



The Simulation of Bracciano Lake (Central Italy) Levels Based on Hydrogeological Water Budget: A Tool for Lake Water Management when Climate Change and Anthropogenic Impacts Occur

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Abstract

Bracciano Lake is one of the major water bodies of Lazio region and the eighth lake in Italy by area. Similarly to other water bodies located on the Tyrrhenian side of the Italian Peninsula, Bracciano Lake has a volcanic origin. This water body is a strategic resource for both the emergency and ordinary water supply of Rome megacity, thanks to the short distance (about 30 km). During the last years, the concurrence of climate change and anthropogenic activities led to important water level drops of the lake: the last and worst in 2017, when the lake faced the most important water crisis of its entire history, with a critical impact on the ecological system and the consequent interruption of water supply. This paper, using the inverse hydrogeological water budget (HWB) method in a GIS environment, aims to define the water budget of Bracciano Lake on a 15-year time series (2008–2022), providing a framework of climate change and human impacts on lake water levels. The outputs have been used for the simulation of lake water levels during the same period, with a focus on the drought of 2017. The variation between simulated and observed level is, on average, 2 cm and in any case never more than 28 cm. Results show the fragile balance between inputs and outputs, highlighting the need for sustainable management of both surface water and groundwater withdrawals from the surrounding aquifer.

Highlights

- In 2017 Bracciano Lake (Italy) faced the hugest level decrease of its history
- The hydrogeological water budget (HWB) was applied for the study area (2008–2022)
- A linear tank model estimated annual groundwater flow to the lake without piezometric data
- A simulation of levels assessed the impact of each HWB component on lake status
- Results can be helpful for a future sustainable water management of this resource

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1 Background

Bracciano Lake is a volcanic lake located in the northwestern part of Lazio region (central Italy), along the Tyrrhenian coast, about 30 km far from Rome. It is one of the most important water bodies of the Lazio volcanic Lake District (Central Italy), and suitable for drinking, tourism, cultural, agricultural, and productive uses. The lake, nearly circular, has an area of about 57 km², a maximum depth of 160 m and a hydrogeological basin of about 110 km² (Rossi et al. 2019). The natural outlet of Bracciano Lake is the Arrone River, in which discharge has gradually dropped in the last decades, as well as it has occurred for other lakes in Central Italy (e.g., Bolsena, Trasimeno, Nemi and Albano Lakes) (Di Francesco et al. 2016; Dragoni et al. 2006, 2015; Frondini et al. 2019). Taking into consideration the high quality of the water, the local water service manager (ACEA Ltd.) has used Bracciano Lake as an emergency reservoir to supply drinking water for Rome in the last decades. Unfortunately, in 2017, a significant drought event affected all the Mediterranean Region with serious damage on water ecosystems and management (Guion et al. 2022; Mathbout et al. 2021; Oroud 2018). SPI and other climatic indices confirmed this important drought event also in Central Italy and the lake faced the most important water crisis, with a critical impact on the ecological system (De Santis et al. 2022; Giuliani et al. 2019; Guyennon et al. 2021; Mazza et al. 2020; Rossi et al. 2019; Sappa et al. 2019; Ventura et al. 2023). Water levels reached a minimum value in September 2017, causing the interruption of water supply for drinking purposes. In recent years, the assessment of climate change effects on water resources plays a key-role worldwide in providing measures to protect them and set up water policies supporting the principles of environmental sustainability (Alehu and Bitana 2023; Alemu et al. 2020; Iacurto et al. 2021; Latinopoulos et al. 2016; Li et al. 2021; Sappa et al. 2016; Šarović and Klaić 2023; VanDeWeghe et al. 2022).

With the same aim of quantifying the climate change and anthropogenic impacts, a lake level simulation is proposed for the study area, starting from GIS-environment water budget results of the last 15 years (2008-2022). A linear tank model, proposed for the surrounding feeding aquifer to estimate the groundwater flow component to the lake (Feyen 2005; Lee et al. 2020), represents a novelty for studies in this area, in the absence of continuously recorded piezometric data. All the previous studies focused on water budget analyses of Bracciano Lake and showed results indicating a natural and intrinsic fragility of this water resource, whose equilibrium is very sensitive to the strong annual variations of rainfall inputs and anthropogenic activities (Musmeci and Correnti 2002; Dragoni et al. 2006; Taviani and Henriksen 2015). In most of these studies, Bracciano Lake is close to the equilibrium of the water system or even worse. However, none of these studies reported the impact of each individual water budget component on a monthly basis for the given period, which is the aim of this study.

2 Geological and Hydrogeological Setting

Bracciano Lake is the second largest lake in Lazio region, and it is located at 164 m a.s.l., occupying an area of approximately 57 km². It originates at the end of the volcanic activity of the Sabatino Volcanic Complex (SVC) and Baccano volcano apparatus. The SVC dates to about 600,000 years ago and is set on a wide flat area, filled with Plio-Pleistocene sediments (De Rita et al. 1996; Nappi and Mattioli 2003). The volcanic products mainly composed of pyroclasts cover the Allochthons Clay basement that represents the regional aquiclude (Mancini et al. 2004). The tectonic and volcanic activity caused the volcano-tectonic collapse in the central part of the SVC, which led to a lowering of the aquiclude, giving origin to the formation of the Bracciano Caldera (De Rita et al. 1996). Numerous ditches collect the meteoric runoff, directly feeding the Bracciano water body. These channels are carved in the Sabatini volcanic soils, have a radial geometry and centripetal flow direction. The volcanic rocks form a dual porosity aquifer characterized by good quality groundwater that flows into the lake (Mazza et al. 2015; Taviani 2013). The volume of water in the lake is estimated to be about 5.05×10^9 m³ with an average depth of 89 m and a maximum one of 154 m (Dragoni et al. 2006). The lake acts as a collection basin for both rainwater and groundwater surrounding the perimeter of the lake. Only in the southeast, near the town of Anguillara, the circular mountain chain is interrupted by an incision through which the lake overflow feeds the Arrone River, which today is always dry in its first branch (Fig. 1).

In the eastern part of the study area there is the Martignano Lake, generated by explosions related to the interaction between the groundwater of the shallow aquifer and the rising magma. The crater that hosts Lake Martignano is considered the last active center of the SVC. Formerly known as Lacus Alsietinus in ancient Roman times, it is located at an altitude of 207 m above sea level, has a surface area of 2.4 km² and a depth of approximately 60 m (Azzella et al. 2013). Variations in the lake level have been found in the Holocene

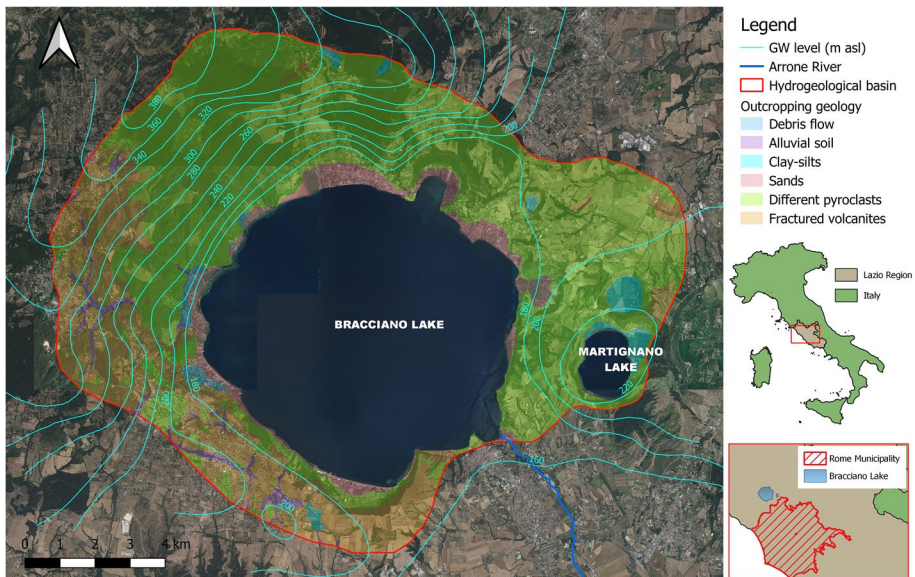


Fig. 1 Location, geological and hydrogeological map of Bracciano and Martignano Lakes. Piezometric lines are related to the study of Taviani and Henriksen (2015)

suggesting that the lake basin was previously in communication with other sectors of the study area (Puglisi and Savi Scarponi 2011). In the whole hydrogeological basin, groundwater flow pattern shows an average gradient of 4–5%, mainly from north to south, where Bracciano Lake represents a sort of aquifer overflow, receiving its water from the north and partly feeding again the aquifer to the south (Manca et al. 2017). The mountains in the north of Bracciano Lake (maximum altitudes about 612 m a.s.l.) represent a morphological high in which rainwater infiltrates, resulting in perched aquifers feeding small springs. Since the lake level is considered linked to the regional aquifer, the underground drainage lines converge into the lake from the north, west and east (Viaroli and Manca 2013). The calculation of older hydrogeological water budgets conjectured that Bracciano water body directly feeds the aquifers located at southeast. This flow was estimated in about 1.00 m³/s (32 Mm³/year) 50 years ago (Camponeschi and Lombardi 1969), but this value is not confirmed by recent studies. In fact, Taviani and Henriksen (2015) assessed a general depletion of groundwater, estimating the lake to aquifer flow at 0.22 m/year (12 Mm³/year). Recent investigations highlighted almost no groundwater flow from the lake (Rossi et al. 2019). Hence, considering the low gradients (the lake level is at 162–163 m a.s.l.) and the limited area involved, this term is today supposed to be very low or even negligible.

3 Water Budget Analysis

The proposed water budget is based on average monthly datasets to bound the seasonal variations. The meteorological datasets were used to evaluate the inputs (Rain P_L) and outputs (Evaporation EV) of the lake in the hydrogeological budget. Datasets were also useful to quantify the catchment runoff (R), evapotranspiration (ETR), and infiltration (Inf). The computation of inputs and outputs (in Mm³/month), towards and from the lake constitutes the water budget that can be expressed by the following relationship (Eq. 1):

$$P_L + GW + R - EV - WL + O_R = \pm \Delta V \quad (1)$$

where the symbols denote: P_L = precipitation falling on the lake area; GW = net groundwater flow from the hydrogeological basin towards the lake; R = runoff from the catchment area towards the lake; EV = evaporation from the lake; W_L = direct withdrawals from the lake by the local water utility; O_R = outflow to the Arnone River (activated only when the lake water level exceeds the specific threshold of 163.04 m a.s.l.); ΔV = change of storage in the Bracciano Lake. The GW and R values are obtained from the water budget carried out separating the hydrogeological and hydrographic basins of the lake. These latter ones were discretized into 500 × 500 m Finite Square Elements (FSE) in GIS environment, considering the following components (Fig. 2): P_B = precipitation falling on the hydrogeological basin (in mm/year); ETR = evapotranspiration (in mm/year); χ = potential infiltration coefficient (dimensionless) (function of the outcropping geology); Inf = effective infiltration (in mm/year). The total infiltration volume is obtained multiplying each Inf value (transformed in m) by each FSE (in m²).

The main aquifer (ACQ) was assumed as a simple linear tank using a lumped hydrological model, where the input is the infiltration rate (Inf), coming from the hydrogeological water budget, and the output is the outflow component (O_{GW}). The groundwater component towards the lake (GW) has been obtained subtracting the groundwater pumping (W_A) from the O_{GW} (see Fig. 3).

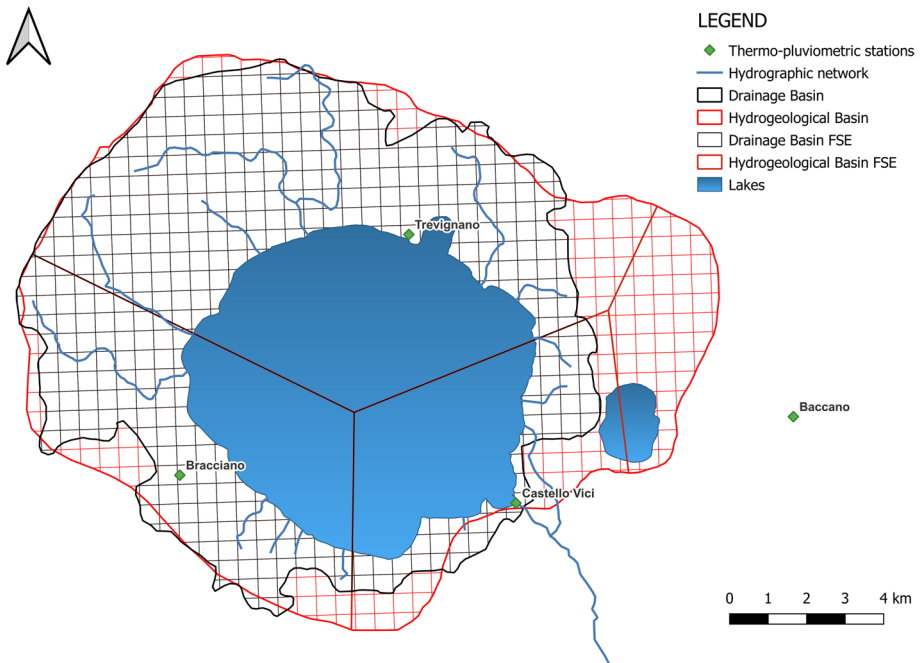


Fig. 2 Finite square elements (FSE) and Thiessen polygons of thermo-pluviometric stations used for the water balance in catchment (black) and hydrogeological basin (red)

This model is based on two assumptions (related to the specific features of the study area): (1) wastewater volumes from domestic use are collected in a network, hydraulically disconnected from the lake; (2) water volumes estimated for irrigation satisfy crop water demand and do not contribute to additional values of runoff or infiltration to the deep aquifer. The overall water budget is represented in the flowchart of Fig. 3.

The components of the water budget will be discussed in the next sections, explaining the data used and the elaborations carried out. For the results obtained in Mm^3/year (from 2008 to 2022), please refer to the Supplementary Material (SM), Table SM1.

3.1 Precipitation

Regarding precipitation falling on the lake area (P_L) (but also precipitation falling on the hydrogeological basin P_B and temperature T), data come from Lazio region thermo-pluviometric monitoring network. Castello Vici, Bracciano, and Trevignano meteorological stations were considered because of their influence (obtained with the Thiessen polygon method) on the lake surface (57 km^2), 29.3%, 24.2%, and 46.5% respectively (Fig. 2). The volume of the P_L contribution into the lake is calculated as the rainfall measured multiplied by the respective influence area. For the further application of the water balance, referred to the hydrogeological basin (P_B), the Baccano station was also considered.

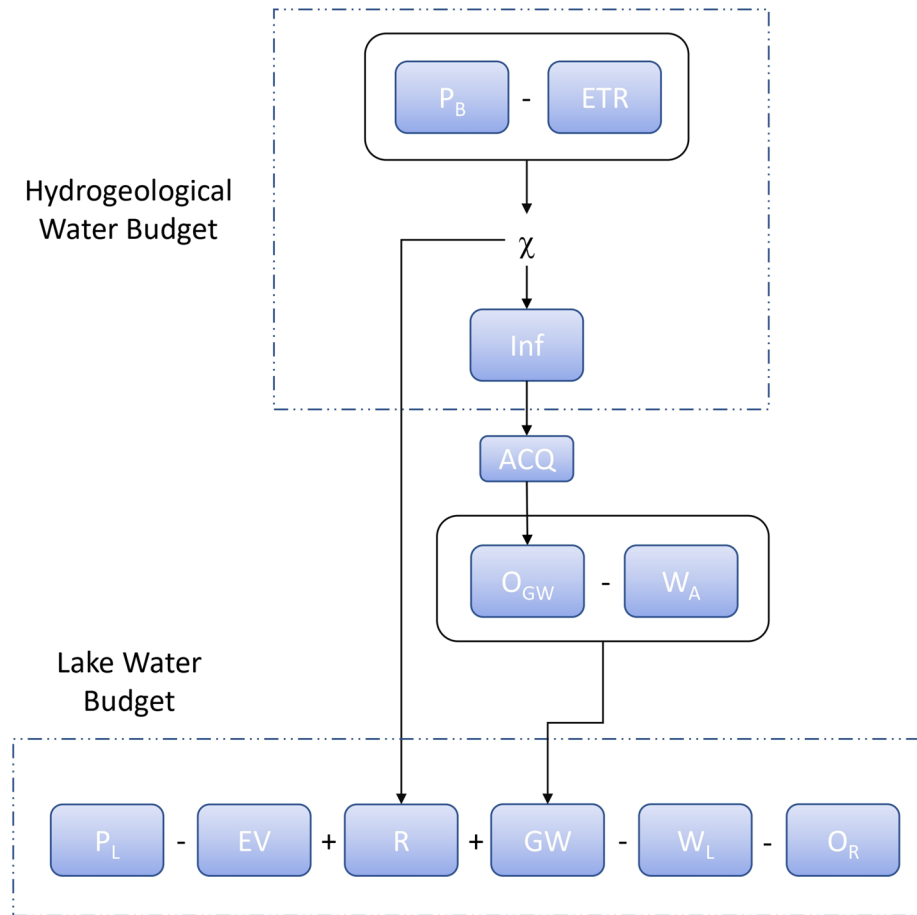


Fig. 3 Flow-chart of the hydrogeological water budget of Bracciano Lake

3.2 Direct Withdrawals from the Lake by the Water Utility

The data related to direct withdrawals from the lake (W_L), carried out for drinking water use by the ACEA Ltd. water supply company, have been obtained from Guyennon et al. (2021) and Ventura et al. (2023).

3.3 Evaporation (EV)

The calculations of the average monthly and annual evaporation from the surface of the lake were carried out using the empirical formula proposed by Dragoni and Valigi (1994). This formula, calibrated on the evaporation values obtained experimentally from Class A evaporation pans, provides monthly evaporation (EV_m) as a function of the average monthly temperature (T_m), and the monthly insolation index of Thornthwaite (i_m) (Dragoni and Valigi 1994; Thornthwaite 1948):

$$EV_m = b (i_m)^{a_1} (T_m)^{a_2} \tag{2}$$

The authors have empirically calibrated the parameters a_1 , a_2 and b for the area of Rome, obtaining respectively the values of 2.506, 0.777 and 8.347.

3.4 Evapotranspiration (ETR)

The hydrogeological basin of the lake, excluding the lake area, was divided into Finite Square Elements (FSE) of 500×500 m each. For all the years of the time series, an annual rainfall value (P_B) and a corrected average annual temperature (T_C) were associated to each FSE. Hence, the Evapotranspiration (ETR) was assessed using the Turc formula:

$$ETR = \frac{P_B}{\sqrt{0.9 + \frac{P_B^2}{L^2}}} \tag{3}$$

where $L = 300 + 25T_C + 0.05T_C^3$.

3.5 Infiltration (Inf)

To obtain the runoff (R) and the net groundwater flow (GW) to the lake, to be added in the water balance of Bracciano Lake, the boundaries of the lake’s hydrogeological basin were first established. The delineated hydrogeological basin (approximately 120 km^2) is the same as the study proposed by Taviani and Henriksen (2015) (Fig. 1). The effective infiltration component (Inf), to be used as input in the aquifer inflows-outflows model (Fig. 3), was estimated for each year with the inverse hydrogeological balance method. Effective infiltration, in fact, is given by the following Eq. (4); it mainly depends on the amount of rain, the temperature and the permeability of the outcropping geological formations:

$$Inf = (P_B - ETR) \chi \tag{4}$$

where: P_B is the annual rainfall value in the i -th FSE of the grid (mm); ETR is the evapotranspiration value in the i -th FSE of the mesh (mm); χ = Potential infiltration coefficient (depending on outcropping rocks).

Inside the hydrogeological basin, the following potential infiltration coefficients have been attributed to the outcropping geological formations (Table 1), based on literature abacus proposed by Civita (2005) for Italian geological formations.

Table 1 Minimum, average and maximum potential infiltration coefficients χ for outcropping geology (Fig. 1)

Outcropping Rocks	χ		
	min	av	max
Alluvial soil and Debris flow	0.65	0.80	0.95
Clay-silts	0.00	0.20	0.25
Sands	0.75	0.80	0.85
Different pyroclasts	0.20	0.40	0.60
Fractured volcanites	0.70	0.80	1.00

For each year, the aquifer recharge is the total volume of effective infiltration Inf , calculated for the hydrogeological basin of Bracciano Lake using the Eq. (5):

$$Inf \left(\frac{m^3}{year} \right) = \left(\sum_{i=1}^N Inf_{FSE_i} \right) \times A_{FSE_i} \quad (5)$$

where: Inf_{FSE_i} is the effective infiltration in the i -th FSE; and A_{FSE_i} is the area of the i -th FSE; The average values were chosen for the elaborations that will be described in the next sections. The value of $24.0 \text{ Mm}^3/\text{year}$ (see Supplementary Material; Table SM1) is similar to the results obtained by Dragoni et al. (2006).

3.6 Runoff (R)

Runoff, as well as infiltration, is defined by following Eq. (6); it mainly depends on the amount of rain, the temperature and the permeability of the outcropping geological formations. The same potential infiltration coefficients explained in Section 3.5 have been used (Table 1).

$$R = (P_B - ETR) (1 - \chi), \quad (6)$$

3.7 Withdrawals from the Aquifer (WA)

To estimate the component related to withdrawals from the aquifer (W_A), a census of the wells present in the hydrogeological basin of the lake was carried out. This census was made by merging various information and data collected from different databases such as the Metropolitan City of Rome and Lazio region waterworks (2004). The wells are in total 1293, divided into types of use: domestic (860), non-domestic (407), water service (26).

3.7.1 Domestic Wells

This type of well is for the exclusive use of the owner. The term "domestic" means that the uses are aimed for the user's family unit and do not constitute a productive or profit-making economic activity. For these wells, according to local water supplies and consumptions, an average daily withdrawal volume of 1500 L/day was assumed, equal to $1.5 \text{ m}^3/\text{day}$. Consumption considers an allocation of $300 \text{ L/inhabitant/day}$ for a core of 4–5 people, plus a rate for watering the vegetable gardens varying between 100 and $200 \text{ m}^3/\text{year}$. Total annual consumption (860 wells) is approximately $0.47 \text{ Mm}^3/\text{year}$.

3.7.2 Non-Domestic Wells

According to Italian legislation (D. Lgs. n° 152/06 and R.D.14/09/1920, n. 1285), this type of wells requires the Concession Title, issued by the competent body. For non-domestic wells (mainly for crop irrigation), an estimate was made considering an average flow rate for each well equal to 1 L/s , with use of 120 days a year. In this way, the total annual consumption (407 wells) is approximately $4.2 \text{ Mm}^3/\text{year}$.

3.7.3 Water Utilities Wells (Drinking)

This type of wells is for the exclusive use of drinking water and managed by the water supply companies (ACEA Ltd. and local municipalities). These wells were obtained from the Lazio Region waterworks database. For drinking water wells information available about flowrates was used (Table 2). The contribution to the withdrawal of drinking water is estimated at an average of 5.52 Mm³/year.

3.7.4 Assessment of Total Pumping Volumes and Temporal Variations

The sum of the previous contributions estimates the annual withdrawals from the aquifer (W_A) at about 10.2 Mm³/y. To consider the variability of well pumping in the analyzed time window (2008–2022), a linear correlation was carried out between abstractions and the demographic trend of the municipal areas surrounding the lake. From 2008 to 2022, the municipalities of Anguillara, Bracciano and Trevignano recorded an increasing population trend in the first two decades and constant during the third one, from 2010 to 2021.

3.8 Groundwater Flow to the Lake (GW)

For the estimation of the groundwater flowrate towards the lake, also due to the lack of piezometric data, within the long-time window considered, a simple hydrological lumped model was used. This model considers the aquifer as a linear reservoir to simulate the effect of lamination and delay (lag) that this entails on the effective infiltration volumes. In the linear tank model, the output flow O_{GW} is a linear function of the aquifer storage, characterized by a reservoir constant K (Feyen 2005; Okiria et al 2022).

Since the water balance is carried out yearly, the input for the year j is represented by the total infiltration volume values estimated, i.e. active recharge (AR_j) previously described in Section 3.5. The overall output ($O_{GW,i}$), relating to each year i , is given by the sum of the contributions relating to the inputs (I_j) of the previous years, according to Eq. (7):

$$O_{GW,i} = \sum_{j=0}^i AR_j \frac{e^{-\frac{(i-j)}{K}}}{K} \quad (7)$$

Table 2 Pumping flowrates from the Lazio Region waterworks database

Well Name	Average Flowrate (L/s)
Celsino 1	4.0
Possesso	0.2
Doganella	3.1
Celsino 2	14.3
Fiora e Gatto	101.0
Dolce	41.6
Giardino 1	2.9
Poggiaccio	8.0
TOTAL	175.0

where: j is the year related to the j -th input.

To obtain the net groundwater component (GW) feeding the lake, the previously exposed withdrawals rate (W_A) must be subtracted from the output (O_{GW}) value (Fig. 3).

4 Lake Water Level Simulations and Impacts Assessment (2008–2022)

Results obtained from the water balance of the lake allow to distinguish all the values impacting the lake water level on a monthly scale, i.e., the incidence of each component on the groundwater budget. This made it possible to set up a simulation model of the lake levels.

Based on Eq. 1, each component has been calculated as an increase or decrease of lake level (ΔH) using the hypsographic curves obtained by Rossi et al. (2019). The monthly level variation in mm, due to each different component of the water balance, was assessed using fluxes ($Mm^3/month$) and the lake area (in km^2). The hydraulic overflow to the Arrone River (O_R) has been considered active, when Bracciano Lake water level exceeds the threshold of 163.04 m a.s.l.

The results of the simulation model are shown in Fig. 4 where simulated levels (orange) are compared with measured levels (blue). These latter are available in Supplementary Material (Table SM2), coming from the measurements carried on by the Bracciano-Martignano regional natural park (<https://www.parcobracciano.it/area-protetta/monitoraggio-acque/>).

The proposed model successfully describes the response of hydrometric levels during the drought episodes, as the 2008, 2012 and 2017 summers. It seems to be less effective to describe seasonal behavior of the groundwater inflow to the lake suggesting the necessity of a more accurate groundwater-surface water interaction model. However, the mean and the median of the deviations between the simulated and measured levels are low (-2 cm), the maximum and minimum are respectively 28 and -28 cm and standard deviation is equal to 11 cm. For the overall model validation, the standard statistical indices assess a quite

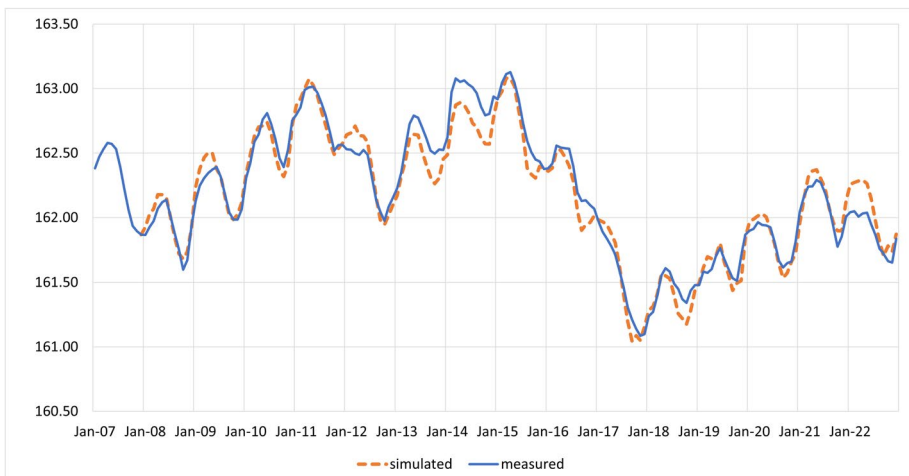


Fig. 4 Trend of the monthly measured levels (in blue) and simulated levels (in orange) of Bracciano Lake

high correlation: the mean squared error (MSE) is 0.013 m^2 , the root mean squared error (RMSE) is 0.113 m , the mean absolute error (MAE) of 0.090 m , the Nash–Sutcliffe model efficiency coefficient (NSE) is equal to 0.949 and the Kling–Gupta efficiency (KGE) is 0.955 . The scattergram of simulated versus observed values (Fig. 5) also reveals excellent fitting results, with a R^2 of 0.950 .

In Fig. 6, the boxplots of water budget outputs and inputs for the time series 2008–2022 (Table SM2) are respectively on the left and right side, describing the statistical behavior of each component impact (in percentage) on the lake water level.

5 Discussion

The water budget of Bracciano Lake clearly shows that the factors that mostly affect the lake level variation, in percentage terms, are rainfall, as a positive contribution, and evaporation as a negative contribution. However, even if these two variables (P and EV) are characterized by a similar annual mean value, they have different extreme event frequencies (Fig. 6). The extreme lack of precipitation, coupled with human impact, as occurred in 2017, affected the water levels, challenging the lake's resilience for the following years (Fig. 4). The critical conditions the lake faced after year 2017 are testified by the interruption of direct withdrawals from the lake (W_L), as the water levels did not recover to the past values. The slight but continuous rise in the minimum annual levels of the lake after 2017

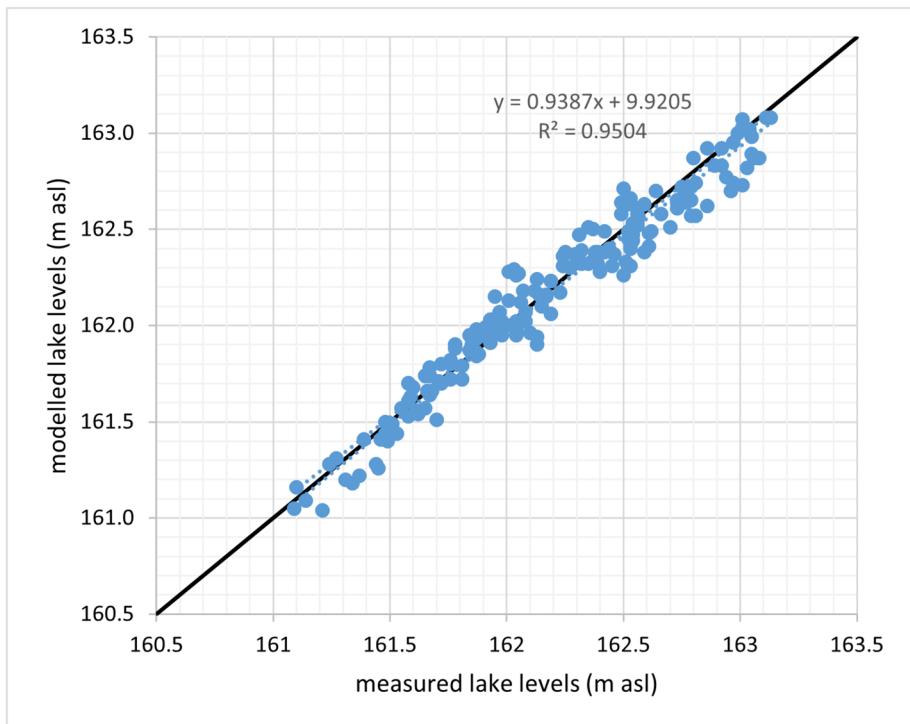


Fig. 5 Scattergram of measured vs modelled Bracciano lake water levels (m asl)

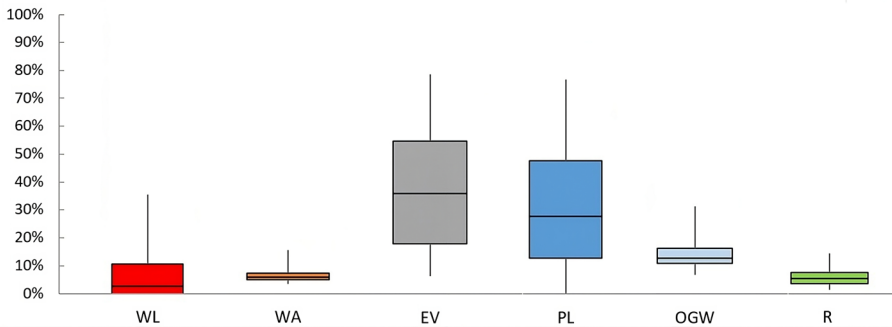


Fig. 6 Box plots of the relative incidence (%) for inputs and outputs on Bracciano Lake water level fluctuations (2008—2022)

and, most of all, during 2022, confirms the presence of a not negligible groundwater base-flow towards the lake, which is slowly recovering the Bracciano Lake. A first outcome is that, differently from rainfall (P), the variation of temperature and therefore of the evaporation component (EV) influence the water levels of the lake to a lesser extent, as concluded in other previous recent studies (Guyennon et al. 2021), but its role is not negligible at all, highlighting an increasing trend (Table SM1). In addition to the evaporation component (EV), the other two factors that negatively affect the lake level variation are the direct withdrawal component from the lake (W_L) and the withdrawal component from the surrounding aquifers (W_A). On average, these last two factors have a similar impact on the lake level variation, but the direct withdrawal W_L has a greater variability and in the month of January 2017 marked a maximum negative incidence of 36%. After September 2017, no more direct withdrawals have been carried on from the lake.

The estimated groundwater outflow component from the aquifer (O_{GW}) is also remarkable, with an average weight of 14%. During periods of water shortages, this is the only factor that makes lake level increase, thanks to the typical reservoir properties of aquifers and it is worth of conducting further studies on its role. The well withdrawal component (W_A) is still indirectly influencing the lake water level and could be higher than the estimation proposed, with a negative impact on the aquifer storage and the resilience of the entire water eco-system. Local authorities should consider activating an extended and sound groundwater-monitoring network in the study area, with groundwater levels continuously registered, or at least measured on a monthly scale. The points of the monitoring network must be distributed around the lake, referring to the areas of major interaction between groundwater and the lake, i.e., intercepting the main direction of the GW flow (NW-SE).

6 Conclusions

This work demonstrated that the combined surface water and groundwater budget is a useful tool in evaluating the inflow and outflow components to and from volcanic lakes, which are often drained by surrounding discharging aquifers. The simulation of lake levels using hydrogeological water budget outputs allows water authorities to estimate the percentage of lake level drop due to possible overexploitation and/or climatic events (drought). In the current context of global climate change, affecting water resources availability with

increasingly frequent drought events, higher temperatures and evaporation rates, this tool allows to improve water management in high water demand areas, quantifying human impacts and driving decision making. In such hydrogeological contexts, where volcanic lakes can be used as strategic water reserve, the interaction between groundwater and surface water should be considered, to assess long term negative effects on the lake health also due to overexploitation of aquifers.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s40710-024-00688-5>.

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- the research did not involve Human Participants and/or Animals.
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