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*Review*

# When Climate Change and Overexploitation Meet in Volcanic Lakes: The Lesson from Lake Bracciano, Rome's Strategic Reservoir

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**Abstract:** Lakes worldwide have been strongly affected by several types of human-caused alteration, including changes in water level. This also affects deep lakes, including volcanic ones. Volcanic lakes in the Mediterranean area are of great importance for the local economy, but local human activities can threaten their rich biodiversity. As a European biodiversity hotspot and habitat of endemic species, the volcanic Lake Bracciano (Central Italy) is an ecosystem of primary conservation interest threatened by sharply falling water levels, particularly since 2017. It also plays a key role in human wellbeing by providing important ecosystem services including drinking water, fisheries and various recreational opportunities. Although the lake has historically been considered to enjoy good ecological status, various environmental problems, often amplified by water level changes, have arisen during the last two decades. Given this recent rapid evolution, the lake can be considered an example of a valuable ecosystem at risk as a result of increasing anthropogenic pressures. The aim of this review is to examine the changes that have affected the lake in the last 20 years, considerably reducing its capacity to provide ecosystem services, and to review existing and potential threats in order to better inform the management of such resources.

**Keywords:** water level change; water pollution; alien species; self-purification capacity; commons

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**Citation:** Ventura, M.; Careddu, G.; Calizza, E.; Sporta Caputi, S.; Argenti, E.; Rossi, D.; Rossi, L.; Costantini, M.L. When Climate Change and Overexploitation Meet in Volcanic Lakes: The Lesson from Lake Bracciano, Rome's Strategic Reservoir. *Water* **2023**, *15*, 1959. https://doi.org/10.3390/w15101959

Academic Editor: Roohollah Noori

Received: 31 March 2023
Revised: 17 May 2023
Accepted: 20 May 2023
Published: 22 May 2023

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## 1. Introduction

Although the amount of water in lakes constitutes less than 0.5% of the total freshwater resources on Earth [1], lakes are often important biodiversity hotspots [2–4]. Lakes also provide multiple ecosystem services including water for drinking and irrigation, fishing, recreation, hydroelectric power generation and climate change mitigation, the latter primarily via carbon sequestration [5–7]. They also function as hydrological buffers for irregular climate events [6,8].

Lakes are among the most vulnerable aquatic systems. Due to their limited size and more importantly landlocked environment, they are strongly affected by natural variation [9–12] and anthropogenic disturbance from the surrounding terrestrial areas [13–15], to which lakes are closely linked via fluxes of organisms, debris and dissolved substances [16–18]. This can threaten both aquatic biodiversity and ecosystem services [19–21]. Global warming, along with water consumption, can also affect water resources, by reducing lake water levels and limiting groundwater recharge [22–28].

Since 1988, a growing number of studies have reported that changes in water levels, due to both climate change and human abstraction, severely affect lakes around the world (Figure 1). However, an acceleration has recently been observed, with a change point [29] in 2017. Water level fluctuations may act in synergy with other types of threats (e.g., invasive species and pollutants, [30,31]), leading to greater impacts on biodiversity and services. Deep lakes, including volcanic lakes, often characterised by large volumes of water relative to their surface area, have also been affected (Figure 1).

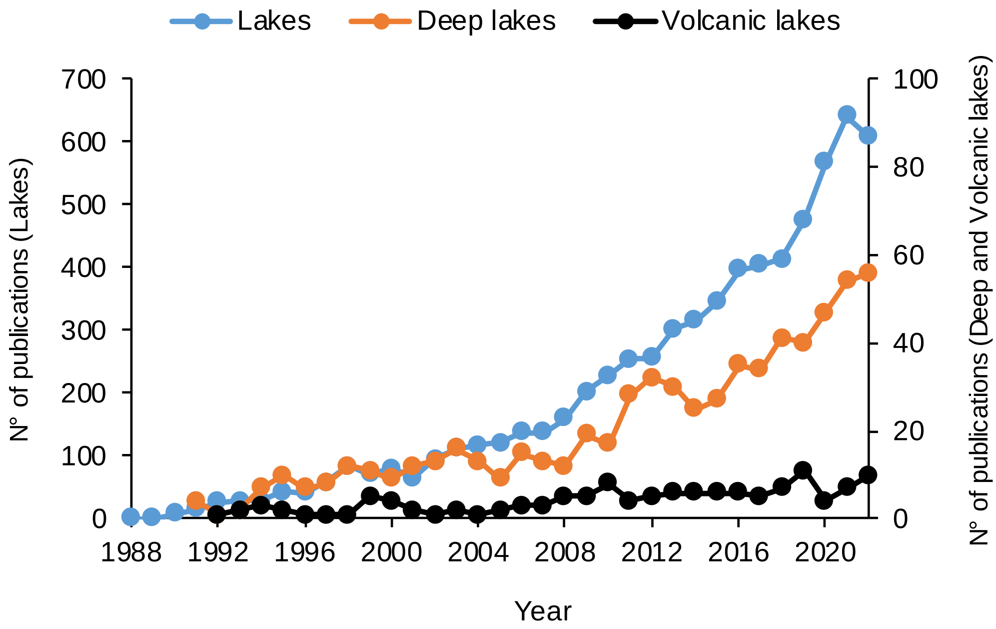


**Figure 1.** Records linking lake water-level changes in lakes around the world with climate change or water abstraction in the period 1988–2022, as returned by a search for "(water level chang* OR water level variation* OR chang* ?? water level*) AND ((climat* OR warm*) OR (withdrawal* OR abstraction*))" in the Topic field of the Web of Science, subsequently refining for "lake*", "deep lake*" or "volcanic lake*". Three nested categories of lakes were considered: all lakes (blue; left axis), deep lakes (orange; right axis) and volcanic lakes (black; right axis). For the period under consideration, on average, publications on deep lakes and on volcanic lakes accounted for 10% and 2% of the total, respectively. "Deep lakes" refers to lakes defined as "deep" in the filtered literature. Note the difference in axis scales.

Volcanic lakes have always been intensely exploited by human beings, often serving as large water reservoirs. Lakes located in dormant or extinct volcanoes tend to have fresh, clear waters, which in some cases are characterised by exceptional oligotrophic conditions mainly due to the lack of inflowing streams [32–34]. However, in recent decades, human pressures such as coastal urbanisation at the expense of natural areas, intensive agriculture, tourism and water extraction have caused a deterioration in water quality and damage to the flora and fauna of volcanic lakes [33,35,36].

Dormant freshwater caldera lakes are found in volcanic districts in all continents [34,37–40] including Europe, especially in Italy. Ice-filled calderas exist in areas such as Alaska and Antarctica, but it is not clear whether they also contain subglacial lakes under the ice [41]. While a specific list of volcanic lakes is not available, with a few exceptions Italian volcanic lakes are concentrated in four volcanic districts in Lazio, central Italy, one of the country's most densely populated regions, where they make up the majority of natural lakes and a large percentage of the deep lakes in the Mediterranean coastal area [34,42,43]. They are generally characterised by great depth (up to 170 m in Lake Albano, Lazio) small catchment areas and long water renewal times, mainly associated with precipitation, that make them very sensitive to anthropic inputs [44–46]. Urbanisation of the catchment area, water extraction and increasing recreational activities have progressively exposed volcanic lakes in Italy to water quality degradation [14,45,46].

Among these lakes, Lake Bracciano, which is the second largest lake in the region (57 $km^2$) and one of the largest and deepest (165 m) in Italy, has been historically considered to enjoy a good ecological status, undergoing only slight ecosystem changes with respect to its expected ecological integrity in the absence of human influence, as per the Water Framework Directive. Nevertheless, it has recently been affected by various types of anthropogenic pressure, exacerbated by the effects of climate change [14,44,45,47]. The lake is a strategic freshwater reservoir for the city of Rome and the Vatican, it hosts a high level of biodiversity, and it represents an important area for both commercial and recreational fishing. For this reason, it is subject to data collection and quarterly monitoring of water quality by the Regional Environmental Protection Agency. The interplay of multiple pressures, together with the well-documented changes that have occurred and its high ecological and economic value, make this lake ecosystem an effective example of a volcanic lake rapidly evolving in response to widespread current sources of change.

Lake Bracciano is located 32 km north-west of Rome in the Sabatini Volcanic district, one of four volcanic districts in Lazio [48], where it occupies a volcano-tectonic depression in the Regional Natural Park of Bracciano-Martignano, which hosts a number of Natura 2000 sites. Historically classified as oligo-mesotrophic [42,49,50], a recent period of severe water crisis, during which the lake reached its historical minimum in 2017, saw an anomalous increase in phosphorus levels that caused the lake to be classified as eutrophic [51]. It has an elevation of 163.04 m above sea level which is the altitude of the River Arrone emissary, taken as a reference level (hereafter the hydrometric zero) [44,52]. The River Arrone is currently not fed by the lake water because the lake is below its outflow level. The lake hosts a rich variety of local aquatic fauna and wintering birds, as well as the only known population of the aquatic plant *Isoëtes sabatina* in the world [53]. Due to the high number of charophyte species (16 species that correspond to about 30% of the European total), it is considered a European hotspot of charophyte diversity [43]. The lake provides a number of ecosystem services. Primarily, it provides water for irrigation, it is an important commercial fishery, it is popular for game fishing and other recreational activities [44,45,54] and it is a strategic source of drinking water for the city of Rome and the Vatican State. The fish of commercial interest harvested in the lake are highly prized for both their nutritional value and the low residues of organic contaminants such as the pesticides dichlorodiphenyltrichloroethane (DDT) and hexachlorocyclohexane (HCH) [55,56].

The overexploitation of the lake for water extraction and recreation, together with climate change, has resulted in a series of alterations such as the lowering of the water level [44,52], increased levels of pollutants [14,57–59] and the establishment of alien species in the food web [54,60]. These changes have compromised the ecological status of the lake. Given this recent rapid evolution, it can be considered an emblematic example of a valuable protected ecosystem at risk from increasing anthropogenic pressure. The aim of this review is to document the rapid changes occurring in the last 20 years, whose consequences are still unpredictable. Our specific goal is to review the main problems affecting this lake that are common to volcanic and deep lakes located in urbanised areas, providing insight for the better management of this type of resource.

## 2. Changes in Water Level, Nutrient Dynamics and Littoral Vegetation

Many lakes around the world are drying out due to rising temperatures, drought and overexploitation [61,62]. Increasing water level fluctuations also affect deep lakes, not only in Mediterranean areas but also in subalpine [63], tropical and temperate regions [31]. Changes in the natural water level can dramatically affect the integrity of lakes, including the deepest ones, by altering the hydromorphology of the littoral areas and thus impairing the structure and functioning of the lake ecosystem. The emergence of littoral areas impedes the growth and colonisation of aquatic plants and reduces the extent of nursery areas for aquatic species including fish. It also affects water quantity and quality, thus compromising the sustainable use of water resources for societal needs. [15,31,64]. Great concern has recently arisen over the fate of Lake Bracciano due to the changes in water level caused by both climate and anthropogenic exploitation [44,65]. Historically, human beings have managed lake waters for societal needs since ancient times [66]. In Etruscan and Roman times (9th century BC–5th century AD), several minor volcanic lakes in the region were drained to reclaim fertile soils for agriculture and to feed aqueducts. Furthermore, water level control systems were used to drain volcanic lakes below their overspill level, in order to prevent the destructive mudflows known as lahars. In the volcanic Lake Albano, which is less than 60 km from Lake Bracciano, the Roman drainage tunnel built in 398 BC is still functioning [67,68]. From the 19th century onwards, engineering systems sought to control water levels and to provide water to cities. In the early 19th century, the water level of Lake Martignano, 2 km from Lake Bracciano, dropped by 17 m, stabilising at 207 m above sea level, and the nearby Lake Stracciacappa was completely and permanently drained [67,69,70].

In more recent times, systems have been built primarily for water abstraction, and together with climate change, their reckless use has caused alterations in lake water levels worldwide, sometimes with dramatic consequences [64,71]. Lake Bracciano is an emblematic example of water level alterations causing ecosystem impairment. Its hydrology began to change in the 17th century, when a dam was built on the River Arrone, both to control the lake water level during floods and for water abstraction, which increased remarkably with increasing societal needs in the 20th and early 21st centuries [52]. This dam, abandoned decades ago, was used to control outflows from the lake into the Arrone. Since 2000 the lake has experienced cyclical water level crises, interspersed with complete or partial recovery of the water level [44,72] (Figure 2). The lake water level recovered by only 40 cm in 2018 with respect to the 2017 historical minimum, and had recovered by 98 cm by April 2023 [44,73] (Figure 2). The reasons for the anomalous water level observed in November 2017, which was −198 cm below the hydrometric zero, were threefold: below-average rainfall since 2015 (50% less in 2017 with respect to the annual average for the period 1961–1990), intense evaporation (6.7 mm day$^{-1}$ during summer 2017), and above-average water extraction since 2015 [44]. During the last two decades, the relative importance of water extraction to the lake water level increased from 24% to 39% [52]. The minimum water level corresponded to a 3.33% reduction in water volume compared to 2015 [51], together with the emergence of littoral areas [72]. In response to the 2017 water crisis, in November 2017 water abstraction from Lake Bracciano was suspended in compliance with a Regional Ordinance issued on 20 July 2017 (REGIONE.LAZIO.REGISTRO UFFICIALE.U.0375916.20-07-2017). Since then, the water level of the lake has fluctuated around the hydrometric minimum set at 161.9 m in the 1984 aqueduct project, which was 1.14 m below the hydrometric zero (Figure 2).

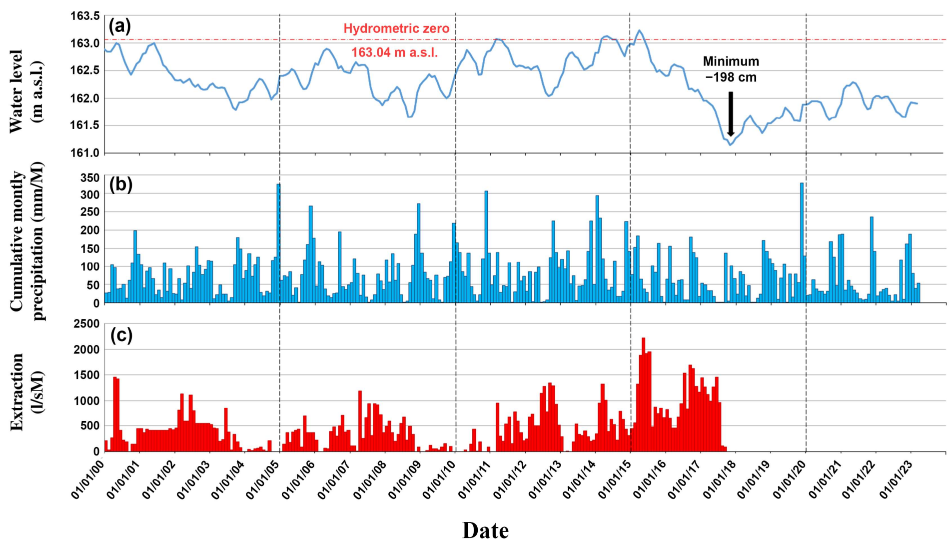


**Figure 2.** Variation in the lake water level (**a**), monthly precipitation over the lake hydrological basin (**b**) and monthly water extraction from the lake (**c**) in the period 2000–2023. Modified after [42].

Since the 2017 historical minimum, a series of changes have occurred [44,45,51,71,72]. First of all, the lake lost 13.5% of the littoral surface area responsible for self-purification [44], i.e., the natural process of dilution and removal of nutrients by means of physical, chemical and biological processes [74–77]. The minimum sustainable water level that guarantees a degree of self-purification capacity sufficient to allow the ecosystem to maintain its biological balance was estimated at −150 cm in Lake Bracciano [78], which was exceeded in 2017. In addition to the reduction of littoral surface area, the lake level dropped even further below its emissary (the River Arrone), the upper part of the river having already dried up several years earlier [34,79]. This increased the vulnerability to eutrophication of the lake, which before the water crisis was characterised by a theoretical water residence time of 137 years, the longest of all Italian lakes. As an important determinant of self-purification capacity in aquatic systems, water residence time has a strong impact on nutrient removal [80]. Long water residence times can also favour the permanence and accumulation of allochthonous non-biodegradable contaminants [81].

Although recovery after lowering events is possible, lake water level fluctuations can have serious consequences, since they affect nutrient dynamics and concentrations, thus compromising water quality and biodiversity [64]. By manipulating artificial substrates in Lake Maggiore (Italy), where lake level fluctuations were frequent from 2005 to 2011, Callieri et al. [82] showed that toxic cyanobacteria blooms can occur as a result of rising water levels even in oligotrophic deep lakes. The reason is the release of phosphorus from the shore following drying-rewetting events. Regarding Lake Bracciano, the anomalous phosphorous increase estimated by modelling Remote Sensing data during the 2017 water crisis was attributed to the decreasing water volume as well as the reduction of the surface area where self-purification can reasonably take place [51]. After 2018, phosphorus concentrations above 20 μg/L were recorded only during a few short-term events [83–85].

The lower water level affected the aquatic vegetation. Specifically, the endemic *Isoëtes sabatina* Troia & Azzella, a small submerged aquatic quillwort (a rooted plant characterised by a dense rosette of long slender leaves) only recently discovered [53,72], experienced habitat emergence and thus root exposure and desiccation [72]. The species has lost about 60% of its population since its first description, and is thus at high risk of extinction [86,87]. The lower water level also affected terrestrial vegetation, leading trees to depend more on groundwater or soil water content [71]. This compromises the neighbouring terrestrial and transitional areas [88], which potentially act as buffer zones by reducing the quantity of nutrients entering lakes [89]. The alteration of riparian vegetation has implications for the functioning of lake ecosystems, given the large contribution of terrestrial organic inputs to lake sediments [90] and the diet of lake invertebrates and fish, which are important resources for commercial fisheries [54,91].

## 3. Legacy and Emerging Pollutants

Lakes can accumulate various kinds of pollutants. For this reason, they have been affected more than other ecosystems by pollutant-induced changes during the Anthropocene. Agricultural and recreational activities, tourism and occasional sewage discharges are the main drivers of pollution. In Lake Bracciano, despite the presence of a sewage collector around the lake and the absence of substantial tributaries and motorised boats, prohibited in the lake, anthropic pollutants have been detected. They include nutrients and emerging compounds such as synthetic polymers (microplastics) and pharmaceuticals [14,57–59].

Human activities such as agriculture, industrial production, wastewater discharge and tourism cause an increase in nutrient loads, particularly phosphorus and nitrogen, in freshwater bodies [15,92,93]. In Lake Bracciano, Fiorentino et al. [14] identified nitrogen inputs in the lake littoral belt and verified their relationship to tourism and agriculture. The magnitude and type of input varied greatly in space and time: the highest organic inputs were recorded near the most popular locations (Figure 3: red), while the highest inorganic inputs were recorded near greenhouses and crops (Figure 3: blue) [14]. In both cases, anthropogenic inputs peaked in early summer, when primary productivity, crop cultivation and tourism are all at their most intense, while they nearly disappeared in winter, which is the period of least human activity. This highlighted a seasonal dynamic of external N inputs that may be considered representative of several lakes in temperate regions. In 2017, the lake was affected by lower anthropogenic organic N pressure than in the period before the water level reduction [45], attributable to the observed decline in tourism [45,94]. Indeed, drought has both direct and indirect impact on the tourism and recreational sectors, negatively influencing the public perception of the ecological status of aquatic ecosystems [95,96].

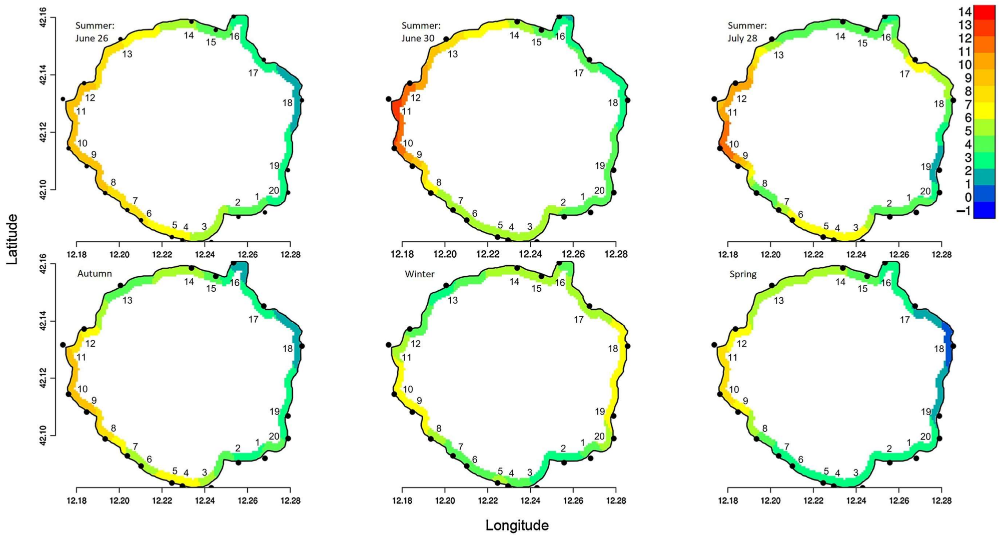


**Figure 3.** Plots of the inputs along the littoral belt of Lake Bracciano at various times. Colours symbolise the nature of the inputs: Inorganic ($\delta^{15}N < 3‰$, blue), Moderate organic ($6 < \delta^{15}N \leq 9‰$, yellow), High organic ($\delta^{15}N > 9‰$, red). Green indicates the non-impacted input range ($3 \leq \delta^{15}N \leq 6‰$). Input measurement times are indicated: three times for summer 2015 and once for each of the following seasons. Numbered dots around the lake perimeter indicate sampling sites located close to towns (1–3 and 20: Anguillara-Sabazia; 7, 9 and 10: Bracciano; 14 and 15: Trevignano Romano), tourism structures (4, 5, 8, 11 and 17), cultivated fields (16 and 18) and naturally vegetated areas (6, 12, 13 and 19). For further details, please refer to Fiorentino et al. [14]. Modified from Fiorentino et al. [14] with permission. License Number 5519300447448.

Regarding other pollutants, plastic debris has been described as one of the top emerging global issues [97]. Microplastics (MPs), defined as pieces of plastic debris smaller than 5 mm [98], can be ingested by living organisms, with consequences for food webs via transfer from prey to predators [99–101]. In addition to ingestion, other concerns arise regarding the presence of low-molecular-weight chemical species, in or adsorbed onto plastics (such as organic pollutants, plastic additives and residual monomers), which might be bioavailable to organisms and, if ingested, may be toxic [102]. In freshwater bodies, exposure to plastic increases oxidative stress in cyanobacteria, promoting microcystin synthesis and release, thereby enhancing the threat of eutrophication [103]. Cyanobacteria and microplastics are thus two mutually enhancing issues affecting Italian lakes that have effects on human health, ecosystems and the quality of drinking and recreational water, with repercussions for economic activities. Cyanobacteria are not currently a problem in Lake Bracciano, although the combined effects of increasing nutrient concentrations and global warming risk driving them to dangerous levels. High concentrations of microplastics have however been reported [58,59,79]. Compared to other volcanic lakes in the area (Lake Albano and Lake Vico), Lake Bracciano has the largest number of plastic particles per unit of sediment volume [59]. Microplastics have also been found in the digestive tract of detritivorous amphipods [59] and in the whitefish *Coregonus lavaretus* L., which is a commercially fished species [79].

Among the emerging organic contaminants, pharmaceuticals and their metabolites can reach freshwater bodies through human excretion, improper waste disposal, industrial waste and run-off from farms and livestock [104,105]. Unfortunately, they are not systematically monitored in Italian freshwater bodies, although their occurrence has been reported by specific studies [102], and literature cited therein. A prominent position in these studies is occupied by NSAIDs (non-steroidal anti-inflammatory drugs), some of which have been found in the waters of Lake Bracciano [57,106,107]. Urban wastewater treatment plants are generally not effective in removing drugs [108–110]. However, the wastewater treatment plant serving the local population does not discharge the treated waters into Lake Bracciano, suggesting that pollutants reach the lake via direct discharge of human organic waste and/or run-off from the catchment area, or due to the capacity of the lake sewage collector being exceeded during the tourist season. This kind of discharge compromises both the quality of drinking water and the health of the organisms living in the lake. It has been demonstrated that NSAIDs inhibit the enzymes catalysing the biosynthesis of prostaglandins, which protect gastrointestinal cells in human beings [111]. In other organisms they may have other effects such as changes in the behaviour and haematology of fish [112]. Concentrations of these substances in Lake Bracciano have been the subject of a limited number of investigations, but no studies of the lake are available regarding other emerging contaminants in freshwaters, which pose a risk to human health and are a hazard for the environment [113].

Finally, it should be mentioned that as in other volcanic lakes, arsenic is also present, but it is not of anthropic origin. Lake Bracciano contains variable quantities of this element, which is naturally present in many environments and is closely related to natural processes including biological and volcanic activities and the local climate [114–116]. Although natural, high concentrations of arsenic are harmful for human health and animals, and the combination of anthropogenic pressure (i.e., eutrophication) and global warming could enhance its release into ecosystems [117,118], with adverse effects on ecosystem functioning, as already reported in other locations [46,117,119]. Therefore, continuous monitoring of this element in volcanic lakes is important.

## 4. Alien Species

It is widely known that alien species can have a major impact on invaded ecosystems, rapidly altering the balance established over long periods. Where the impact of multiple introductions in a single lake has been assessed, the loss/deterioration of several crucial services has been identified, with the associated socio-economic costs (e.g., the case of Lake Naivasha [120]). Lake Bracciano is an example of a protected and yet repeatedly invaded ecosystem. To date, the presence of several alien species has been recorded, many of which are common lake invaders both locally in the same region and globally, including species listed among the world's 100 worst invaders and species of European Union concern [121,122].

Alien plant species in the lake include terrestrial Malvaceae and Solanaceae, whose invasive potential in once-submerged coastal areas is being evaluated, and the highly productive emergent perennial *Ludwigia hexapetala* (Hook. & Arn.) Zardini, H.Y. Gu & P.H. Raven, which is considered a problematic weed in several countries [123–125]. This species was first reported as *L. peploides* (Kunth) P.H. Raven in 2007 [123], and then identified as *L. hexapetala* in 2019 [124]. Since it was first recorded in Lake Bracciano, this highly opportunistic species, which has two morphological types (aquatic and terrestrial [126]) and is able to exploit a wide range of hydrological and climatic conditions, has rapidly colonised extensive littoral areas. It is currently found in dense populations, mainly in anthropised areas [123,124,127] (Figure 4). The spread of this alien plant species has been ascribed to the lowering of the water level, which has critically reduced the extent of the marshy and aquatic habitats along the coastal belt and has favoured the conspicuous growth of hygro-nitrophilous species, able to survive prolonged hypoxic conditions.


**Figure 4.** Areas of Lake Bracciano near the source of the River Arrone (Anguillara Sabazia), with the invasive *Ludwigia hexapetala*. Panels show: (**a**) lake overview with littoral vegetation in the foreground and the local water supply building in the distance on the right, (**b**) terrestrial vegetation on the dry bed of the initial stretch of the River Arrone, (**c**) the water supply building commissioned by Pope Pio VI in 1787, (**d**) river source dominated by *L. hexapetala*.

Tolerant of a wide range of environmental conditions including low oxygen concentrations, extreme temperatures, pollution and wide fluctuations in water level, the Louisiana crayfish *Procambarus clarkii* Girard, the most cosmopolitan crayfish and the dominant macroinvertebrate in several European countries [128], has also been reported to occur in Lake Bracciano [129]. Alien mammals are also present, such as the nutria *Myocastor coypus* Molina, now naturalised [130]. As far as fish are concerned, more species have been introduced than any other category of aquatic animals [131]. In Lake Bracciano, species introduction and restocking for sport and professional fishing have modified the original structure of the fish communities. Non-native species are almost more numerous than native ones and many of them are now naturalised [47,130,132–134]. The non-native fish include the largemouth bass *Micropterus salmoides* Lacépède, one of the world's 100 worst invasive species [121], which is an opportunistic predator [135], known for its ecological impact on native ecosystems [136–138]. *Micropterus salmoides* has been widely introduced outside its native range (North America) due to its suitability for sport fishing [54,60,134,139], and its presence in Lake Bracciano has been recorded since 1998 [139]. Serious impacts on the lake food web were soon observed, with highly negative effects on long-naturalised species and/or species of major economic interest such as *Atherina boyeri* Risso and *Perca fluviatilis* L., which are both commercially fished [54,60]. The native stickleback (*Gasterosteus aculeatus* L.), historically present in the lake [140] is now probably extinct [141]. Differences in the distribution of aquatic vegetation and the associated invertebrate species in the lake are reflected in different impacts on the fish food web, in some cases with economic implications [47,54], highlighting the need to maintain habitat complexity including littoral vegetation in order to contain the negative effects of the largemouth bass.

Other numerous non-native fish species include: the whitefish (*Coregonus lavaretus*), which is regularly restocked, and the perch (*Perca fluviatilis*), brought from Swiss Alpine lakes; the bluegill (*Lepomis gibbosus* L.) and the gambusia (*Gambusia holdbrooki* Girard), brought from North America; the crucian carp (*Carassius carassius* L.), brought from Asia; the common rudd (*Scardinius erythrophthalmus* L.), the Eurasian ruffe (*Gymnocephalus cernua* L.) and the Eurasian carp (*Cyprinus carpio* L.), brought from other areas of Europe and Asia; and the roach (*Rutilus aula* Bonaparte) brought from northern Italy.

The presence of these non-native species, which in many cases are not important to the local economy, affects the densities of native species'. The impact of whitefish restocking to support professional fishing is currently under evaluation in Lake Bracciano after the Habitats Directive (DPR No 357/1997) was amended by modifying the term "species introduction" (DPR 102/2019 Art.1 r-*bis*), and criteria for reintroduction of non-native species have been established (GU No 98/2020 Art. 1 b). While in Lake Ring whitefish may be responsible for lower cladoceran density and greater chl-a, indicating eutrophication [142], its potential to limit the highly invasive *M. salmoides*, as observed in Lake Bracciano [47,54], merits further investigation.

## 5. Conclusions and Suggestions for Lake Management

Considering the uniqueness of volcanic lakes, which in recent decades have suffered various forms of impact from climate change and human activities, we regard Lake Bracciano as an emblematic example of a valuable lake ecosystem in rapid evolution under natural and human pressures. Although the lake is historically believed to enjoy a good ecological status, recent models have shown the potential for ecological disaster [65]. This review of the main issues this lake ecosystem is facing found that in recent years the biggest threat to the functioning of the lake has been the fluctuation in the water level. Indeed, changes in the water level can lead to the accumulation and resuspension of nutrient-rich organic matter. They can also alter habitat availability, complexity and quality, thus increasing susceptibility to both eutrophication and invasive species [137], and the literature cited therein.

The threats facing Lake Bracciano, including water level changes, species introductions and rising levels of nutrients and emerging pollutants, are common to other volcanic lakes both within the same region [57,59,118] and elsewhere in the world [15,143–145]. Lake Bracciano is taken as a reference here because both the synergy between various threats and the consequences for biodiversity and associated ecosystem services have been well documented.

In Lake Bracciano the historic minimum water level, associated with water extraction and climate change, had a series of drastic consequences for water quality and biodiversity [44,51,72,86,87]. Models developed to forecast the vulnerability of the lake to climate and water-use stresses [65,146] have shown that the lake ecosystem, which is exposed to a high risk of losing its self-purification capacity due to the lowering of the water level, could collapse [65,146]. The System Dynamics approach applied by these models allowed the authors to analyse the resilience of the water system in several scenarios differing in terms of the local strategies and policies adopted in periods of crisis. The scenario that assumed no increase in the price of water (one of the most important levers for controlling consumption) and no infrastructure maintenance showed that the lake water level could decrease further, indicating no resilience. This was mainly attributed to the obsolescence of the infrastructure used for water abstraction, which obliges the water company to extract more water to compensate for losses [65]. Other alterations, exacerbated by the habitat degradation associated with water level fluctuations, include the introduction of pollutants such as nutrients [14] and the establishment of invasive plant and fish species. Pollutants have compromised the quality of the lake water both as a source of drinking water and as a habitat for living organisms. The invasive *M. salmoides* has endangered both native species and those of economic interest [47,54,60], with a greater impact where habitat complexity is lower [47,54]. Unfortunately, the effects of the introduction and spread of the other alien species have not yet been assessed in the lake. As for the other threats facing Lake Bracciano, especially microplastics and pharmaceuticals, their impact on biodiversity and ecosystem functioning is virtually unknown. However, understanding their occurrence is an essential requirement for effective management of the lake's resources.

Since many volcanic lakes, with their delicate balances, represent vulnerable hotspots of biodiversity and offer important ecosystem services, including clean drinking water and commercial fishing, it is necessary to ensure good management, taking account of the synergic effects of stressors when making policy decisions.

In the case of Lake Bracciano, the most easily applicable measure is to carefully regulate water extraction in order to avoid the risk of future water level crises. Falling water levels may indeed exacerbate the various problems which the lake is facing, including: inputs of pollutants, by compromising its self-purification capacity and increasing the release of phosphorus from rehydrated sediments [44,82]; invasive species, by reducing littoral complexity and biodiversity, which impede invasion processes [147]; and overfishing, by reducing fish nursery areas and thus recruitment [15]. Historically, the lake appears to have undergone such crises on a cyclical basis, after which it has completely recovered on several occasions [44,72]. However, this was not the case with the prolonged 2015–2017 drought, because of reduced rainfall and overexploitation of the water for human consumption [44,52].

Unfortunately, comprehensive data on surface flows leaving the lake via the River Arrone, streamflows entering the lake from the 147 $km^2$ catchment area and groundwater inflows/outflows are not available [44,52]. Additional data are needed for a complete analysis of the mass balance of Lake Bracciano. An integrated surface and subsurface flow model of the regional hydrological system including Lake Bracciano and its contributing catchment area [148], such as the MIKESHE model, which requires extensive model data and physical parameters but has a higher processing ability than other models [149], might help determine why Lake Bracciano's water levels failed to recover over the winter following the excessive drop in 2017, despite the cessation of abstraction for Rome's water supply. The integrated model can also be used to test various quantity management scenarios to establish a sustainable water extraction model for Lake Bracciano and rescue the lake from ecosystem collapse.

Although a comprehensive mass balance analysis, which is an essential prerequisite for developing a plan for sustainable lake management, is not available for Lake Bracciano, it is known that the relative importance of human abstraction ranged from 24% of the total lake water volume loss before 1985 to 39% after 1985 [48]. In this case, in the light of future global warming scenarios, a decisive way to reduce the risk of falling water levels would be to return, at least in part, the water reclaimed by the local WWTP, which collects about $4 \times 10^6$ $m^3$ water/year [150], to the lake after tertiary wastewater treatment. While for example this occurs in the lower Great Lakes region, the most densely populated region of Canada, where municipalities discharge treated sewage into lakes [151], it is not the case in Lake Bracciano and other volcanic lakes. Currently, after chlorination, the reclaimed water of the municipalities around Lake Bracciano is released into the River Arrone, which discharges into the Tyrrhenian Sea. Paying careful attention to the hydrometric level will enable maintenance of the lake's self-purifying capacity at the minimum sustainable level [78]. This is crucial for the removal of the nutrients responsible for eutrophication, which in many other cases besides Lake Bracciano mainly come from agriculture and tourism [14] and compromise aquatic biodiversity and the quality of water for human use.

In the vicinity of lakes there are frequently cultivated areas, above all in the case of proportionally small catchment areas [14,152,153], which are considered the causes of algal blooms. In these cases, a good way to reduce the quantity of nutrients entering the water is to limit the amount of fertilisers and to revise agricultural practices so as not to exceed crop uptake [154]. Furthermore, since a certain degree of leakage is unavoidable due to natural phenomena such as failed uptake and leaching, in order to reduce the quantity of fertiliser reaching the water body, crops should be placed farther away from the shore. A lake protection zone (including riparian vegetation as a buffer) should be maintained or restored so as to ensure uptake of chemicals from the cultivated areas [155].

Regarding tourism, which sometimes represents a major issue for lake ecosystems, the sustainable use of lakes can be ensured by means of appropriate management strategies including a 'Triple Bottom Line' approach (environmental, social and economic) to protect biodiversity, safeguard the business practices of the local community and support tourism, as well as the implementation of a zoning plan that sets out the areas that can be used for tourism development and operation [156,157].

Lastly, since eradication is difficult, especially in large deep lakes, the literature suggests that a promising strategy for controlling alien species is to maintain complex ecosystems, which are more difficult to invade than simple ones [147]. However, given the high density of the invasive alien weed *Ludwigia hexapetala*, particularly in some areas of the lake, the Bracciano-Martignano Regional Natural Park authority has initiated manual eradication in pilot littoral areas (Argenti, pers. comm.). Maintaining complex ecosystems, especially food webs, is particularly important with respect to the invasive *M. salmoides*, which in many volcanic and other lakes around the world has put severe pressure on native fish since its introduction [138,158]. Unfortunately, eradication of *Micropterus salmoides* has been successful only in ponds and small lakes [159–161]. For larger water bodies, management remains the only way to reduce impacts. For example, the Park authority has instructed fisherman to not release specimens of *M. salmoides* once they are caught (Argenti, pers. comm.). Several studies have highlighted the role of structural complexity (such as aquatic vegetation and coarse woody habitats) in reducing the pressure of *M. salmoides* and other fish invaders on littoral fish communities [147,162–164]. The adoption of measures to protect and increase the native littoral vegetation (e.g., the aforementioned limitation of changes in the water level and the regulation of human development along the lakeshore) could therefore help reduce the predation exerted by invasive fish on native species, including those of economic interest, thus supporting local commercial fishing.

The above-cited measures should follow an *ecosystem*-based approach, which requires a shift from an environmental to an ecosystemic (politics-in-an-ecosystem) perspective. This means adopting "an integrated set of policies and managerial practices that relate people to ecosystems of which they are part rather than to external resources or environments with which they interact" [165]. To this end, administrations should practice this approach regardless of political boundaries.

**Author Contributions:** Conceptualisation, M.L.C. and L.R.; investigation, M.V.; writing—original draft preparation, M.V.; writing—review and editing, G.C., E.C., S.S.C., E.A., D.R., L.R. and M.L.C.; visualisation, M.V, G.C., E.C., S.S.C. and D.R.; supervision, M.L.C.; funding acquisition, L.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding and the APC was funded by CoNISMa (Consorzio Nazionale Interuniversitario per le Scienze del Mare) grant number PNRA 2018/B2Z1.08.

**Data Availability Statement:** Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

**Acknowledgments:** We thank the Regional Natural Park of Bracciano-Martignano staff and in particular the Park director Daniele Badaloni who contributed to information used in this study. We thank George Metcalf for revising the English text. We also thank Andrea Frusone for the photographic images used in this review. We are grateful to the Servizio Meteorologico dell'Aeronautica Militare for providing the Bracciano climate data set, to ACEA-ATO2 for providing abstraction data and to the Bracciano-Martignano Park Authority for providing lake water level data.

**Conflicts of Interest:** The authors have no competing interests to declare that are relevant to the content of this article.

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