Reframing water management from the lake's perspective: lessons learnt on Lake Garda

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Lakes break the continuity of catchments, often decoupling upstream and downstream fluxes in terms of water quantity and quality. They host strong interactions between physical, geochemical, and ecological processes and human activities, often concealed by relatively long residence times. Hence, lakes constitute a formidable challenge for the sustainable management of water resources but also a fertile ground for high-impact engineering research and innovation. In this article, we present an overview of the work of the newly established Physical Limnology Laboratory of the University of Trento, focusing on the lessons learned from our research on Lake Garda.

Lake Garda, Italy

Lake Garda as a representative example of perialpine lakes

Over the last decades, large perialpine European lakes have been facing the risk of progressive deterioration in water quality due to increasing anthropogenic pressures[6]. Typically, these lakes store large water volumes, have long renewal times, and host delicate ecological equilibria. These factors make them extremely vulnerable to pollution and climate change, especially when located near densely populated and industrialised areas.

Lake Garda, in Northern Italy (Figure 1), exemplifies most features and complexities of large perialpine lakes. Located at 65 m a.s.l., with a surface area of 368 km^2 and a volume of 49 km^3, it is the largest Italian lake. It connects the Sarca River (main tributary) and the Mincio River (main outflow) catchments, as well as a few minor tributaries. Lake Garda combines two completely different morphologies: a north-western deep and narrow (maximum depth 350 m, average width 4 km) trunk nestled in the steep Garda Prealps; and a south-eastern shallower and round-shaped (maximum depth 80 m, average diameter 15 km) basin surrounded by moraine hills and flat plains.

Lakes as hotspots of multiple interest

Lake Garda attracts multiple and diverse socio-economic interests. Tourism is among the strongest economic assets for the area: it hosts about 25 million tourists per year, fostering the development of many lake-related services and recreational activities. Lake Garda is also a strategic water resource and supplies drinking water to multiple aqueducts and irrigation waters during the summer. The wastewater of most lakeside towns is processed into a large treatment plant and released downstream of the lake through a 170 km long conduit network, including an underwater 7 km long double pipeline crossing the lake at a point where the maximum depth is 242 m. The obsolescence of pipes and the sanitary sewer overflow discharging into the lake are a matter of concern for water quality.

Lake Garda is also subject to regulation for hydropower, flood protection, and water distribution. Two hydroelectric pumped-storage systems using Lake Garda as their lower reservoir are located in Riva del Garda (116 MW) and Gargnano (137 MW). Occasionally, during extreme flood events, a 10 km long artificial diversion tunnel named "Galleria Adige-Garda" discharges part of the Adige River waters into Lake Garda to prevent flooding of the downstream city of Verona. The Salionze Dam regulates the lake level at the outlet of the Mincio River, which feeds a watershed intensively exploited by agriculture. The jurisdiction over the lake is split between two separate Regions (Lombardia, Veneto) and the Autonomous Province of Trento, each applying different policies for the different parts of the lake. The plurality of stakeholders hinders lake-wide actions and complicates the various stages of research activity, from fundraising, monitoring and requesting authorisations, to data access.

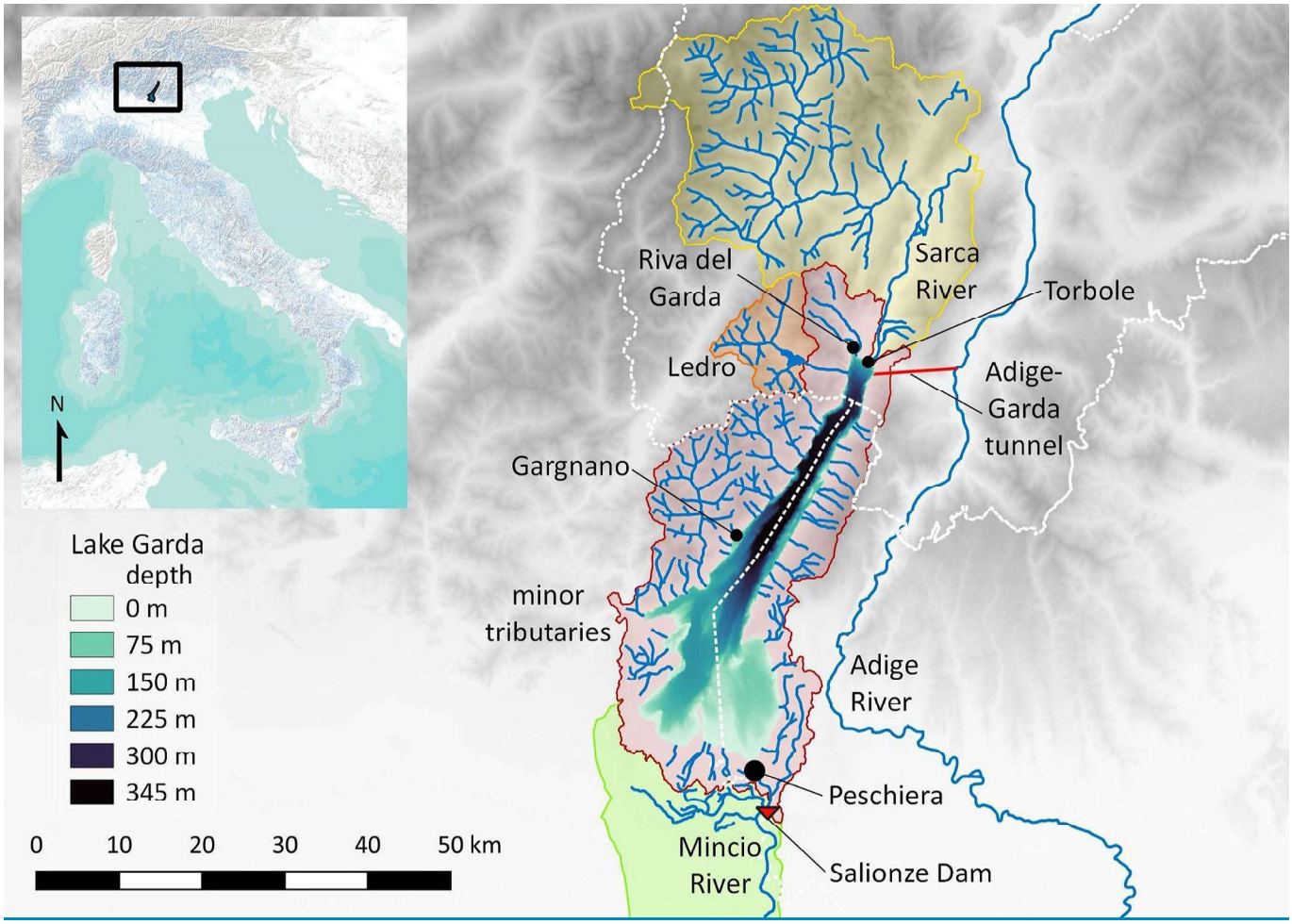

Figure 1 | Location of Lake Garda in Italy and focus on the Sarca-Garda-Mincio system with relevant sub-basins. The red triangle indicates the Salionze Dam, while the red line connecting the Adige River and Lake Garda outlines the Adige Garda tunnel.

Compared to other similar lakes in the world, the physical dynamics in Lake Garda used to be understudied, also because limnology in Italy has a long tradition as a subdiscipline of biological sciences while being generally less popular amongst engineers. Recent concerted efforts by the environmental engineering schools in Trento and Brescia have been trying to reverse this trend. To complement the substantial existing knowledge of ecological aspects of Lake Garda[6], we have directed our investigations on the quantitative aspects governing water quality, adopting a hybrid approach that combines hydrodynamic modelling, field activities, remote sensing, and data analysis.

The need to manage water quantity and quality at the same time

The unique water balance, transport and mixing processes of every lake are critical to its health and must be thoroughly studied and understood to enable effective management and protection strategies. In this respect, the simultaneous management of both water quantity and quality is crucial.

In terms of water quantity, the evolution of the Sarca-Garda-Mincio system has been reconstructed through a multi-decadal analysis of the water balance in the period 1928-2020[3]. The lake transitioned from a natural basin to a regulated one in the 1950s with the construction of the downstream Salionze Dam, initially designed for flood protection rather than water quality objectives. The analysis of the long-term trends suggests that the regulation determined an average increase of the water level of +0.08 m from 1951 to 2020, together with a 10% reduction of the lake outflow. The enactment of the Water Framework Directive in 2000 required a substantial redesign of the system to allow refined hydraulic manoeuvres such as a minimum vital flow or (from 2025) the ecological flow of the downstream Mincio River. Significant changes in local climate (including snow- and glacier-melt inputs) and land use affected the water balance in the last decades.

In terms of water quality, the health of deep lakes depends strongly on the frequency of deep mixing events (DMEs), allowing vertical redistribution of oxygen, nutrients and energy between well-oxygenated surface waters and nutrient-rich deep layers. The mixing regime of Lake Garda is oligomictic, i.e., long periods of incomplete mixing are interspersed with occasional complete overturns. The most intense DMEs in Lake Garda are buoyancy-driven (Figure 2a) and generally occur during harsh winters, when surface cooling drives the downwelling of cooler and denser surface waters towards the lake bottom. This generates convective mixing and lake overturning, which manifest as homogeneous temperature profiles (Figure 2b). DMEs can also be driven by strong and persistent along-lake winds generating the expected longitudinal overturning circulation (Figure 2c). However, they also trigger a less-expected (given the small

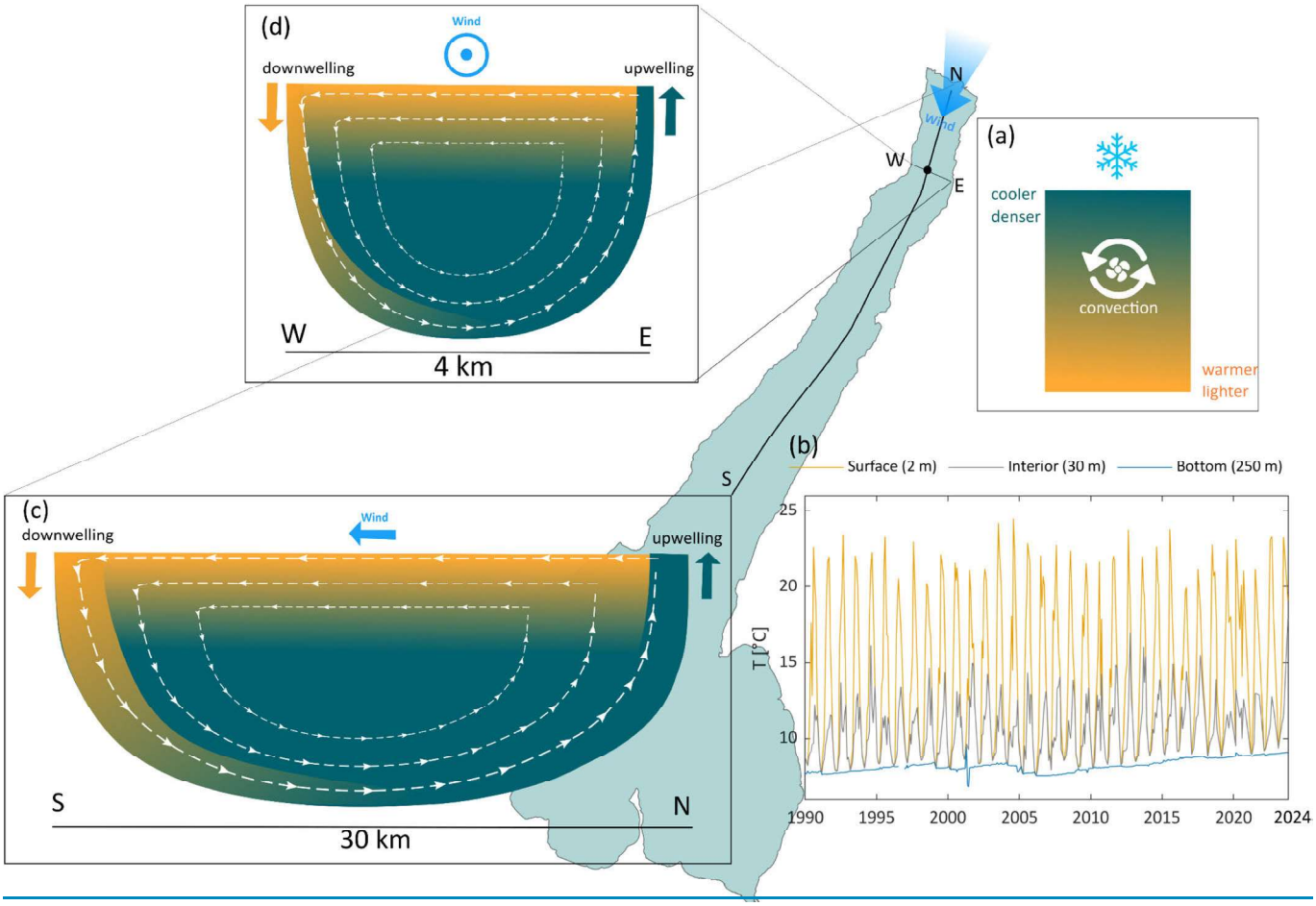

Figure 2 | Main mixing mechanisms in Lake Garda: a) buoyancy-driven convective mixing; b) historical records of water temperature in a monitoring point (black dot in the map); c) lake-wide circulation induced by wind along a longitudinal (S-N) section of the lake; d) secondary circulation along a cross-section W-E resulting from the interaction of wind-driven flow along the main axis and Coriolis acceleration.

lake width) lake-wide secondary circulation influenced by Coriolis acceleration (Figure 2d), forcing a downwelling along the shore at the right of the wind direction and an upwelling along the opposite shore[5]. Buoyancy-driven DMEs are usually more efficient than wind-driven ones and used to occur, on average, once every 6 years before 2006. Since then, no complete overturns have been observed in Lake Garda, as in many perialpine lakes, due to climate warming, which has led to warmer winters with more limited surface cooling and downwelling that would cause overturn[6]. Thus, from a climate change perspective, the relative importance of wind-induced DMEs may increase in the future. Wind-driven circulation also affects surface water quality patterns: secondary circulations drive lateral temperature and turbidity gradients along the northern trunk, and eddy-like structures are often generated in the southern, larger and shallower region, causing the entrainment of chlorophyll- and turbidity-rich waters from the coasts towards the pelagic areas, ultimately influencing the overall water quality and trophic status of the lake (Figure 4).

Managing risks and opportunities

Being a collector of many different interests and a strategic natural resource on several levels, Lake Garda is both a source of opportunities and risks. Despite the importance of the Adige-Garda diversion tunnel for flood protection, its activation often fuels the debate among local communities over its alleged role in transporting wood debris and turbid water into the lake[4] (Figure 3). Although these and similar controversies are often not based on scientific evidence, they raise important questions, such as: What is the input of nutrients, pollutants and biological matter through the diversion tunnel compared to that of the natural inflows? What is the contribution of sewage overflows to the total nutrient load? How do external inputs, including those from trailered boats, contribute to the spread of aquatic invasive species in the lake? How will the lake ecosystem be affected by ongoing climate change?

These questions are particularly relevant in view of the ongoing transformations driven by climate and land use changes, such as modifications of the thermal regime and alterations of the trophic status, observed in many deep perialpine lakes in the south of the Alps, including Lake Garda. These changes impact the taxonomic composition of lake phytoplankton including harmful toxigenic Cyanobacteria[6], or modify habitat suitability and extension for autochthonous and allochthonous aquatic communities (the latter introduced sometimes inadvertently by human activities). Alterations of the hydrological cycle can also cause more frequent and extreme water level fluctuations, e.g., the recent new historical minimum (summer 2023) and maximum (spring 2024) levels observed in Lake Garda. High lake levels potentially lead to a loss of coastal areas and ecotones, particularly in the presence of large wind waves during lake surges. Further research on water level regulation could identify opportunities for lake management optimisation.

Strategies for an integrated management

Thanks to a voluntary network of research institutes and local administrations in the lake area, Lake Garda is becoming a natural laboratory for innovative monitoring techniques, ranging from high-resolution sensors[5], in-situ instrumentation (**Aeronet:** aeronet.gsfc.nasa.gov, **Hypernet:** www.hypernets.eu, **LTER:** lternet.edu, **Aquatic Drones:** intcatch.eu, **Synthetic Aperture Radar products:** sarlakes.irea.cnr.it), and **citizen-science experiments**[1].

Among these tools, the three-dimensional hydrodynamic model of Lake Garda[2] provides real-time simulations and forecasts via the web platform **Alplakes:** www.alplakes.eawag.ch (Figure 4), which integrates the modelling of transport and mixing processes in the lake interior with key geophysical quantities at the lake surface measured by remote sensing. Such a tool supports a new pathway for novel guidelines on lake-side civil infrastructures such as waterworks and sewerage systems.

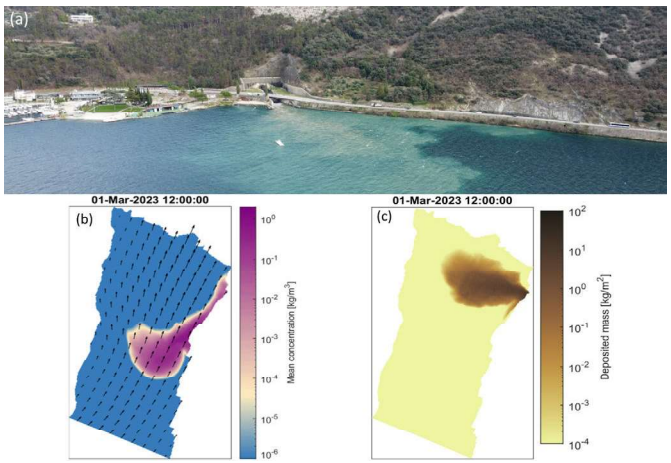

Figure 3 | (a) Opening of the Adige-Garda diversion tunnel on 28 February 2024 (drone view during the monitoring campaign; courtesy of Tulio Soto Parra); (b) Surface map of a passive tracer used as a proxy for the finest fractions of sediments, on 1 March 2023 at 12:00 UTC as modelled by the Delft3D model of the lake [2]; (c) Map of sediment deposition at the same time as in (b).

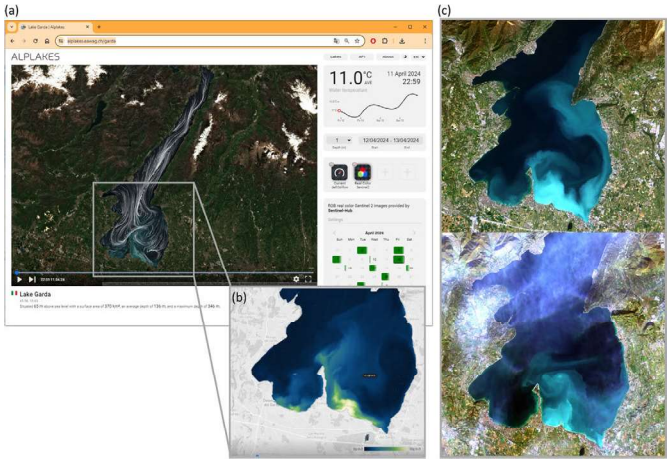

Figure 4 | (a) Screenshot from the operational platform Alplakes showing Lake Garda flow field on 11 April 2024. (b) Turbidity map available on the platform for 12 April 2024 showing a resuspension event in the southern region of the lake. (c) Examples of similar events as in (b) from Sentinel 2 true colour images on 11 April 2022 (top) and 15 November 2017 (bottom).

In the face of the increasing touristic function of Lake Garda, the adoption of citizen-science approaches in future model developments could further expand the platform's capabilities[1].

The variety of processes relevant to Lake Garda demonstrates the importance of multidisciplinary skills and competencies and the need for a thorough knowledge of physical processes to tackle the complexity of water management in perialpine deep lakes. Structured data acquisition, management, and sharing protocols are crucial in large lakes, where often conflicting interests are introduced by a plurality of entities, and where the range of spatial, temporal, and cultural scales is extremely wide. Such complexity is often disregarded and our experience with Lake Garda suggests that further research is still needed to inform conservation strategies for such important water resources. In this context, the added societal value brought by the activity of a multidisciplinary research centre would be significant, especially in light of the difficult choices that must be made to tackle the challenges of a changing climate.

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The Physical Limnology Laboratory (PhyLL) *https://sites.google.com/unitn.it/phyll)* of the University of Trento was established in 2023, building on the experience gained in the previous two decades of research activities in various lakes in Italy and in the world. PhyLL's researchers are mostly focused on physical processes, but they have developed tight connections with experts of other disciplines to obtain an integrated view of lakes's dynamics. The PhyLL's members involved in this article are: Marco Toffolon (head), associate professor of hydraulics; Marina Amadori, currently postdoc researcher at CNR-IREA, Italy; Sebastiano Piccolroaz, associate professor of hydraulics; Luca Adami, researcher; Marco Tubino, full professor of hydraulics; Giulio Dolcetti, postdoc researcher; and the Ph.D. students Matteo de Vincenzi, Gaia Donini, Francesca Hinegk, and Maria-Vittoria Tenci.