REVIEW

Lake Maggiore: geomorphological genesis, lake-level evolution, and present and future ecosystems importance

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ABSTRACT

Lake Maggiore, the second deeper and larger south alpine lake, was selected as a model system to detect the potential damages on water resources, biodiversity and ecosystem health caused by different water levels during the lake-level regulation period (March to November). With a drainage basin exceeding an altitude difference of 4400 m, Lake Maggiore fills a deep valley floor whose bedrock reaches up to 700 m below the present sea level. The cryptodepression occupied by the lake was probably formed during the end of the Miocene and the Pliocene and was shaped successively during the Pleistocene glaciations. Lake Maggiore originated following the Last Glaciation, when it reached its maximum lake-level and extension just after its deglaciation. The mean secular lake-level progressively decreased throughout the Holocene, causing a gradual shrinkage of the lake because of the constant depositional input that created the fluvio-deltaic plains at the mouth of the main tributaries of the lake. The regime of the tributaries is of mixed type, with a spring maximum mainly due to snowmelt and an autumn maximum exclusively of pluvial origin. Water levels naturally tend to reflect the amount of rain or snow precipitation and are expressed through a double cycle: winter and summer characterised by low waters, and spring and autumn by high waters. In 1943, the need to use the waters of the great lakes to have water available in the less favourable periods, led to the construction of a dam at the Lake Maggiore outlet. This structure allows to store water during heavy rainfall or snowmelt periods. The accumulated water is then supplied during the irrigation periods to agriculture (spring and summer) and to industrial users (mainly in autumn and winter). The geomorphological genesis and the ecosystems description was focused on riparian, fluvio-deltaic, and ephemeral systems. For these ecosystems, their evolution considering the hydrological regime of the tributaries, the anthropogenic activities in the watershed and the effects of lake-level management since 1943, was also described. Considering the summer increase, between April and July, to +1.25 m (with possible peaks to +1.50 m) experimentally tested between 2015 and 2020, and the approval of the proposal to continue the test for the next five-year period (2022–2026), we finally emphasise the potential further reduction of reeds and natural habitats and the subsequent loss of biodiversity related to the plan of raise the lake-level to +1.50 m all year round.

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Key words: chemistry; geomorphology; hydrology; lake-river ecosystem; limnology; water level management.

Conflict of interest: the authors declare that they have no competing interests, and all authors confirm accuracy.

Contributions: all the authors made a substantive intellectual contribution, read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Citation: Scapozza C, Patocchi N. Lake Maggiore: geomorphological genesis, lake-level evolution, and present and future ecosystems importance. *J. Limnol. 2022;81:2146.*

Edited by: Silvia Quadroni, *University of Insubria, Varese, Italy*.

Received: 30 May 2023.
Accepted: 23 August 2023.

J. Limnol., 2022; 81(s2):2146
DOI: 10.4081/jlimnol.2022.2146

INTRODUCTION

Lake Maggiore is located in a strategic and crucial position, on the border between natural Alpine areas rich in freshwaters and the industrialized areas of the Po Plain. This lake has been continuously monitored since 1978 within the International Commission for the Protection of Italian-Swiss Waters (CIPAIS) and within the Subalpine large and deep lakes of the Long-Term Ecological Research network (LTER Italy: http://www.lteritalia.it/, accessed on May 12, 2023). Since the creation of the Miorina dam in 1943, its water level is regulated thanks to an Italian-Swiss cooperation agreement. The establishment of a technical table, composed of experts with different skills, and stakeholders with different interests, to test a summer increase of water level was thought to verify the effects on the littoral biota (both vegetation and animals inhabiting the lake shores) of the increased levels.

These aspects contribute to its importance at national level as a large water storage and as a provider of several ecosystem services and have served to consider it as a model system in the framework of the Project "Parks Verbano Ticino" (Cooperation Program INTERREG V-A Italy-Switzerland 2014-2020). The lake plays a key role in providing ecosystem services (water supply, fisheries and aquaculture, hydropower generation, navigation/water transport, tourism), but it is also a crucial source of biodiversity. The increased frequency of extreme events (particularly prolonged droughts) and the increased demands for water during drought periods require water levels to be updated to meet user requests.

Main aims of the Interreg project are to detect the potential damages on water resources, biodiversity and ecosystem health caused by the modification of the upper limit of water level regulation in spring-summer period (Tab. 1). Specific aim is to increase common strategies for a shared and sustainable management of Lake Maggiore water resources. Water level management strategies are also an urgent task for lake protection and restoration.

The general purpose of the present paper is to present the state of knowledge on the geomorphological genesis of the lake, its conversion to a reservoir, the trophic status of its waters, the introduction of a technical table for the water level management, and the summary of the potential effects on ecosystems and biodiversity of a change of the Italian/Swiss level management agreement. The specific objective of this contribution is the contextualization of Lake Maggiore from a geomorphological and bio-ecological point of view, in order to introduce and set up the framework for the other contributions of this special issue.

GEOMORPHOLOGICAL FEATURES

Topographical characteristics

Lake Maggiore, or Verbano (Fig. 1, Tab. 2), is the largest of the Insubric lakes (also including Lake Lugano and Lake Como) and is the second largest lake (after Lake Garda) and the second deepest (after Lake Como) in Italy. In Switzerland, it is the fourth largest lake (after lakes Geneva, Constance, and Neuchâtel) but the first in terms of maximum depth (Fig. 2).

Its watershed area (6599 km^2) includes most of the Lepontine Alps (watersheds of rivers Ticino, Brenno, Moesa, Verzasca and Maggia), the eastern part of the Pennine Alps (watershed of river Toce) and the Lugano Prealps (watersheds of Lake Lugano and river Tresa) and enters the northern edge of the Po Plain. The altitude difference of the drainage basin is remarkable and exceeds 4400 m, as it ranges from 193.50 m asl (average level of the lake-water surface) to 4617 m asl of Grenzgipfel, a secondary peak of Punta Dufour (4634 m asl) in the Monte Rosa massif.

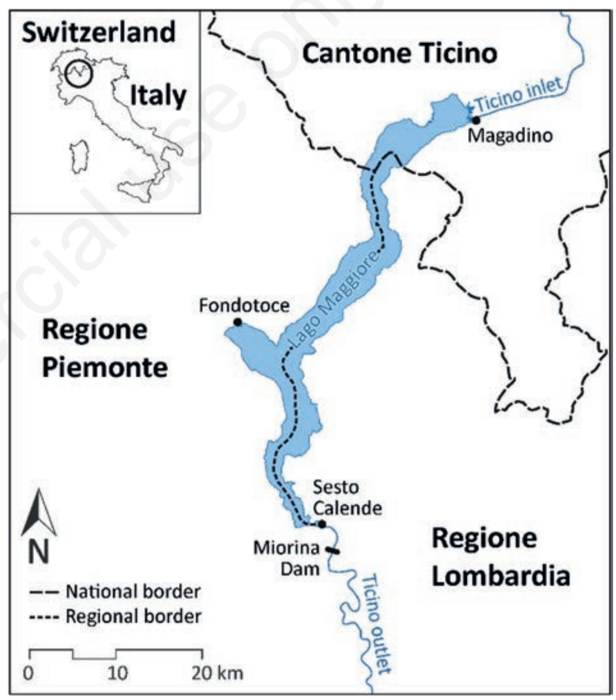

Fig. 1. Lake Maggiore, at the border between Switzerland (Cantone Ticino) and Italy and between Piedmont and Lombardy Regions.

Tab. 1. Conversion lake-level measures (expressed in metres above sea level: m asl) from Swiss to Italian gauge zero points. In the text, the Swiss value of the lake-level is reported, followed (in brackets) by the difference in altitude from today's reference lake-level in Sesto Calende.

	Gauge zero point in Sesto Calende*	Lower limit of regulation range (-0.5 m)	Upper limit of regulation range March 15 – November 15 (+ 1.0 m)	Upper limit of regulation range November 15 – March 15 (+ 1.5 m)
Switzerland (CH)	192.65	192.15	193.65	194.15
Italy (ITA)	193.00	192.50	194.00	194.50

*$hITA = hCH + 0.35$ (m).

Geomorphological history

Lake Maggiore fills a deep valley floor whose bedrock is up to 700 meters below the present sea level (Finckh, 1978; Fig. 2). Like other main Insubric lakes, it was probably formed during the end of the Miocene [from 23.03 to 5.33 millions of years ago (Ma)] and the Pliocene (from 5.33 to 2.58 Ma), *i.e.*, before the Quaternary (from 2.58 Ma to today), which in the Alps was marked by several tens of glaciations during the Pleistocene (from 2.58 Ma to 11.70 ka b2k = thousands of years before 2000).

The pre-Quaternary formation of the deep valleys now occupied by Insubric lakes took place by increased fluvial erosion in a sub-tropical climatic context (Bini *et al*., 1978; Finckh, 1978; Scapozza and Ambrosi, 2021). River erosion, well below today's sea level, was particularly intense during the repeated episodes of Mediterranean marine regression that occurred during the Messinian (from 7.25 to 5.33 Ma). These episodes, called the Messinian Salinity Crisis (Hsü *et al*., 1973; Roveri *et al*., 2014), were triggered by the closure of the Strait of Gibraltar for tectonic reasons, and caused the almost complete evaporation of the Mediterranean Sea, as evidenced by hundreds of meters of saline deposits found on the bottom of the sea. The

Tab. 2. Lake Maggiore: main geographical features. *Source: https://www.treccani.it/enciclopedia/lago-maggiore_(Enciclopedia-Italiana)/ (accessed on May 8, 2023).*

Parameter	Value	Remarks
Surface area (km^2)	212.16	After Marinelli, 1893-1897
Water surface average level (m)	193.50 (+0.85)	After Fantoli, 1897
Perimeter (km)	170.02	After Marinelli, 1893-1897
Maximum length (km)	64.37	Between Magadino and Sesto Calende
Maximum width (km)	12	Between Mergozzo and Cerro
Mean width (km)	3.90	–
Volume (km^3)	37.10	Hydrographic office of the *Regia Marina* (Royal Italian Navy), 1891
Maximum depth (m)	372	Between Caldé and Ghiffa
Mean depth (m)	175	Hydrographic office of the *Regia Marina* (Royal Italian Navy), 1891
Islands (#)	7	With a total surface of 0.24 km^2

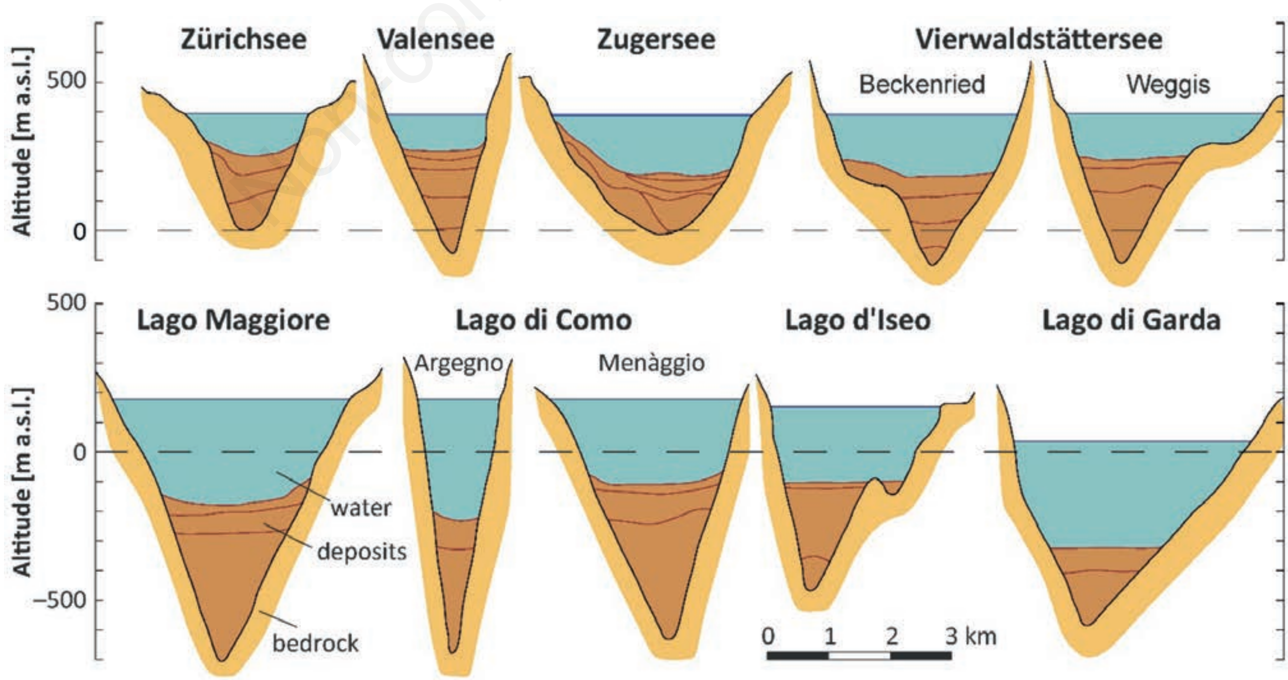

Fig. 2. Cross-sections of the deepest part of some Northern (upper panel) and Southern (lower panel) Alpine lakes based on seismic reflection and refraction prospecting. *Adapted from Finckh (1978).*

consequent lowering of the river erosion level caused the formation of valleys and canyons, now partially buried, and Messinian erosion surfaces, recognized by geological and geophysical prospections carried out on the Magadino plain, in the Mendrisiotto area, on the Insubric lakes themselves (Fig. 2) and downstream of these in the Po Valley (Bini *et al*., 1978; Pfiffner *et al*., 1997; Bernoulli *et al*., 2018).

If the valley occupied by waters originated more than 5 Ma, Lake Maggiore as it is known today was originated following the Last glaciation, which reached its maximum advance in the watershed of the Ticino-Toce rivers during the Last Glacial Maximum (LGM), dated between 28.90 and 19.98 ka b2k (Rey *et al*., 2020; Kamleitner *et al*., 2022; Scapozza, 2022). During the LGM, the moraines that dam Lake Maggiore between Meina, Arona, Castelletto Ticino, Sesto Calende, and Taino were deposited by the Ticino-Toce glacier system (Monegato *et al*., 2022). The lake watershed dammed downstream by the moraines of the Ticino-Toce glacier system then gradually filled up following the ice-melting, after the end of the LGM, between 19.98 (radiocarbon dating BE-8023.1.1 in Tab. 3) and 18.15 ka b2k. The latter date corresponds to the upper chronological limit of the so-called Cugnasco Stadial, determined by Cosmogenic nuclide dating of erratic boulders (Scapozza *et al*., 2022). During the Cugnasco Stadial, the front of the Ticino paleo-glacier was already attested between Cadenazzo and Cugnasco in the middle of the Piano di Magadino, which at the time was entirely occupied by Lake Maggiore (Scapozza *et al*., 2014).

Lake Maggiore had a higher maximum lake-level than today and was consequently more extensive. During the Last deglaciation (19.98–16.94 ka b2k according to radiocarbon dating BE-8023.1.1 and Poz-129011 in Tab. 3), when the Ticino paleo-glacier still occupied the upper part of the lake (glacio-lacustrine phase), the maximum lake-level was about 220 m asl (+27.35 m compared to the Sesto Calende gauge zero point, 192.65 m asl; Tab. 1), progressively lowering first to 215 m asl (+22.35 m), and then to 212–210 m asl (+19.35/+17.35 m) between 16.94 and 14.69 ka b2k (Poz-129011 and end of GS-2), at the beginning of the lacustrine phase (Scapozza, 2023; Fig. 3).

During the maximum extension phase, Lake Maggiore reached Giubiasco in the Ticino Valley and Ponte Brolla in the Terre di Pedemonte at the mouth of the Maggia Valley. In Lombardy, it reached Mirandola in Travaglia Valley, occupied the alluvial plain today between Angera and Taino, and the plain of Sesto Calende. Going up the Piedmont shore, it occupied the area of Castelletto Ticino, incorporated Lake Mergozzo and the plain of Gravellona Toce, up the Ossola Valley until Pieve Vergonte (Fig. 4).

The mean secular lake-level progressively decreased throughout the Holocene (from 11.70 ka to today), settling towards 207-204 m asl (+14.35/+11.35 m) during the Greenlandian (from 11.70 to 8.24 ka b2k), going down to 200 m asl (+7.35 m) during the Northgrippian (from 8.24 to 4.25 ka b2k), and finally settling progressively to 198-195 m asl (+5.35/+2.35 m) during the Meghalayan but before the end of Middle Ages (from 4.25 to 0.51 ka b2k) (Fig. 3).

The lowering of the average lake-level during the Holocene was accompanied by a gradual shrinkage of Lake Maggiore because of the constant depositional input that created the fluvio-deltaic plains at the mouth of the main tributaries of the lake (rivers Ticino and Verzasca, Maggia and Melezza, Toce and Tresa). The progradation of the river Ticino delta into the Piano di Magadino during the Holocene was well documented thanks to numerous geological boreholes and radiocarbon dating (Tab. 3) of organic material found in fluvial deposits (Scapozza, 2016; Scapozza and Ambrosi, 2021; Czerski *et al*., 2022; Scapozza *et al*., 2022). Just before 10.75 ka b2k (UZ-5958/ETH-42562 in Tab. 3), the lake still reached Camorino, about 10

Tab. 3. Geochronological data cited in the text to assess the timing of deglaciation of Lake Maggiore and Late Glacial and Holocene infilling of the Piano di Magadino. Calibration of conventional ages was performed with OxCal 4.4 software, using the IntCal20 curve and a 2σ range (95.4% probability).

Laboratory code	Conventional age (^{14}C BP)	Calibrated age (cal BP)	Calibrated age (ka b2k)	Prob. (%)	Source
B-4565	6270±40	7280-7150 7120-7020	7.33-7.20 7.18-7.07	80.2 15.3	Donati (1986)
BE-8023.1.1	16,000±250	19,930-18,810	19.98-18.86	95.4	Rey *et al.* (2020)
Poz-31084	1940±35	1980-1960 1950-1740	2.03-2.01 2.00-1.79	1.5 94.0	Scapozza (2016)
Poz-129011	13,710±70	16,890-16,340	16.94-16.39	95.4	Scapozza *et al.* (2022)
Poz-145688	6410±40	7430-7260	7.48-7.31	95.4	Scapozza *et al.* (2022)
UZ-5079/ETH-28509	3480±50	3890-3580	3.94-3.63	95.4	Scapozza (2016)
UZ-5958/ETH-42562	9355±40	10,700-10,490 10,470-10,430	10.75-10.54 10.52-10.48	90.7 4.7	Scapozza (2016)

km upstream of the mouth of the current River Ticino. In the Early Neolithic, just before 7.48 ka b2k (Poz-145688 in Tab. 3), at the time of the first human settlement established upstream of the lake attested on the Castel Grande hill in Bellinzona between 7.33 and 7.20 ka b2k (B-4565), the delta ended just downstream of the Cadenazzo-Gudo line. Between 3.94 and 3.63 ka b2k (UZ-5079/ETH-28509 in Tab. 3), the present Bolle di Magadino territory began to form, as the front of the River Ticino delta was attested downstream of the Quartino-Riazzino line.

In more recent times, the discovery of several tombs with pottery, glass, and bronzes from the Roman Period in Riazzino, indicates with certainty that the front of the delta was at that time further downstream, probably between Quartino and Magadino di Sopra on the left side and between Riazzino and Gordola on the right side of the Piano di Magadino (Scapozza, 2016). On the right side, the delta front passed downstream from Gordola between 1400 and 1490 (Scapozza, 2016). The complete burial of the estuary that led to the port of Gordola probably occurred because of the well-known Buzza di Biasca (May 20, 1515). This event, which can be considered the most catastrophic flood in historical times to have affected the South of the Alps, was the consequence of the enormous rock avalanche that occurred on September 30, 1513, on the western slope of Pizzo Magn (2329 m asl, also called Monte Crenone), upstream of Biasca (De Pedrini *et al*., 2022). The 85.5 million m^3 of rock avalanche deposits produced a vast barrier that dammed the course of the Brenno river and produced the formation of a temporary lake 4.5 km long, 1.2 km wide and with a volume of 130 million m^3 which submerged the village of Malvaglia up to half the bell tower. The sudden failure of the debris dam on May 20, 1515, destroyed the village of Biasca, flooded the city of Bellinzona and devastated the Piano di Magadino as far as Lake Maggiore (De Pedrini *et al*., 2022). Finally, a borehole carried out in Castellaccio in the Bolle di Magadino, as well as information from historical documents and maps, allowed us to document the transition from an open lake to a delta plain between 1365 and 1600 (Scapozza, 2016). By relating the distance of the delta front from the lake and its chronology, a mean delta progradation rate during the Holocene of 1 m a^{-1} (10.60 km in 10.75-10.54 ka) was obtained.

Considering all the long geomorphological history of Lake Maggiore over the last 5 Ma, the contribution of fluvial, glacial, fluvio-glacial, glacio-lacustrine and lacustrine deposits in the pre-Quaternary and Quaternary periods caused a debris filling of more than 700 m thick at the deepest point of the Piano di Magadino (Ramello in

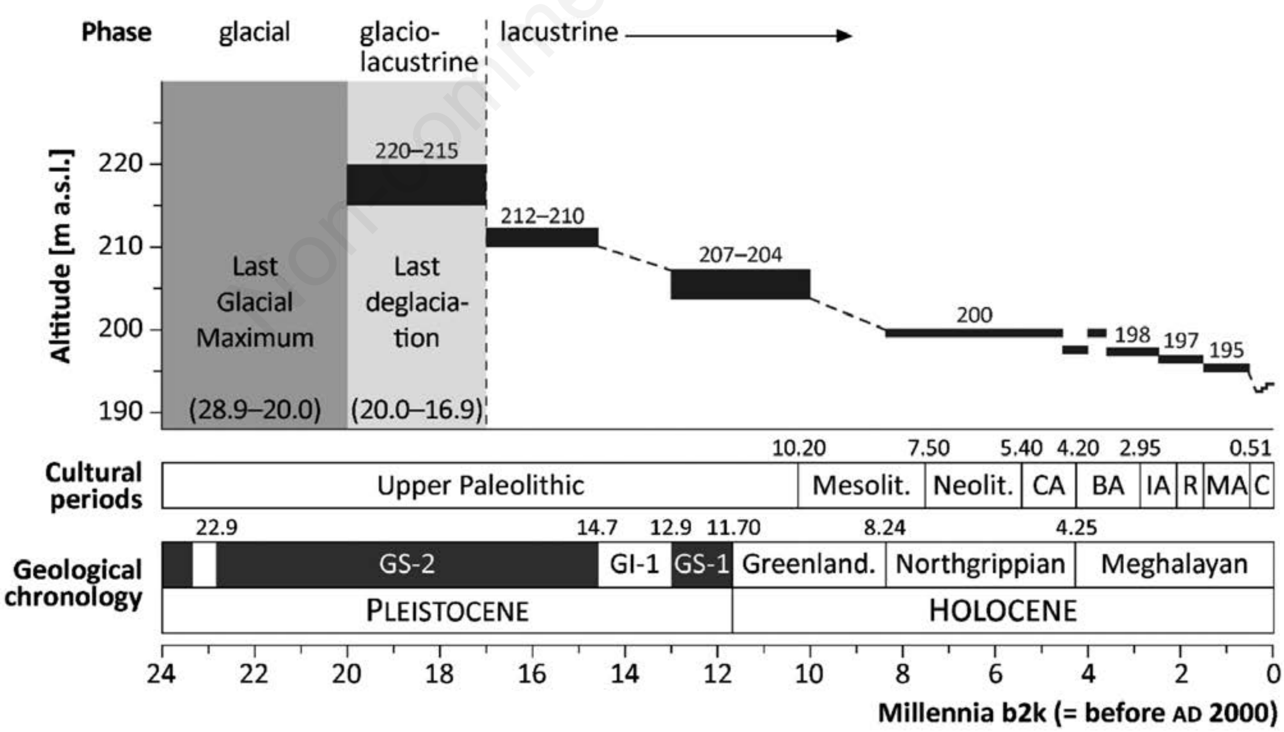

Fig. 3. Evolution of the mean secular lake-level of Lake Maggiore and chronostratigraphic reference framework from the Last Glacial Maximum to today. BA, Bronze Age; C, Modern and Contemporary period; CA, Copper Age; GI, Greenland Interstadial; Greenland., Greenlandian; GS, Greenland Stadial; IA, Iron Age; MA, Middle Ages; Mesolit., Mesolithic; Neolit., Neolithic; R, Roman Period. Greenland isotope stratigraphy of the Pleistocene adapted from Rasmussen *et al.* (2014). *Adapted from Scapozza (2023).*

Cadenazzo), and of varying thicknesses between 300 and 500 m of the bottom of Lake Maggiore, considering the sectors of greater depth and greater debris filling.

LIMNOLOGICAL FEATURES

Hydrological regime of tributaries

The drainage basin of Lake Maggiore is divided into 15 sub-basins, of which rivers Ticino (1616 km^2), Toce excluding Strona (1551 km^2), Maggia (927 km^2) and Tresa including Lake Lugano (754 km^2) are the four most important (their main hydrological data are reported in Tab. 4). These four sub-basins cover 73.5% of the total area. The regime of these four main tributaries is of a mixed type, with two annual maxima in May (and June for rivers Ticino and Toce) and November, a pronounced minimum from December to March and a second summer minimum (until early autumn), visible both in the values of the average monthly flows rates in the period 2008-2020 (Fig. 5, above) and in the values of the Pardé coefficient (PC_i; Fig. 5, below), defined as the ratio

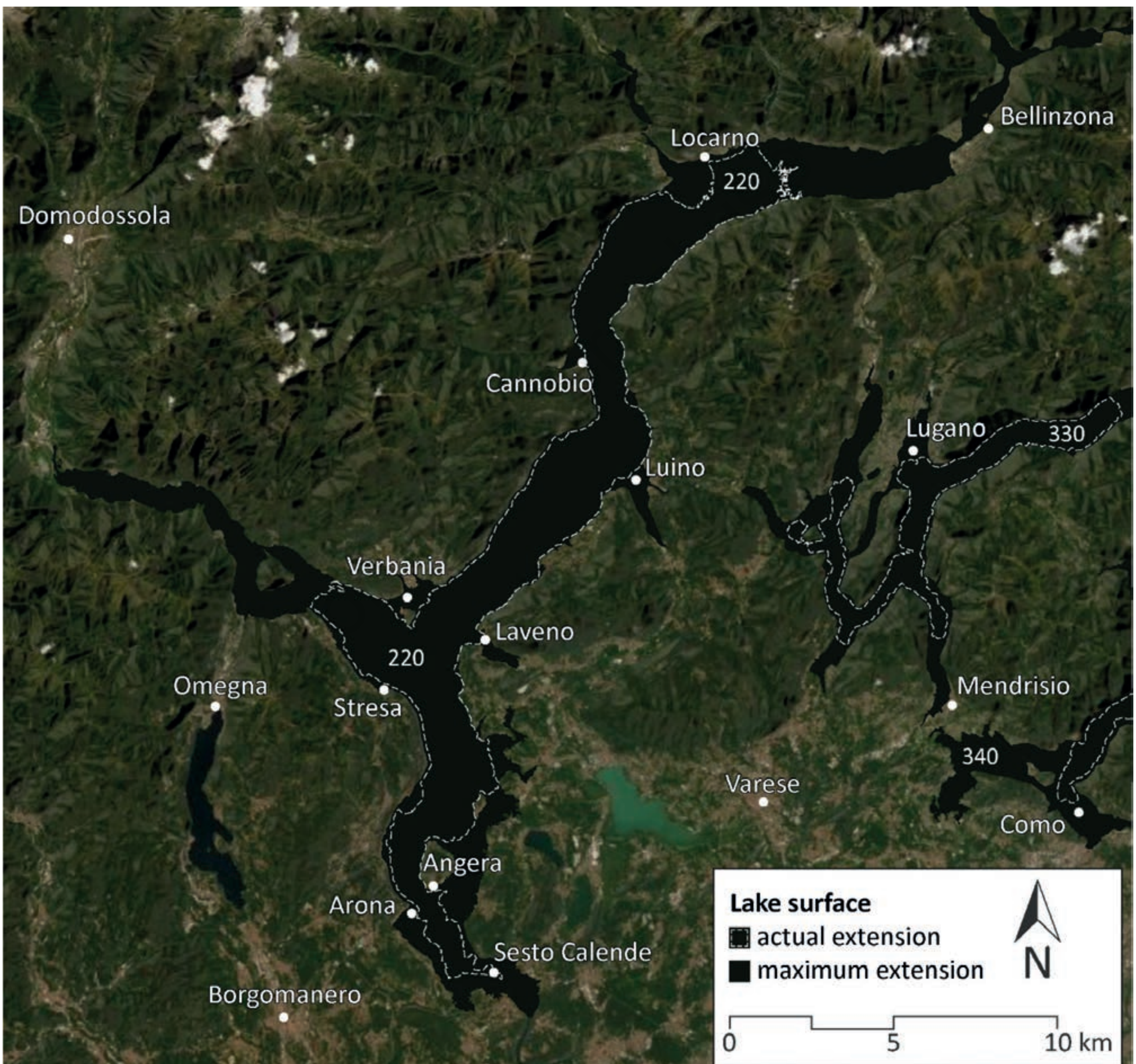

Fig. 4. Reconstruction of the maximum extension of lakes Maggiore, Lugano, and Como at the end of the deglaciation of the lake basins around 17.00 ka. *Aerial photograph: ArcGIS Online ©ESRI. Cartography and graphic elaboration: C. Scapozza.*

between the average monthly discharge and the mean annual discharge (Spreafico and Weingartner, 2005).

The spring (and early summer) maximum is mainly due to snowmelt (PC_i between 1.7 and 2.1), while the autumn maximum is exclusively of pluvial origin (PC_i between 1.1 and 1.8). Considering the greater amplitude of the peak flow in May-June than in November, the regime of rivers Ticino (factor 1.6) and Toce (factor 1.4) can be considered of nival-pluvial type, fed by snowmelt and rain. Conversely, for the river Tresa, the regime is of pluvial-nival type, as the amplitude of the autumn peak is almost as marked as the spring peak (factor 1.1). The Maggia river has a hybrid regime between pure nival-pluvial and pure pluvial-nival (factor 1.2 between spring and autumn).

The feeding regime of Lake Maggiore is highly dependent upon nival-pluvial regimes, supplied by snowmelt and rain. Moreover, the water supply from melting ice (glacial) is scarce, since glaciers cover only 0.2 to 0.4% of the Ticino, Maggia and Toce Rivers catchment areas and are absent in the Lake Lugano and Tresa river basin.

Hydrological regime of the lake

Lake Maggiore natural regulation

Lake Maggiore water level naturally tends to reflect that of precipitation and its state (rain or snow) and is expressed through a double cycle: winter and summer characterised by low water, and spring and autumn by high water. As a consequence, the riparian layer emerging during winter is a characteristic component of the lake landscape, as evidenced by some 19th century paintings or by artefacts calibrated at lower lake-levels such as the wash house still present and visible on the shore in Ascona during drought periods.

Spring periods are characterised by barely high-water levels caused by snowmelt and spring rains, whereas autumn periods showed high water levels due to the autumn storms (particularly in September and October). Flood peaks can reach very high levels, creating a natural oscillation between low and high-water levels of over 5.50 m. Several factors determine this natural behaviour of the lake, which is however close to the artificial one: the catchment area, about 30 times larger than the lake surface, the pre-Alpine and Alpine orography that creates a strong barrier against the atmospheric currents coming from the Mediterranean Sea, the high rainfall intensity with relative short times of occurrence and the narrowness of the outlet in Sesto Calende.

Lake floods (with thresholds exceeding 195 m asl; +2.35 m) occur on average every 19 months (Ciampittiello

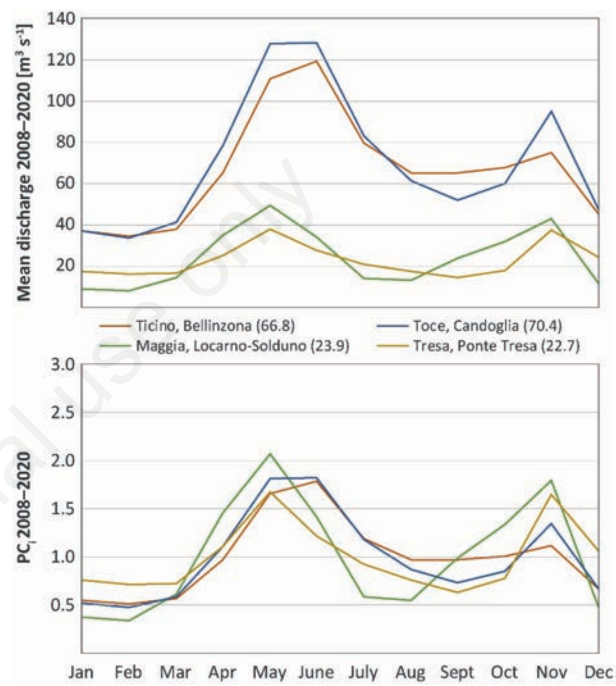

Fig. 5. Evolution of the average monthly discharge (above) and of the Pardé coefficient (PCi; below) for the period 2008–2020 for the four main tributaries of Lake Maggiore. In brackets: mean annual discharge. Ticino river in Bellinzona (coordinates WGS84: 46.19425, 9.00950; 224 m asl); Maggia river in Locarno-Solduno (46.16845, 8.77360; 201 m asl); Tresa river in Ponte Tresa (45.97200, 8.85240; 271 m asl), data property of the Swiss Federal Office for the Environment. Toce river in Candoglia (45.97465, 8.42135; 196 m asl), data property of ARPA Piemonte. *Data source: Osservatorio Ambientale della Svizzera Italiana (OASI), Repubblica e Cantone Ticino (https://www.oasi.ti.ch/web/dati/idrologia.html, accessed on May 22, 2023).*

Tab. 4. Main hydrological data of the four major tributaries of Lake Maggiore. Discharge in $m^{3\ s-1}$. *Source: Ticino, Maggia and Tresa rivers, Swiss Federal Office for the Environment; Toce river, ARPA Piedmont.*

River, station	Mean discharge	Mean discharge of the annual flood	Maximum discharge	Date of maximum discharge	Observation period
Ticino, Bellinzona	67.6	880	1500	25.09.1927	1914-2018
Maggia, Locarno-Solduno	22.8	1370	4500	07.08.1978	1970-2018
Toce, Candoglia	70.4*	–	2600	15.10.2000	1974-2020
Tresa, Ponte Tresa	23.5	122	255	27.11.2002	1901-2018

**Average 2008-2020.*

et al., 2023). The major floods exceeding the threshold of 196 m a.s.l. (+3.35 m) have occurred about thirty times from 1868 to today. The maximum was measured on October 4, 1868 (200.23 m asl; +7.58 m); followed by the event of October 17, 2000 (197.48 m asl; +4.83 m) (data source: https://www.hydrodaten.admin.ch/it/2022.html, accessed on May 12, 2023).

Given the short time of concentration, in the event of extensive and slow-passing atmospheric disturbances on the catchment area, an impressive quantity of water enters Lake Maggiore in a short time (see Tab. 4) causing a rapid increase in water level. Noteworthy is what was measured in October 2020, when the lake showed high lake-level increase from 193.12 m asl (+0.47 m) on October 2, to 195.42 m asl (+2.77 m) in 24 h (*i.e.*, a total rise of 2.30 m).

Low water corresponding to prolonged drought periods caused the lake-level retreat to the incile, corresponding to about 192.10 m a.s.l. (-0.55 m) (Zampaglione, 1993; historic minimum: 191.99 m asl; -0.66 m, measured on January 17, 1922). More decisive for the ecosystems, rather than the minimum peaks, is the duration of the low waters (or water shortage), which can last for several months. In 2003, during the mid-April early-November period, the lake remained below 193 m asl (+0.35 m) for 164 days.

Lake-level management

In 1943, the need to use the waters of the great lakes to have water available towards the less favourable periods, led to the construction of a dam at the Lake Maggiore outlet. This structure allows water to be stored during heavy rainfall (spring and autumn) or snowmelt periods (June). The accumulated water is then supplied during the irrigation periods to agriculture (spring and summer) and industrial users (mainly in autumn and winter) (Zampaglione, 1993).

Since 1943 an Italian-Swiss agreement has been in force, establishing the extremes within which the water level can be regulated (Tab. 1): thresholds of 193.65 m asl (+1.00 m) from March 15 to November 15, and of 194.15 m asl (+1.50 m) from November 15 to March 15. This corresponds to a volume of 315 million m^3, rising to 420 million m^3 in winter (data source: https://ticinoconsorzio. it/attivita/regolazione/, accessed on May 12, 2023). The average monthly lake-levels measured before and after the construction of the Miorina dam are shown in Fig. 6. The double peak cycle is therefore attenuated, with winter showing average water levels 1 m higher than the natural situation.

The structural typology of the Miorina dam does not allow adjustments during floods, so its influence on the flood peak remains significant only on the starting water level at the beginning of the rainfall event. In case of prolonged rainfall, forecasting can be done a few days before the event, but the leeway remains limited.

The most important hydrodynamic aspect in Lake Maggiore and, in general in the deep subalpine lakes, is the vertical mixing of the water at the end of the limnological winter (late February to early March), which ensures the oxygenation of the hypolimnic waters and the distribution of nutrients along the water column.

From late spring to autumn, the lake presents a stratification due to the differences in temperature and density between surface and deep water layers. Due to the great depth and the meteorological conditions of the region, the complete mixing of the waters does not occur every year. Lake Maggiore is indeed defined as holo-oligomictic because only during very cold and windy winters the mixing may be complete (Ambrosetti and Barbanti, 1999). The oxygenation of the deep layers is guaranteed, at least partially, by the supply of oxygen by the tributaries. The mixing depth at winter overturn normally reaches depths of 100-150 m (Ambrosetti and Barbanti, 1999). However, climate change is causing evident effects on the lake thermal and hydrodynamic features, with important consequences on the oxygen status (Fenocchi *et al*., 2018; Rogora *et al*., 2018).

ECOLOGICAL FEATURES

Trophic status and water quality

The water quality of Lake Maggiore is strongly related to the occurrence of anthropogenic activities in its watershed. The present trophic status of the lake is oligotrophic. However, since the 1970s, human pressures have triggered a eutrophication process. With the entry into operation of the wastewater treatment plants and the implementation of rules to control the dispersion of algal nutrients in the environment, the water quality of the tributaries and, consequently, of the lake basin, began to improve, reaching a situation practically corresponding to

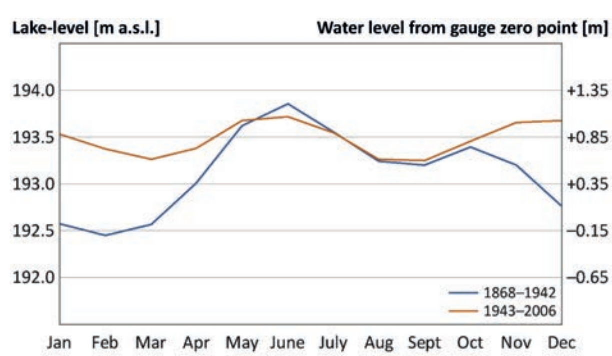

Fig. 6. Comparison of lake-level monthly averages for the periods before and after the construction of the Miorina dam in 1943. The lake-levels (in m asl) are indicated with the Swiss elevation, whereas water level (in m) is the difference with respect to the Sesto Calende gauge zero point (192.65 m asl).

the objective of the allowable load to recover and maintain oligotrophic conditions. In relation to the oligotrophication process of Lake Maggiore, which began in the 1980s, the annual average values of the overall biovolume of phytoplankton and of the chlorophyll-a concentrations are constantly decreasing (Ruggiu *et al*., 1998; Salmaso and Mosello, 2010).

Despite a strong interannual variability, mainly due to meteo-climatic drivers, the most recent data show a slight reversal in the trend of some trophic related variables. As an example, the phytoplankton community composition showed a reduction in some species typical of oligotrophic waters and an increase in meso-eutrophic species. However, the total annual volume of phytoplankton remains within the values of oligotrophic waters. According to total phosphorus concentrations measured at winter overturn, Lake Maggiore is presently in a situation of rather unstable equilibrium between oligotrophy and mesotrophy (Rogora *et al*., 2021).

The recently observed nutrient increase in the lake does not appear to be due to changes in nutrient inputs from the basin, but rather to climate warming and its effects on lake hydrodynamics (Rogora *et al*., 2021). Short and intense meteorological events (heavy rainfall), especially after important drought periods, and lake-level changes may play a role in promoting nutrient supply to the lake and development of algal blooms (Callieri *et al*., 2014; Morabito *et al*., 2018).

An example of a critical issue recently investigated is the presence of antibiotic resistance in Lake Maggiore, which proved to be a reservoir of antibiotic resistance genes (ARGs), but other investigations are needed to better understand the sources of ARGs and their persistence in lake waters (Di Cesare *et al*., 2015). Contaminants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbon (PAH) and polybrominated diphenyl ethers (PBDE) show a state of contamination within the regulatory limits, with the exception of mercury in some fish species (Guzzella *et al*., 2018). DDT (dichloro-diphenyl-trichloroethane) still plays a special role in the lake today (Binelli and Provini, 2003). This insecticide, which is very dangerous due to its persistence in the environment and its tendency to accumulate along food webs, was produced in Pieve Vergonte, along the Toce river, until 1997. The contaminated soils and deposits of the river near the old production plant, where DDT accumulated as it is poorly soluble in water, were mobilized at each river flood and spread into the lake (Kulbe *et al*., 2008). The concentrations of DDx (the set of metabolites derived from DDT) in recent years show continuous fluctuations, closely linked to meteorological events, which seem to indicate a non-equilibrium for these contaminants, although important remediation measures are underway in Pieve Vergonte.

Peri-lacustrine ecosystems

Geomorphological genesis

Numerous wetlands of high biodiversity value surround Lake Maggore, which occupy sectors of fluvio-deltaic plains of recent formation (several millennia) or are related to the geomorphological history of the lake.

The wetlands of fluvio-deltaic origin located in direct contact with the lake have developed on medium to fine deposits (mostly silty fine sand or sandy silt) due to calm fluvial depositions in the deltaic plain environment or on fine deposits (inorganic and organic silts) in the environments occupied by seasonal fluctuations of the lake-level typical of the deltaic front. Being located at elevations below 200 m asl (+7.35 m), their formation occurred over the last 5 millennia, with the sectors closest to the lake shore having formed since the Roman Period, as evidenced *e.g.*, by radiocarbon dating of 1-210 cal AD (Poz-31084 in Tab. 3) in a borehole at Castellaccio in Magadino di Sopra, Bolle di Magadino, 1.5 km from the lake (Scapozza, 2016).

The gradual lowering of the mean lake-level that occurred over the millennia (Fig. 3) also favoured the creation of riparian systems in perilacual depressions, which emerged with lake regression. These depressions were probably originated by glacial erosion/deposition along structural terraces of the bedrock. Lodgement till deposits, characterized by a fine matrix (fine sand and silt), and the same lacustrine/palustrine deposits of progressive infilling of the basins, once favoured the persistence of partially wet environments.

A different case applies to the Lagoni di Mercurago, whose lacustrine/palustrine depressions are located among the moraine ridges that were deposited on the right side of the Ticino-Toce paleo-glacier system. These are not the moraines of the LGM deposited between 25.0±0.9 and 19.9±0.7 ka (Kamleitner *et al*., 2022), but the deposits of the Penultimate Glacial Maximum (PGM), which occurred at around 140 ka (Colleoni *et al*., 2016). The partial sealing of the basin floor, which allowed the establishment of lakes and marshes, occurred due to the washing of the fine matrix of the glacial deposits by surface runoff, which selected the material by removing fine sand and silt and transporting it to the bottom of the depressions between the moraine ridges.

Fluvio-deltaic systems

Fluvio-deltaic systems are characterized both by the convergence of dynamically transported fluvial deposits on the lake waters and the combination of alluvial and marshland ecological processes. Where embankments have blocked or limited floodplain dynamics, ecological processes related to marsh successions have become predominant, particularly after the construction of the Miorina dam in 1943, which raised the average annual lake-level by at least 40 cm (Fig. 6).

The most important aspect is the potential of neoformation, which is the creation of new littoral or marsh environments with the delta progradation into the lake. These newly formed habitats will come into balance with the currently regulated lake conditions.

The Maggia delta is undoubtedly the most spectacular example of an active river-delta system for the Lake Maggiore (Fig. 7). But relative to its own size, the Ticino river in Switzerland, the Toce and the Tresa rivers in Italy also show this active dynamic, particularly where the new islets are protected and, consequently, can be preserved. The Verzasca river in Switzerland, on the other hand, is today a delta with no more neoformation, as the large hydroelectric dam immediately upstream (Diga della Verzasca) blocks the inflow of fluvial deposits necessary for its progradation.

On the so-called wet bank, where the water touches the banks most of the time, the vegetation zonation that develops is very close to the classical marshy one, but without the laminar belt as the violence of floods eradicates the floating leaf seedlings. The reedbed also forms very vigorous consortia, but without development of floating root rafts. In this case, if the force of the river flooding is added to the highly likely increase in the lake-level, the development of this type of floating habitats becomes almost impossible on the Lake Maggiore, even in marshy areas located far from the rivers.

The soils are still characterized by fluvial processes, with sandy, gravelly, and pebbly skeletal components, and no peat accumulation (Fig. 8, above). For this reason also, the connection with the lake aquifer is direct and determined by elevation alone.

The presence of pioneer environments, due to fluvial processes, enriches and diversifies the ecosystem, constantly reactivating the ecological succession, which is an excellent premise for long-term conservation.

Riparian systems

In riparian systems, characterized by marsh processes, the successional series is fully developed, from lamineto to wet forest of White Willow or Black Alder. In contact with the wet bank we find the same formations as in the lateral areas of the deltas. In the higher and outer parts, the accumulation of eutrophic peat combined with a very fine soil skeleton allows the formation of ground conditions that guarantee a soggy character of the formations, even in periods of medium to low water levels (Fig. 8, below). The link with the lake-level is thus no longer direct, as it is in deltaic systems, and the marshier vegetation formations seem to be able to move up the gradient inland.

Fig. 7. Delta front and prodelta of the Maggia river the May 19, 2021, with the creation of a new island (centre of the image) after the flood of October 2020. *Photo credit: N. Patocchi.*

Fig. 8. Upper panel: polyphasic coarse alluvial soil on the Ticino river delta (water table depth of several meters). Lower panel: hydromorphic gley and eutrophic peat soil at the Sabbie d'oro marsh (Brebbia: water table depth of 20 cm). *Photos credits: L. Giollo (upper panel), N. Patocchi (lower panel).*

These riparian systems are present in the southern part of the lake, with a more extensive development of the zonation around Angera (Bozza, Sabbie d'oro, Bruschera) and near Sesto Calende, or on the Piedmont shore as reedbed formations (Dormelletto).

Ephemeral systems

Strong natural variations in Lake Maggiore levels create ephemeral environments, both during floods and during periods of water withdrawal. Ecologically, these are real temporary ecosystems, which can only succeed in hosting a specific coenose if they are repeated over time with some frequency.

When they are important and extensive, lake overflows create aquatic environments where only a few hours earlier there was a marshy or terrestrial environment. This ecological niche is occupied by opportunistic species, which know how to colonize the new habitat quickly (this is the case, for example, with some aquatic beetles) or which use a form of resistance, developing as soon as water arrives. The latter is the case with the mosquito eggs of *Aedes vexans* and *Aedes sticticus*, which are deposited in the muddy soil as soon as the flood recedes and can wait in the ground for years for the next flood. For this reason, these mosquito species can give rise to true spikes in spring swarms, when the lake waters do not carry fry during floods and there are no other predatory antagonists, as the habitat was dry until a few moments earlier. It should be noted that the notorious “tiger mosquito” *Aedes albopictus*, an anthropophilic species, fortunately fails to colonize these natural marshes, remaining confined to the urbanized area.

During low water periods, when the waters recede and the lake-level drops, the riparian beds emerge into the air and become dry. The significance of this phenomenon depends, of course, on the morphology of the banks and is more important in delta systems, where bank sinking is gentler, at least in the delta front and in the upper part of the prodelta. The duration of emersion will allow or disallow the development, colonization, or even simply access to different species. The frequency of emersion over time will determine the development of true coenoses weakened by this ephemeral habitat.

These habitats are very rare throughout Europe, where natural environments with these characteristics are infrequent, even more when associated with lakes of significant size. This is why they should be regarded as precious pearls that sometimes adorn the banks of Lake Maggiore. They have been known for a long time, especially by botanists, because they could be a coveted source of observation for very rare and localized species. But they can also be interesting environments for the ornithologist to observe rare species of waders in their migratory period.

Unfortunately, since 1943, the regulation of the lake and the accumulation of the so-called "new waters" with the Miorina dam (Fig. 6) have resulted in the submersion, often continuous over several years, of these shallow beaches, which can no longer be observable in the form described by Jäggli (1922). The most valuable species have not observed since decades. However, several rare and valuable species still remain, growing and flourishing in the increasingly long drought periods with low lake-levels, such as in 2003 and 2022.

CHANGE OF THE ITALIAN/SWISS LEVEL MANAGEMENT AGREEMENT

Water is precious, even more with the increase in drought periods caused by global warming. The needs of higher water storage during rainy periods and its easier use during droughts were the topic for the establishment of the lake regulation technical table. The technical table is chaired by the General Secretary of the Po River Basin Authority and experts representing several institutions distributed throughout the territory have been invited to participate, such as: Lombardy and Piedmont Regions, Consorzio del Ticino, Department of Civil Protection, Ministry of Infrastructure and Transport, Ministry of Cultural Heritage and Activities and Tourism, Water Research Institute of the National Research Council (CNR-IRSA) of Verbania, Management body of the protected areas of Ticino and Lake Maggiore, Lombard Park of the Ticino Valley, Associated management of lake water state property, various provinces.

Downstream users have always been particularly interested in agricultural and industrial production, for which they ask to raise the upper limit of water storage threshold, while upstream users, worried about possible flooding of their lands and cities, tend to require a lowering. The current range of regulation is no longer considered satisfactory. As a consequence, new compromise proposals are being tested and planned (Soncini Sessa, 2004). A summer increase, between April and July, to +1.25 m (with possible peaks to +1.50 m) was experimentally tested between 2015 and 2020. The resolution 7/2021 of December 20, 2021, approved the proposal to continue the test on the summer regulation of Lake Maggiore water levels for the next five-year period (2022–2026). This resolution plans to raise the lake-level to +1.50 m all year round, with a potential further reduction of reeds and natural habitats and a subsequent loss of biodiversity.

The still existing biotopes and natural banks cover only slightly more than 7% of the total banks. The raising of the management threshold, in addition to the 1943 intervention, leads to a further shoreline retreat. In the natural reserves or parks, this corresponds to a net loss of marshy surface. Furthermore, the marsh gradient is shifted inland, with the loss of aquatic reeds and transformation of the marsh surfaces behind the shoreline. This loss could be compensated locally, where delta systems allow the formation of new environments (in-lake progradation), if adequately protected. Otherwise, it is a direct loss of protected surface where the conservation of biodiversity of riparian and marshy environments is no longer possible.

ACKNOWLEDGEMENTS

This work was supported by the INTERREG Italy-Switzerland project ParchiVerbanoTicino funded by the European Regional Development Fund (ERDF), ID: 481668. A special thanks is expressed for the revision of a previous version of the manuscript to Angela Boggero, Marzia Ciampittiello and Michela Rogora (National Research Council, Water Research Institute CNR-IRSA, Verbania Pallanza, Italy), as well as to Chantal Del Siro for proofreading the manuscript. We would particularly like to thank the Editor, Silvia Quadroni, as well as two anonymous reviewers for their comments that helped to improve the final version of the manuscript.

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