (March 2018) shows the lake level at 174 cm below the reference level (corresponding to a loss of 12.7% in self-purification surface area). In November 2017, the lake level reached a historical low of − 198 cm (corresponding to a loss of 13.5% in self-purification surface area, with a loss of 1.57 km^2 in the water-surface area).

Analysing the water table, rainfall, evaporation, and human water supply over the period 2000–2018 allow us to evaluate changes in the shoreline and to estimate the loss/increase in water volume. Despite the changes in the water level recorded over the last decade, 2017 represents one of the most anomalous ever, with shoreline retreat ranging from 65 to 100 m, corresponding to a loss in water-surface area of 1.52 km^2. The data recorded, since 2000 highlight the water-level reduction in the last 3 years. Despite the average water-level reduction of 50–60 cm during the summer season (a rate of loss that has changed little the last 17 years), the water level has always partially or totally recovered in winter, except in 2017 (Fig. 3). A decrease of 60 cm was recorded in 2015, 45 cm in 2016, and 98 cm in 2017, with a total loss in volume of 114 millions of m^3 (Table 1). The absence of the recovery phase during winter 2016/2017 represents one of the main causes of the anomalous decrease in the water level, although water supply to the human population (ACEA 2017) has also contributed (Fig. 3).

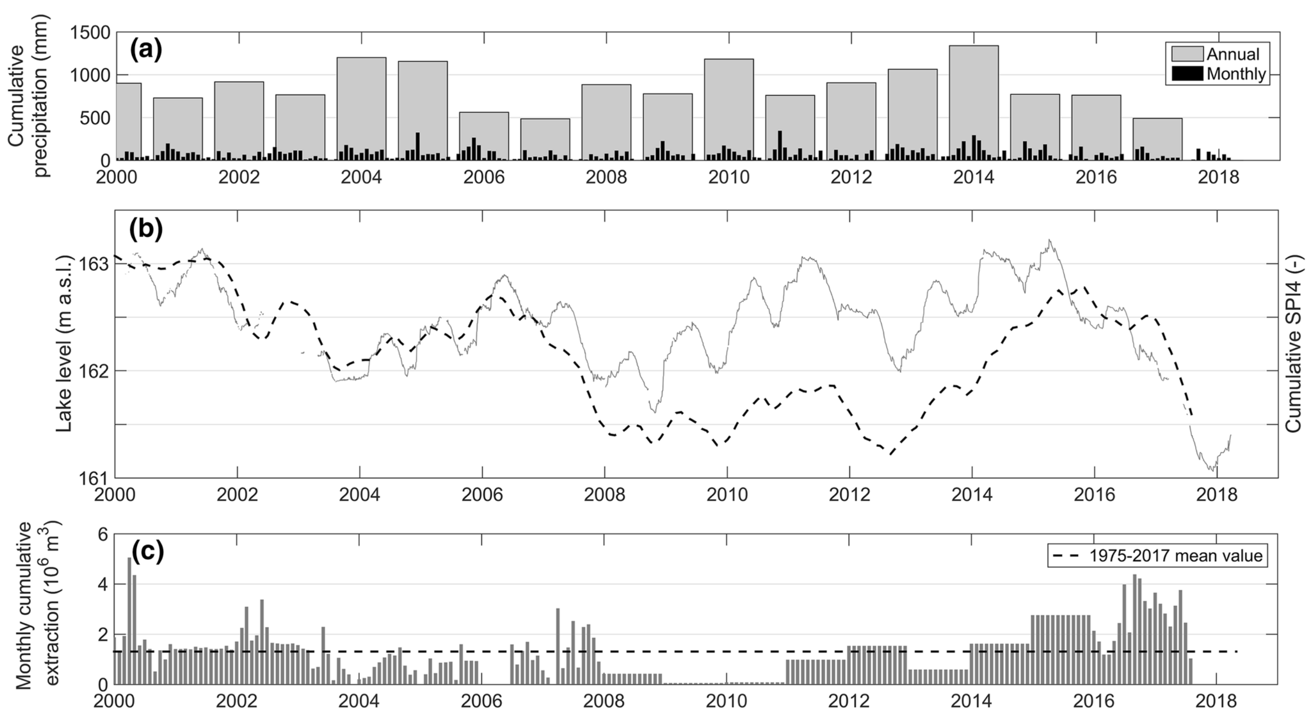

Fig. 3 Panel **a**: reconstruction of annual and monthly precipitations over the Lake Bracciano hydrological basin. Panel **b**: variation in the water level of Lake Bracciano (solid grey line) and cumulative SPI4 time series (dashed dark line). Panel **c**: monthly extraction from the lake (grey bars) and mean monthly extraction over the period 1975–2017

To explore the potential impact of meteorological forcing on the lake water level, the evaporation and precipitation terms of the water budget were analysed. Mean seasonal evaporation rates for the past 3 years are similar to those of the past 10 years (Fig. 4), with the exception of summer 2017, for which the mean evaporation rate increased by about 0.7 mm/day (from 6.0 to 6.7 mm/day). This increase in the evaporation rate corresponds to a further fall in the water level of roughly 65 mm during summer 2017 when compared with the previous decade.

The results of the precipitation analysis (not shown here for the sake of brevity) can be summarised as follows (Romano et al. 2017): (a) decreasing winter precipitation over the whole period 1951–2018 (Mann–Kendall test). This decrease is statistically significant at the 95% level in December and January. Therefore, the 2017 drought event took place amid a general decrease in rainfall occurring mostly during the typical recovery period for the lake and connected aquifer. (b) The 5-year moving window for annual precipitation highlights the cyclical behaviour of the precipitation regime, with a period of 4–6 years, modulated by a longer periodicity of approximately 15 years. This periodicity was confirmed by the wavelet analysis. (c) Precipitation recorded in winter, spring, and summer 2017 was systematically below the monthly means computed from the 1960–1990 baseline, with an anomaly of about − 50 to − 60% in winter (including December 2016) and spring and about − 70% in summer. In contrast, precipitation in autumn 2016 was close to the baseline.

To qualitatively assess the impact of the annual and inter-annual variabilities of precipitation on the lake water level, the Standardized Precipitation Index (McKee et al. 1993), computed at the 4-month scale (*SPI4*), was cumulated over the period 2000–2018 (Fig. 3, panel b). This highlights the lake system's "memory". Figure 3 clearly shows that when extraction is close to its historical mean (represented by the dotted line in panel c), as in the period 2000–2006, the seasonal, annual, and inter-annual variabilities of the lake level are well explained by fluctuations in precipitation. Conversely, when extraction is significantly below (2007–2010) or above (2015–2017) the mean, precipitation alone is not able to explain inter-annual variability in lake water level. Indeed, the period 2007–2010 saw a clear recovery of the lake level, despite the relatively low precipitation.

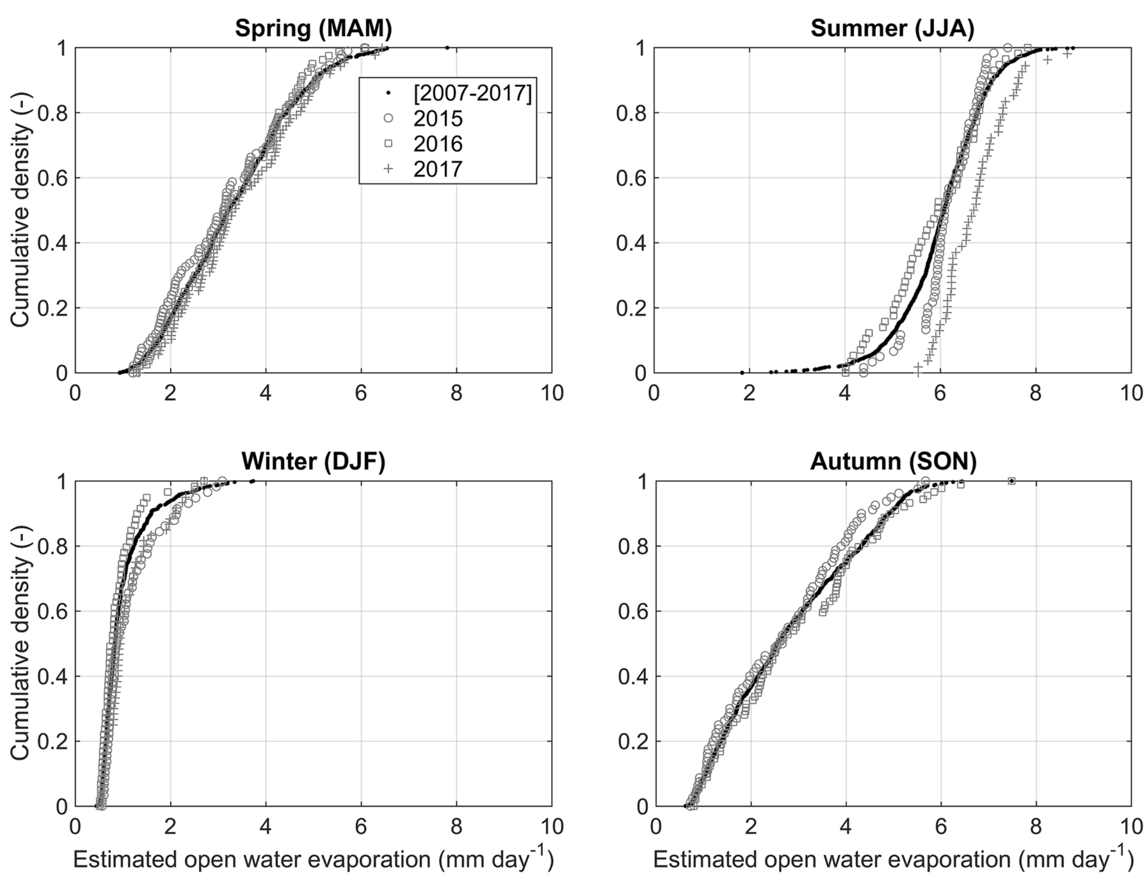

Fig. 4 Cumulative density function of the estimated seasonal daily evaporation rate from Lake Bracciano for 2007–2017, 2015, 2016, and 2017

5 Conclusions

The reduced precipitation (approximately − 50% on the annual scale with respect to the 1961–1990 baseline) and the increased evaporation and extraction led to Lake Bracciano experiencing serious stress in 2017 due to the observed record low in the lake water level (163.04 m a.s.l.), approximately 200 cm below the hydrometric zero (November 2017). This is more than 0.5 m below the minimum for the period 2000–2016. This situation exposes the lacustrine system to significant risks, requiring a careful assessment of its state of health to further improve our knowledge of environmental vulnerability. The Lake Bracciano crisis appears to have started in 2015. In the last 3 years, no recovery in levels has been recorded, due to the scarce precipitation and increased human extraction, with the water-level falling by up to 2.14 m. If the weather conditions and water extraction continue, causing the lake water level to fall once again by 200 cm as in 2017, this will lead to a 13.5% reduction in the surface area of the lake bed responsible for self-purification (the average lake water level for 2000–2014 corresponding to a 8% reduction). Despite the precipitation from December 2017 to March 2018 being consistent with seasonal averages, the Lake Bracciano system (groundwater and surface water) has not yet been able to recover to a level comparable to those observed even in the recent past. From 2000 to 2018, the lake has seen cyclical water-level crises every 3 years, interspersed with complete or partial recovery of the water level. However, in April 2018, the lake water level has recovered by only 40 cm with respect to the November 2017 minimum, despite the suspension of human extraction and the low evaporation rates. Falling lake water levels have significant repercussions for the circumlacual area (Wantzen et al. 2008; Costantini et al. 2007, 2012, 2018), which plays an important role in reducing the risk of triggering eutrophic processes, influencing nutrient concentrations and shoreline water circulation (Bentivoglio et al. 2016).

The case of Lake Bracciano represents a perfect example of a critical water resource that has been brought to an almost irreversible situation. Our case study seeks to highlight, on the national and international levels, the need to urgently develop predictive models for water resources to mitigate their vulnerability to climatic fluctuations. Such vulnerability requires careful and conscious use of water, knowing that the value of water resources lies not only in its anthropic uses, but also in the numerous ecosystem services that it provides. In its various forms and places, water deserves respect and must be seen as an essential asset, not only cultural but civil, ethical, and economic, influencing the health of the environment, the quality of life and social well-being.

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References

ACEA (2015) Sustainability report. http://annualreport2015.acea.it/sustainability/download-area/. Accessed 5 Feb 2018

ACEA (2017) Criticità dell'approvvigionamento idropotabile nei comuni dell'Ato2. https://www.acea.it/content/dam/aceafoundation/pdf/acqua/ato_2/acea-ato-2-incontro-fornace-23maggio-2017.pdf. Accessed 5 Feb 2018

ACQUAITAL SRL (1997) Studi preliminari per il Piano di Bacino. ST8 Modello di gestione del Lago di Bracciano. Relazione inedita

Ayenew T, Becht R (2008) Comparative assessment of the water lake balance and hydrology of selected Ethiopian and Kenyan rift lakes. Lakes Reserv Res Manag 13:181–196

Baccetti N, Bellucci V, Bernabei S, Bianco P, Braca G, Bussettini M, Cascone C, Ciccarese L, D'Antoni S, Grignetti A, Lastoria B, Mandrone S, Mariani S, Silli V, Venturelli S (2017) Analisi e valutazione dello stato ambientale del Lago di Bracciano riferito all'estate 2017. Rapporto ISPRA, 18 ottobre 2017, 56 p

Bentivoglio F, Calizza E, Rossi D, Carlino P, Rossi L, Costantini ML (2016) Site-scale isotopic variations along a river course help localize drainage basin influence on river food webs. Hydrobiologia 770(1):257–272

Buonasorte G, Carboni MG, Conti MA (1991) Il substrato Plio-Pleistocenico delle vulcaniti sabatine: considerazioni stratirafiche e paleoambientali. Boll Soc Geol Italiana 110:35–40

Calizza E, Rossi L, Costantini ML (2013) Predators and resources influence phosphorus transfer along an invertebrate food web through changes in prey behaviour. PLoS One 8:e65186

Calizza E, Costantini ML, Rossi D, Pasquali V, Careddu G, Rossi L (2016) Stable isotopes and digital elevation models to study nutrient inputs in high-Arctic lakes. Rend Fis Acc Lincei 27:191–199

Calizza E, Fiorentino F, Careddu G, Rossi L, Costantini ML (2017) Lake water quality for human use and tourism in central Italy (Rome). WIT Trans Ecol Environ 216:229–236

Camponeschi B, Lombardi L (1968) Idrogeologia dell'area vulcanica Sabatina [Hydrogeology of Sabatini volcanic area]. Mem Soc Geol Ital 8:25–55

Capelli G, Mazza R, Gazzetti C (2005) Strumenti e strategie per la tutela e uso compatibile della risorsa idrica nel Lazio. Gli acquiferi vulcanici. Quaderni di Tecniche di protezione ambientale. Protezione delle acque sotterranee, 78. Pitagora, Bologna, p 186

Costantini ML, Rossi L (1998) Competition between two aquatic detritivorous isopods—a laboratory study. Hydrobiologia 368:17–27

Costantini ML, Rossi L, Scialanca F, Nascetti G, Rossi D, Sabetta L (2007) Association of riparian features and water chemistry with reed litter breakdown in a volcanic lake (Lake Vico, Italy). Aquat Sci 69(4):503–510

Costantini ML, Zaccarelli N, Mandrone S, Rossi D, Calizza E, Rossi L (2012) NDVI spatial pattern and potential fragility of mixed forested areas in volcanic lake watersheds. For Ecol Manag 285:133–141

Costantini ML, Calizza E, Rossi L (2014) Stable isotope variation during fungal colonisation of leaf detritus in aquatic environments. Fungal Ecol 11:154–163

Costantini ML, Carlino P, Calizza E, Careddu G, Cicala D, Sporta Caputi S, Fiorentino F, Rossi L (2018) The role of alien fish (the centrarchid *Micropterus salmoides*) in lake food webs highlighted

by stable isotope analysis. Freshw Biol. https://doi.org/10.1111/fwb.13122
Cressie N (1988) Spatial prediction and ordinary kriging. Math Geol 20:405–421
De Rita D, Funiciello R, Rossi U, Sposato A (1983) Structure and evolution of the Sacrofano-Baccano caldera, Sabatini volcanic complex, Rome. J Volcanol Geoth Res 17(1–4):219–236. https://doi.org/10.1016/0377-0273(83)90069-0
Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Bechtold P (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc 137(656):553–597
Demlie M, Ayenew T, Wohnlich S (2007) Comprehensive hydrological and hydrogeological study of topographically closed lakes in highland Ethiopia: the case of Hayq and Ardibo. J Hydrol 339:145–158
Di Matteo L, Dragoni W, Giontella C (2010) Environmental and hydrological problems in time of climatic change and increasing water demand: the case of Bracciano Lake and its aquifer (Central Italy). Hydrological responses of small basins to a changing environment, 5–8 September 2010. Book of Abstracts, 187–190
Dragoni W, Piscopo V, Di Matteo L, Gnucci L, Leone A, Lotto F, Melillo M, Petitta M (2006) Risultati del Progetto di ricerca PRIN "Laghi 2003–2005". Giornale di Geologia Applicata 3(2006):39–46
Fazi S, Rossi L (2000) Effects of macro-detritivores density on leaf detritus processing rate: a macrocosm experiment. Hydrobiologia 435:127–134
Fiorentino F, Cicala D, Careddu G, Calizza E, Jona-Lasinio G, Rossi L, Costantini ML (2017) Epilithon δ15 N signatures indicate the origins of nitrogen loading and its seasonal dynamics in a volcanic lake. Ecol Indic 79:19–27
Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB, Cosby BJ (2003) The nitrogen cascade. Bioscience 53(4):341–356
Hadwen WL, Bunn SE, Arthington AH, Mosisch TD (2005) Within-lake detection of the effects of tourist activities in the littoral zone of oligotrophic dune lakes. Aquat Ecosyst Health Manag 8(2):159–173
Karner DB, Marra F, Renne PR (2001) The history of the Monti Sabatini and Alban Hills volcanoes: groundwork for assessing volcanic-tectonic hazards for Rome. J Volcanol Geotherm Res 107(1–3):185–215
Kendall MG (1975) Rank correlation methods. Griffin, London
Kendall C, Elliot EM, Wankel SD (2007) Tracing anthropogenic inputs of nitrogen to ecosystems. Stable isotopes in ecology and environmental science. Blackwell Publishing, Oxford, pp 375–449
Linacre ET (1993) Data-sparse estimation of lake evaporation, using a simplified Penman equation. Agric For Meteorol 64(3–4):237–256
Manca F, Viaroli S, Mazza R (2017) Hydrogeology of the Sabatini Volcanic District (Central Italy). J Map 13(2):252–259
Mancinelli G, Costantini ML, Rossi L (2007) Top–down control of reed detritus processing in a lake littoral zone: experimental evidence of a seasonal compensation between fish and invertebrate predation. Int Rev Hydrobiol 92:117–134
Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259
Mattias PP, Ventriglia U (1970) La regione vulcanica dei monti Sabatini e cimini. Memorie della Società Geologica Italiana 9:331–384
Mazza R, Taviani S, Capelli G, De Benedetti A, Giordano G (2015) Quantitative hydrogeology of volcanic lakes: examples from the central Italy volcanic lake district. In: Rouwet D, Christenson B, Tassi F, Vandemeulebrouck J (eds) Volcanic lakes. Springer, Berlin, pp 355–377
McKee TB, Doesken NJ, Kleist K (1993). The relationship of drought frequency and duration to time scale. In: 8th Conference on applied climatology. Am. Meteor. Soc: Boston
Ostroumov SA (2010) Biocontrol of water quality: multifunctional role of biota in water self-purification. Russ J Gen Chem 80(13):2754–2761
Ostroumov SA (2017) Water quality and conditioning in natural ecosystems: biomachinery theory of self-purification of water. Russ J Gen Chem 87(13):3199–3204
Peccerillo A (2005) Plio-quaternary volcanism in italy petrology, geochemistry, geodynamics. Springer, Berlin
Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc R Soc Lond A 193:120–146
Penman HL (1956) Evaporation: an introductory survey. Neth J Agric Sci 4:9–29
Romano E, Giudici M (2007) Experimental and modeling study of the soil-atmosphere interaction and unsaturated water flow to estimate the recharge of a phreatic aquifer. J Hydrol Eng 12(6):573–584. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:6(573)
Romano E, Giudici M (2009) On the use of meteorological data to assess the evaporation from a bare soil. J Hydrol 372:30–40. https://doi.org/10.1016/j.jhydrol.2009.04.003
Romano E, Preziosi E (2013) Precipitation pattern analysis in the Tiber River basin (central Italy) using standardized indices. Int J Climatol 33(7):1781–1792. https://doi.org/10.1002/joc.3549
Romano E, Preziosi E, Petrangeli AB (2011) Spatial and time analysis of rainfall in the Tiber river basin (Central Italy) in relation to discharge measurements (1920–2010). Proced Environ Sci 7:258–263. https://doi.org/10.1016/j.proenv.2011.07.045
Romano E, Guyennon N, Petrangeli AB, Preziosi E (2017) Caratterizzazione climatica del regime pluviometrico nell'area del distretto idrografico dell'appennino centrale nel periodo 1951–2017. Technical report. http://www.irsa.cnr.it/index.php/ita/news/item/192-report-regime-climatico. Accessed 5 Feb 2018
Rossi D (2006) Variazioni della linea di costa del lago di Bracciano in relazione al nuovo modello 3D bati-morfologico del fondale. Volume Speciale S.It.E. p 5
Rossi D, Gherardi L, Mandrone S, Costantini ML, Balestri A, Rossi L (2006) Sistema Reason Seabat 8125 per il rilievo bati-morfologico di fondali applicato ad un lago: primi rilevamenti nel lago di Bracciano. Rend Fis Acc Lincei 222:289–296
Rossi L, Costantini ML, Carlino P, Di Lascio A, Rossi D (2010) Autochthonous and allochthonous plant detritus contributions to volcanic lake coastal deposition: stable isotopes and mixing model study. Aquat Sci 72(2):227–236
Rossi L, Calizza E, Careddu G, Rossi D, Orlandi L, Jona-Lasinio G, Aguzzi L, Costantini ML (2018) Space-time monitoring of coastal pollution in the Gulf of Gaeta, Italy, using δ15 N values of *Ulva lactuca*, landscape hydromorphology, and Bayesian Kriging modelling. Mar Pollut Bull 126:479–487
Shuttleworth WJ, Maidment DR (1993) Evaporation, Chapter 4. McGraw-Hill, New York, pp 4.1–4.53
Sottili G, Palladino DM, Zanon V (2004) Plinian activity during the early eruptive history of the Sabatini Volcanic District, Central Italy. J Volcanol Geotherm Res 135:361–379
Strosnider WH, Hitchcock DR, Burke MK, Lewitus AJ (2007) Predicting hydrology in wetlands designed for coastal stormwater management. ASABE 077084:1–17
Taviani S, Henriksen HJ (2015) The application of a groundwater/surface model to test the vulnerability of a deep lake in the vicinity of Roma, Italy to climatic and water use stresses. Hydrogeol J 23(7):1481–1498
Torrence C, Compo GP (1998) A practical guide to wavelet analysis. Bull Am Meteorol Soc 79:61–78
Vilmi A, Karjalainen SM, Landeiro VL, Heino J (2015) Freshwater diatoms as environmental indicators: evaluating the effects of

eutrophication using species morphology and biological indices. Environ Monit Assess 187(5):1–10
Vitousek PM, Aber JD, Howarth RW, Linkens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7(3):737–750
Wantzen KM, Rothhaupt KO, Mortl M, Cantonati M, Làszlò G, Fischer P (2008) Ecological effects of water-level fluctuations in lakes: an urgent issue. Springer, Berlin, pp 1–4
WCED (1987) Our common future. World Commission on Environment and Development. Oxford University Press, Oxford
Xu H, Paerl HW, Qin B, Zhu G, Gao G (2010) Nitrogen and phosphorus input control phytoplankton growth in eutrophic Lake Taihu, China. Limnol Oceanogr 55(1):420–432