

Modelling physical and ecological processes in medium-to-large deep European perialpine lakes: a review

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ABSTRACT

In this paper we review a significant sample of the modelling studies carried out on medium-to-large deep European perialpine lakes (MLDEPLs). The reviewed bibliographic corpus was obtained querying Elsevier's Scopus® database with a tailored search string on 8 January 2021. Results were filtered, accepting only journal papers written in English dealing with natural lakes having surface area >10 km². A list of 75 works was obtained, published between 1986 and 2021. Most studies have been carried out on Swiss lakes (44 out of 75 papers), Lake Geneva being the most investigated environment. A significant positive correlation was found between lake surface area and volume and the number of dedicated papers, suggesting that scientific attention is higher for environments characterised by large dimensions and relevant socio-economic interests. Both the number of papers and their citation count have experienced an exponential growth in time, pointing to a rising interest in quantitative modelling applications, but also to the increasing availability and ease of use of numerical modelling tools. Among the 75 selected papers, 55 employ a hydrodynamic driver, used alone or coupled with an ecological module, while the remnant 20 works adopt an ecological-only model. Among the papers employing hydrodynamic models, the use of three-dimensional (3D) drivers is surprisingly slightly more frequent (28 papers) than that of one-dimensional (1D) ones (26 papers), with almost all 3D applications having been published in the last 2011–2020 decade (24 papers). This reflects the interest on the hydrodynamic processes leading to the observed spatial heterogeneities in the biochemical properties of the MLDEPLs. However, coupling of ecological modules with 3D hydrodynamic drivers, to directly simulate these phenomena, is still restricted (2 papers) compared to that of 1D hydrodynamic drivers (8 papers), due to calibration and computational difficulties, which could be strongly reduced by future research achievements. Nevertheless, 1D models allow performing long-term prognoses considering multiple climate change and watershed management scenarios, due to their much smaller computational burden. The largest group of works dealing with ecological-only models (6 papers) is dedicated to applications of phosphorus budget models, which can above all be used to forecast variations in lake productivity in response to changes in the availability of the limiting nutrient.

INTRODUCTION

Medium-to-large deep European perialpine lakes (MLDEPLs) are lacustrine environments of glacial origin located at the northern and southern foothills of the European Alps (Tolotti *et al.*, 2018). These lakes are important water sources, supporting different local economic sectors including tourism, fishing, agriculture and industry

(Salmaso *et al.*, 2019, 2020). They are among the most studied and well-known lentic ecosystems in the world and have been the subject of two recent papers that reviewed the main research activities carried out on them (Salmaso *et al.*, 2018, 2020). The MLDEPLs share similar morphometric features and climatic conditions and have been subjected to comparable anthropogenic stresses (Salmaso *et al.*, 2003; Gallina *et al.*, 2013). The economic development occurred after World War II caused generally increasing nutrient loadings with consequent trophic enrichment, worst conditions being reached around the mid-1980s (Salmaso and Mosello, 2010). The subsequent implementation of sewage systems and of wastewater treatment plants, combined with the abatement of phosphorus concentrations within detergents, allowed a reduction of phosphorus concentrations in their waters (Anneville *et al.*, 2005; Rogora *et al.*, 2018). This implied consistent re-oligotrophication of these ecosystems (Salmaso *et al.*, 2020). Despite the clear improvement in their trophic status, in recent years the MLDEPLs have been subjected to massive blooms of harmful cyanobacteria species (Bresciani *et al.*, 2018; Salmaso, 2019; Salmaso *et al.*, 2020), some of which (*e.g.* *Planktothrix rubescens*) have successfully adapted to current mesotrophic conditions (Anneville *et al.*, 2004). Climate change contributes to the intensification of such

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blooms (Paerl and Paul, 2012; Posch *et al.*, 2012; Gallina *et al.*, 2013; Yankova *et al.*, 2017), through the warming of surface water and the increasing stability of the water column that have long been observed (Ambrosetti and Barbanti, 1999; Livingstone, 2003). These physical phenomena have been related to both global warming and to the leading modes of interannual atmospheric variability in the Northern Hemisphere, the East Atlantic (EA) pattern and the North Atlantic Oscillation (NAO) (Livingstone, 2003; Salmaso *et al.*, 2014; Lepori and Roberts, 2015; Rogora *et al.*, 2018).

The past, present and future evolution of the MLDEPLs has been explained and forecasted in the last decades through models. In this paper, we review a thorough sample of papers dealing with this topic, to determine the current state-of-the-art including limitations, problems and research prospects.

Conceptually, lake models can be divided into two main categories: i) statistical models and ii) process-based models (Fornarelli *et al.*, 2013). Statistical models consist of inferential relations between the predictor variables and the variables of interest such as nutrient and chlorophyll-*a* (Chl-*a*) concentrations (Huszar *et al.*, 2006). A recent evolution of this approach lies in the use of artificial-intelligence methods (Jung *et al.*, 2010; García-Nieto *et al.*, 2018), employing machine-learning (ML) techniques (*e.g.*, support-vector-machine or tree-based models). Process-based numerical models instead simulate lake physical and biogeochemical processes through differential equations (Fornarelli *et al.*, 2013; Vinçon-Leite and Casenave, 2019), which should ensure better model performances (Trolle *et al.*, 2012; Vinçon-Leite and Casenave, 2019). Process-based models can deal with only lake physics (hydrodynamic models) or ecology (ecological models), or with both (coupled ecological-hydrodynamic models). In the latter case, the hydrodynamic model drives the mixing processes of the ecological variables (Trolle *et al.*, 2012).

One-dimensional (1D) hydrodynamic models represent the horizontally averaged physics of the lake water column, *i.e.* mainly water temperature dynamics, assuming that horizontal gradients are negligible. This is legitimate for deep stratified basins, in which horizontal mixing is much faster than vertical mixing (Perroud *et al.*, 2009; Rinke *et al.*, 2010). Two-dimensional (2D) models in the horizontal plane are restricted to shallow, vertically mixed basins (Fragoso *et al.*, 2008; Huang *et al.*, 2012; Fenocchi *et al.*, 2016), whereas 2D models in the vertical plane are suitable for elongated reservoirs in narrow valleys (Cole and Wells, 2013). Two-dimensional models, therefore, are not suitable for the MLDEPLs. Three-dimensional (3D) hydrodynamic models allow solving circulation processes with spatial and temporal continuity (Caramatti *et al.*, 2020). These models can capture the spatial variability of physical and biogeochemical processes, yet they require

relevant computational resources as well as extensive field measurements, since they must be calibrated and validated at multiple stations (Baracchini *et al.*, 2020).

Ecological-only models lack a dynamic physical description, being thus called zero-dimensional (0D) or box models (Nyholm, 1978). In those models, the lake water column is represented through a single layer, or, to mimic stratification, through 2-3 layers whose thickness and physical properties are fixed a priori (Dietzel and Reichert, 2012; Dietzel *et al.*, 2013). The most complete ecological models, being them isolated or coupled to a hydrodynamic driver, simulate the food chain originating and ending with nutrients after the decomposition of living organisms, reproducing the underlying dissolved oxygen (DO), carbon (C), nitrogen (N), phosphorus (P) and silica (SiO₂) biogeochemical cycles (Hipsey *et al.*, 2013).

METHODS

The bibliographic search was carried out using Elsevier's Scopus® database. The following query was employed, looking for specific words present in the title (TITLE), abstract (ABS) or keywords (KEY) of the database entries:

TITLE-ABS-KEY ((perialpine OR peri-alpine OR pre-alpine OR pre-alpine OR subalpine OR sub-alpine OR alpine OR Alps OR France OR French OR Switzerland OR Swiss OR Italy OR Italian OR Austria OR Austrian OR Germany OR German) AND (lake OR basin) AND (hydrodynamic OR hydrodynamics OR thermodynamic OR thermodynamics OR ecology OR ecological OR ecologic OR ecosystem) AND (model OR modelling))

To be made part of the reviewed bibliographic corpus, a paper had to include in the mentioned fields at least one word for each of the 4 word groups separated by the **AND** Boolean operator. Manual addition of further works was not performed. The query was submitted to Scopus® on 8 January 2021, returning 1883 entries. These were filtered to include only journal papers in English dealing with models of natural perialpine lakes having surface area >10 km². The restriction to journal papers in English was established to maximise the availability and intelligibility of the reviewed bibliographic corpus, books and national journals being generally more difficult to obtain from library services. This choice affects retrieval of older scientific production, as in the past it was common to publish research in books or in national journals (*e.g.*, the Italian “Memorie/Documenta dell’Istituto Italiano di Idrobiologia”, the German “Archiv für Hydrobiologie”, the Swiss “Schweizerische Zeitschrift für Hydrologie” or the French “La Houille Blanche”). The constraint to natural lakes having surface area >10 km² was introduced to consider

only models of basins with similar features, leaving out peculiar environments such as ponds or high-mountain reservoirs. In the end, 75 papers fulfilled all our requirements, being listed in Tab. 1.

We designed the research query to be: i) as inclusive as possible to minimise shortcomings, hence the many synonyms and alternatives separated by the OR Boolean operator; ii) precise enough to limit the subsequent man-

Tab. 1. Papers included in the reviewed bibliographic corpus, with indication of the studied lakes, the model types and the employed codes.

Paper	Lake	Model type	Employed code
Rossi <i>et al.</i> (1986)	Lugano	0D ecosystem	own
Salvadè <i>et al.</i> (1992)	Lugano	surface seiche / internal seiche / 3D	own / own / own
Panizzuti and Tartari (1995)	Orta	1D coupled	own
Vinçon-Leite <i>et al.</i> (1995)	Bourget	1D coupled	own
Joehnk and Umlauf (2001)	Ammer	1D coupled	own
Omlin <i>et al.</i> (2001a)	Zürich	0D ecosystem	own inside AQUASIM
Omlin <i>et al.</i> (2001b)	Zürich	0D ecosystem	own inside AQUASIM
Baudo (2002)	Orta	0D stochastic population growth	own
Enz <i>et al.</i> (2002)	Hallwil	0D fish population dynamics	own inside STELLA
Peeters <i>et al.</i> (2002)	Zürich	1D	SIMSTRAT
Buerge <i>et al.</i> (2003)	Zürich	0D caffeine cycle	own inside AQUASIM
Livingstone (2003)	Zürich	0D thermodynamic	own
Danis <i>et al.</i> (2004)	Ammer / Annecy	1D	own
Schauser <i>et al.</i> (2004)	Sempach	0D P budget	own
Schauser <i>et al.</i> (2006)	Sempach	0D P budget	own
Dueri <i>et al.</i> (2009)	Maggiore	1D coupled	COHERENS
Janjua and Gerdeaux (2009)	Annecy	0D ecosystem	own inside Ecopath with Ecosim
Mari <i>et al.</i> (2009)	Garda	3D coupled	own
Morillo <i>et al.</i> (2009)	Como	3D	ELCOM
Bryhn <i>et al.</i> (2010)	Bourget	0D P budget	own
Laborde <i>et al.</i> (2010)	Como	3D	ELCOM
Cuyppers <i>et al.</i> (2011)	Bourget	internal seiche	own
Saha <i>et al.</i> (2011)	Constance	3D	ELCOM
Ambrosetti <i>et al.</i> (2012)	Maggiore	3D	own
Dietzel and Reichert (2012)	Zürich	0D ecosystem	own inside AQUASIM
Laborde <i>et al.</i> (2012)	Como	3D	ELCOM
Weinberger and Vetter (2012)	Ammer	1D	DYRESM
Bonvin <i>et al.</i> (2013)	Geneva	3D coupled	Delft3D-own photolysis
Finger <i>et al.</i> (2013)	Lucerne	0D phytoplankton interpolation	own
Moschet <i>et al.</i> (2013)	Constance	0D micropollutant budget	MASAS
Razmi <i>et al.</i> (2013)	Geneva	3D	Delft3D
Vilhena <i>et al.</i> (2013)	Iseo	3D	ELCOM non-hydrostatic / ELCOM
Bueche and Vetter (2014a)	Ammer	1D	DYRESM
Bueche and Vetter (2014b)	Ammer	1D	DYRESM
Müller <i>et al.</i> (2014)	Hallwil / Sempach	0D P budget	Vollenweider (1975)
Pilotti <i>et al.</i> (2014a)	Iseo	1D	DYRESM
Pilotti <i>et al.</i> (2014b)	Iseo	3D	ELCOM
Razmi <i>et al.</i> (2014)	Geneva	3D	Delft3D
Vinçon-Leite <i>et al.</i> (2014)	Bourget	1D	own
Weinberger and Vetter (2014)	Ammer	1D	DYRESM
Bueche and Vetter (2015)	Ammer	1D	DYRESM
Straille <i>et al.</i> (2015)	Constance	1D	SIMSTRAT

To be continued on next page

ual selection of results. The first word group addresses the geographical location, thus including the word “perialpine” and its synonyms, “alpine” and “Alps” themselves, plus the names and the related adjectives of the countries that are crossed by the Alps and have lakes fulfilling our criteria (Slovenia and Liechtenstein are hence not included). The third word group refers to the types of models relevant for this review (*i.e.*, separate or coupled hydrodynamic and ecological models). Such specification is needed as the word “model” is often used in limnological papers to describe case studies whose analysis would

lead to conclusions which can be broadened to similar environments and for the application of statistical techniques to analyse field data.

REVIEW

Statistics of the bibliographic corpus

Tab. 2 lists the 34 natural European perialpine lakes having surface area $>10 \text{ km}^2$, with the number of papers dealing with each of them in the reviewed bibliographic

Tab. 1. Continued from previous page.

Paper	Lake	Model type	Employed code
Valerio <i>et al.</i> (2015)	Iseo	1D	DYRESM
Minella <i>et al.</i> (2016)	Garda / Geneva / Iseo	OD photochemistry	APEX
Bueche <i>et al.</i> (2017)	Ammer	1D	GLM
Fenocchi <i>et al.</i> (2017)	Maggiore	1D	GLM
Franchini <i>et al.</i> (2017)	Lugano	0D phytoplankton interpolation	own
Gallina <i>et al.</i> (2017)	Geneva	0D ML phytoplankton prediction	own
Kerimoglu <i>et al.</i> (2017)	Bourget	1D coupled	GOTM-FABM-own biogeochemical
Lepori and Roberts (2017)	Lugano	0D P budget	Nürnberg (1998)
Råman Vinnå <i>et al.</i> (2017)	Biel	1D / 3D	SIMSTRAT / Delft3D
Valerio <i>et al.</i> (2017)	Iseo	3D	ELCOM
Amadori <i>et al.</i> (2018)	Garda	3D	Delft3D
Fenocchi <i>et al.</i> (2018)	Maggiore	1D	GLM
Mirbach and Lang (2018)	Constance	3D	ELCOM
Scheu <i>et al.</i> (2018)	Maggiore	3D	SUNTANS
Schwefel <i>et al.</i> (2018)	Geneva	3D	Delft3D
Soullignac <i>et al.</i> (2018)	Geneva	3D	Delft3D
Dissanayake <i>et al.</i> (2019)	Constance	3D	ELCOM / Delft3D
Fenocchi <i>et al.</i> (2019)	Maggiore	1D coupled	GLM-AED2
Gaudard <i>et al.</i> (2019a)	Biel / Brienz / Constance / Geneva / Hallwil / Lucerne / Lugano / Maggiore / Murten / Neuchâtel / Sempach / Thun / Walen / Zug / Zürich	1D	SIMSTRAT
Gaudard <i>et al.</i> (2019b)	Constance / Zürich	1D	SIMSTRAT
Nouchi <i>et al.</i> (2019)	Geneva	3D	Delft3D
Piccolroaz <i>et al.</i> (2019)	Garda	3D	Delft3D
Ulloa <i>et al.</i> (2019)	Lucerne	3D	own
Amadori <i>et al.</i> (2020)	Garda	3D	Delft3D
Baracchini <i>et al.</i> (2020)	Geneva	3D	Delft3D
Bueche <i>et al.</i> (2020)	Ammer	1D	GLM
Caramatti <i>et al.</i> (2020)	Constance	3D	AEM3D
Copetti <i>et al.</i> (2020)	Como	3D	ELCOM
Derot <i>et al.</i> (2020)	Geneva	0D ML phytoplankton prediction	own
Fenocchi <i>et al.</i> (2020)	Maggiore	1D coupled	GLM-AED2
Lemaire <i>et al.</i> (2020)	Annecy	0D ecosystem	own inside Ecopath with Ecosim
Råman Vinnå <i>et al.</i> (2020)	Biel	3D	Delft3D
Krishna <i>et al.</i> (2021)	Geneva	1D coupled	GOTM-FABM-ERGOM

corpus, the lake country(ies), and the main morphometric properties. For multi-basin lakes (Lake Constance, Lake Lucerne, Lake Lugano, Lake Zürich), we do not distinguish between their individual basins for simplicity. A map of these perialpine lakes is given in Fig. 1, in which the basins included as case studies in the works of the bibliographic corpus are distinguished from the missing ones. Swiss lakes clearly received the widest attention, being the object of 44 out of 75 papers, with 60 case studies, Lake Geneva being the most investigated basin. All the Swiss lakes fulfilling our selection criteria are the object of at least one paper in-

side the bibliographic corpus. The great attention given to Swiss lakes should be attributed to the consolidated tradition of limnological research in Switzerland, motivated by the socio-economic relevance held by the many lakes present in such country, which has no access to the sea, thus channelling national aquatic science towards inland waters. Italian and French lakes are significantly represented in the bibliographic corpus. Among the Italian MLDEPLs, only the smallest Lake Idro and Lake Varese are not addressed. A clear West/East separation yet emerges from Fig. 1, as no German lakes apart from Lake Constance and Lake

Tab. 2. Natural European deep perialpine lakes with surface area >10 km² (MLDEPLs), with the number of papers dealing with each of them in the reviewed bibliographic corpus, the lake country(ies) and the main morphometric properties (obtained from the German version of Wikipedia).

Lake	Papers	Country	Area (km ²)	Volume (km ³)	Max. depth (m)
Geneva	12	Switzerland / France	581.3	89.9	310
Ammer	9	Germany	46.6	1.8	81
Constance	8	Germany / Switzerland / Austria	536.0	48.0	251
Maggiore	8	Italy / Switzerland	212.3	37.1	372
Zürich	8	Switzerland	90.1	3.9	136
Iseo	6	Italy	65.3	8.1	251
Bourget	5	France	44.5	3.6	145
Garda	5	Italy	370.0	49.3	346
Lugano	5	Switzerland / Italy	48.7	5.9	288
Como	4	Italy	146.0	22.5	425
Sempach	4	Switzerland	14.5	0.7	87
Annecey	3	France	27.6	1.1	82
Biel	3	Switzerland	39.8	1.2	74
Hallwil	3	Switzerland	10.3	0.2	47
Lucerne	3	Switzerland	113.6	11.8	214
Orta	2	Italy	18.2	1.3	143
Brienz	1	Switzerland	29.8	5.2	261
Murten	1	Switzerland	23.0	0.6	46
Neuchâtel	1	Switzerland	217.9	14.2	153
Thun	1	Switzerland	48.4	6.5	217
Walen	1	Switzerland	24.1	2.5	150
Zug	1	Switzerland	38.3	3.2	198
Atter	0	Austria	46.2	3.9	169
Chiem	0	Germany	79.9	2.0	73
Idro	0	Italy	11.0	0.6	122
Millstatt	0	Austria	13.3	1.2	141
Mond	0	Austria	13.8	0.5	68
Ossiach	0	Austria	10.8	0.2	53
Starnberg	0	Germany	56.4	3.0	128
Traun	0	Austria	24.4	2.3	191
Varese	0	Italy	15.0	0.2	26
Walchen	0	Germany	16.3	1.3	190
Wolfgang	0	Austria	12.8	0.7	114
Wörth	0	Austria	19.4	0.8	85

Ammer and no Austrian Lakes apart from Lake Constance are dealt within the bibliographic corpus, leaving out 3 and 6 MLDEPLs, respectively. A significant correlation was found between the number of papers dealing with each lake and both lake surface area ($r = 0.66$, $p < 0.001$) and volume ($r = 0.68$, $p < 0.001$), showing that larger lakes attract more research attention, likely due to their higher socio-economic relevance.

As of 8 January 2021, the 75 reviewed papers attained 1954 citations, *i.e.*, on average ~ 26 citations per article. The works with more than 100 citations are: Buerge *et al.* (2003) with 500 citations, Livingstone (2003) with 280 citations, Peeters *et al.* (2002) with 128 citations and Omlin *et al.* (2001a) with 121 citations. These were pub-

lished at the latest in 2003, suggesting that both quality and age of the papers contribute to the citation count. Considering the whole bibliographic corpus, both the number of published papers and of citations per year have experienced an exponential growth in time (Fig. 2). Such growth is even more striking with data aggregation: for 1986-2010 there are 4 papers and 10 citations, for the decade 2001-2010 there are 17 papers and 355 citations, while for the last 2011-2020 decade there are 53 papers and 1557 citations.

Not surprisingly, the most popular journal for the selected works is *Ecological Modelling* (13 papers) followed by the *Journal of Limnology and Water Resources Research* (5 papers each).



Fig. 1. Map of the 34 natural European deep perialpine lakes with surface area $> 10 \text{ km}^2$ (MLDEPLs): the lakes employed as case studies in the papers of the reviewed bibliographic corpus are filled in red, the neglected ones in blue (lake polygons were obtained from the HydroLAKES database (Messenger *et al.*, 2016), international boundaries were retrieved from the Eurostat geographical database, the orthophoto is courtesy of Google).

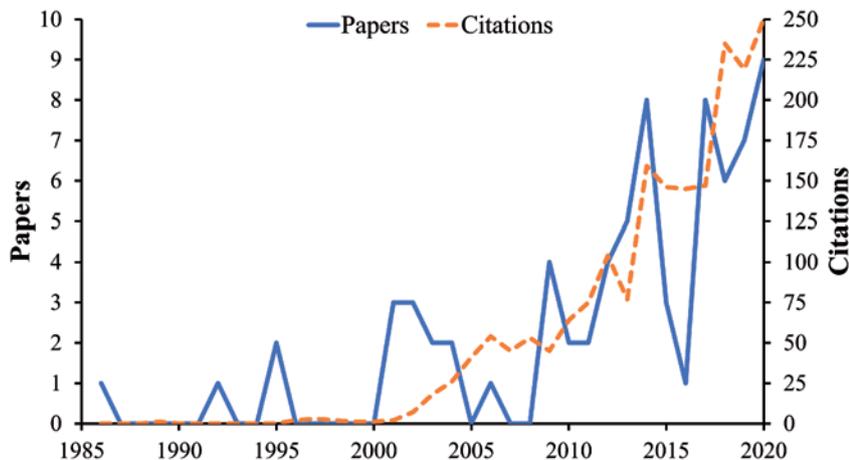


Fig. 2. Number of papers and citations per year for the reviewed bibliographic corpus.

1D models

The bibliographic corpus includes 26 papers with applications of 1D models, 18 employing a hydrodynamic-only setup and 8 adopting a coupled ecological-hydrodynamic layout.

Hydrodynamic models

Among 1D hydrodynamic model applications, 7 papers employed DYRESM (DYnamics REservoir Simulation Model; Imberger *et al.*, 1978; Imberger and Patterson, 1981). This model adopts a Lagrangian approach, with layers along the vertical joining and separating at each time step according to mixing and buoyancy forces. A mixed-layer approach is employed for turbulence closure.

Five of the papers adopting DYRESM deal with Lake Ammer. Weinberger and Vetter (2012) calibrated and validated the simulation of the vertical temperature profile in the lake for 2004–2007. Preliminary simulations of the 2041–2050 period were then performed, employing meteorological data from the regional climate model (RCM) REMO (Jacob *et al.*, 2007) for the IPCC emission scenario A1B. These climate-change simulations were developed in Weinberger and Vetter (2014), using REMO and DYRESM to estimate the heat content and the thermal stability of the water column of Lake Ammer for 2041–2050. In Bueche and Vetter (2015), results of the RCM WETTREG (Spekat *et al.*, 2010) were used to feed a DYRESM simulation of the 2042–2050 period, which was then compared to one of 2002–2010 to detect the impact of climate change. An extension of the stratified period and an increase of the metalimnion thickness in summer were identified. The relevance of groundwater inflows on the vertical thermal structure of Lake Ammer was studied in Bueche and Vetter (2014a). The inclusion in the model of a subsurface inflow based on available groundwater data effectively improved the reproduction of the observed water temperature profile. Bueche and Vetter (2014b) last analysed model performances under synthetic variations of the meteorological variables, concluding that DYRESM can reproduce long-term changes in water temperature due to climate change (see also Copetti *et al.*, 2013).

The two other papers employing DYRESM concern Lake Iseo. In Pilotti *et al.* (2014a), DYRESM was applied to verify the results obtained by a simple non-parametric model estimating water age distribution in stratified lakes. Valerio *et al.* (2015) instead used DYRESM to assess the impact of climate change on Lake Iseo. First, they calibrated the model over 2010 and validated it over 1995–2009, showing that the main thermal features were reproduced, except for the seasonal variations in the 50–150 m layer. Then, they ran a single continuous 2011–2050 simulation, forced by a climatic-hydrological model

(Barontini *et al.*, 2009), highlighting a differential warming rate (Livingstone, 2003) among the epilimnion ($0.02^{\circ}\text{C}/\text{year}$), the metalimnion ($0.015^{\circ}\text{C}/\text{year}$) and the hypolimnion ($0.009^{\circ}\text{C}/\text{year}$).

Four papers applied the General Lake Model (GLM; Hipsey *et al.*, 2019). GLM originated from DYRESM, employing most of its basic algorithms, yet it has since been improved and expanded. Two papers employing GLM deal with Lake Ammer. In Bueche *et al.* (2017), GLM v2.2.0 beta 1 was calibrated and validated, finding better results than those obtained with DYRESM in previous works for the same lake in the epilimnion and in the hypolimnion. The capabilities of reproducing ice cover and heatwave events were also tested. Bueche *et al.* (2020) presented the open-source R-based graphical user interface (GUI) for GLM glmGUI, which includes tools for Monte Carlo autocalibration and parameter sensitivity analysis, testing those features over Lake Ammer.

The other two GLM papers concern Lake Maggiore. Fenocchi *et al.* (2017) carried out a study aimed at evaluating the differences in the reproduction of the vertical thermal structure by two different model configurations, one with an enclosed-lake and fixed-level approximation, considering atmospheric heat fluxes only, and another one considering riverine throughflows and implementing the hydrological balance. Their results show that a simpler model neglecting throughflows can reproduce the relevant thermal evolution of a lake with significant inflow contributions as Lake Maggiore, at the cost of adopting an unrealistically low light extinction coefficient to mimic riverine heat penetration. The use of the more complete model led to more accurate predictions in the lower metalimnion and upper hypolimnion, where inflows intrude during most of the year. Fenocchi *et al.* (2018) employed GLM to estimate the evolution of the thermal structure of Lake Maggiore under the Swiss climate change scenarios CH2011 (CH2011, 2011) for the period 2016–2085. They adopted the enclosed-lake and fixed-level approximation presented in the previous study and performed for each CH2011 scenario of air temperature warming multiple simulations, having produced random daily series of input meteorological variables through the Vector-Autoregressive Weather Generator (VG) (Schlabing *et al.*, 2014). The statistical analysis of results over the manifold realisations for each scenario allowed removing the effects of the random occurrence of complete-mixing events on single simulations. The work concluded that Lake Maggiore would gradually pass from the current oligomictic regime to persistent thermal stratification during the 21st century, unless reduction of global greenhouse gas (GHG) emissions started immediately.

The 1D model SIMSTRAT (Goudsmit *et al.*, 2002) was used in 5 papers. SIMSTRAT computes vertical transport of heat by vertical turbulent diffusion over a

Eulerian array of layers, employing a k - ε turbulence closure (where k is the turbulence kinetic energy and ε is the dissipation rate of the turbulence kinetic energy). Peeters *et al.* (2002) calibrated and validated SIMSTRAT over a 50-year period for Lake Zürich, observing that the model could adequately reproduce the vertical thermal structure even under extreme conditions. Straile *et al.* (2015) modelled the warming of Lake Constance in the past 1979–2007 period, to investigate the sensitivity of the observed phenology between phytoplankton, *Daphnia galeata* and whitefish (*Coregonus suidteri*) to increasing air temperature. They concluded that asynchronous variations in phenology only occur if warming is seasonally heterogeneous and not constant throughout the year. The degree and the direction of such asynchrony depend on the specific seasonality of the warming, so that it is fundamental to have reliable warming predictions at a sub-seasonal resolution. Råman Vinnå *et al.* (2017) compared SIMSTRAT against the 3D model Delft3D (Lesser *et al.*, 2004), to study the effects of anthropogenic thermal pollution in Lake Biel due to cooling water from a nuclear power plant entering the inflowing River Aare. The effects of such thermal pollution source were also compared to those of ongoing climate change. A river intrusion algorithm, not originally present in SIMSTRAT, was introduced for the purpose, neglecting turbulent entrainment and thus providing a lower limit for the intrusion depth as the level of equal density. The outflowing volume was set equal to the inflowing one, as changes in lake level could not be simulated by the model. Results showed that SIMSTRAT reproduced well the observed temperatures in the epilimnion and hypolimnion, while errors were the largest in the metalimnion, due to baroclinic movements being unresolved by 1D models. When the model was run without the river intrusion, its performances decreased drastically, highlighting the relevance of inflows for a lake with such a short water residence time (58 days). Gaudard *et al.* (2019a) presented an open-access web platform to visualise the real-time continuous outputs of the model SIMSTRAT for 54 Swiss basins (among which there are 15 MLDEPLs), for use by environmental and water management agencies. The potential of high-frequency lake model data was illustrated, highlighting the different responses of Swiss lakes. Gaudard *et al.* (2019b) estimated the potentials for heat extraction and disposal for the main Swiss lakes, detailing the study for Upper Lake Constance and Lower Lake Zürich, for which SIMSTRAT was applied to investigate the effects on the lake thermal structure for different design and operating parameters. They concluded that safe use of lakes as heat sources or sinks led to a general energy availability which is an order of magnitude higher than the maximum regional demand of heating and cooling, potentially allowing a strong reduction in the use of fossil fuels in Switzerland.

Two further studies proposed an own 1D hydrodynamic model. Danis *et al.* (2004) implemented a model combining the eddy diffusivity model by Henderson-Sellers (1986), the ice model by Patterson and Hamblin (1988) and a water transparency model considering the optical effect of the seasonal algal cycle. They applied it to Lake Annecy and Lake Ammer, calibrating over past observations and performing prognostic continuous simulations for the 21st century. Results projected Lake Annecy to maintain rather regular full overturns, while Lake Ammer would be expected to become meromictic. Vinçon-Leite *et al.* (2014) instead used a 1D hydrodynamic model of Lake Bourget which had been already implemented in Vinçon-Leite (1991), employing for the eddy diffusivity the model by Simons (1981) in the surface mixed layer and a power function of the Brunt-Väisälä frequency below. The long-term thermal evolution of Lake Bourget in the period 1976–2008 was simulated, highlighting the importance of numerical models in filling the gaps between discrete water temperature observations.

We last mention in this paragraph the work by Livingstone (2003), in which a heat exchange model with a single layer was employed, *i.e.*, as a matter of fact, a 0D one-box thermodynamic model. Such model was applied to evaluate the warming of Lake Zürich in the period 1947–1998, focusing on the heterogeneous changes that have occurred in surface heat flux balance between night and day, altering the lake thermal structure.

Coupled ecological-hydrodynamic models

Among the papers dealing with 1D coupled ecological-hydrodynamic models, two works employed as physical driver the General Ocean Turbulence Model (GOTM), which solves the Reynolds-Averaged Navier-Stokes (RANS) equations with several available options for turbulence closure, coupled to a biogeochemical model through the Framework for Aquatic Biogeochemical Models (FABM) interface. Kerimoglu *et al.* (2017) studied Lake Bourget and linked GOTM-FABM to an own ecological model including 6 plankton groups identified through allometric relationships (*P. rubescens*, small and large phytoplankton, mixotrophs, herbivorous and carnivorous zooplankton). The simulation of the 2004–2010 period led to good estimates of water temperature and dissolved inorganic P concentration and intermediate ones of plankton succession. Krishna *et al.* (2021) interfaced GOTM-FABM with the biogeochemical model Ecological Regional Ocean Model (ERGOM; Neumann *et al.*, 2002), to understand the mechanisms leading to the large differences in primary production rates and nutrient concentrations observed in two consecutive years (2012–2013) on Lake Geneva. The simulation showed that the exceptionally cold winter in the first year triggered deep

convection in the lake, resulting in an almost complete overturn. This led to high algal biomass build-up in the productive season due to the abundance of dissolved inorganic P in the surface layer. On the contrary, in the following year strong P limitation was present, due to weak nutrient replenishment at the end of winter.

Two further studies on Lake Maggiore coupled GLM to the Aquatic EcoDynamics biogeochemical model (AED2; Hipsey *et al.*, 2013). In Fenocchi *et al.* (2019), the coupled model was calibrated and validated over an almost 17-year-long period, concentrating on the reproduction of deep-water chemistry and of phytoplankton biomass and succession. Even if some simplifications, leading to some limitations for long-term prognoses, were necessary to model such a complex basin, the resulting performances were comparable to those obtained in literature for smaller and shallower lakes over shorter periods. The coupled model was later applied in Fenocchi *et al.* (2020) to simulate the 2020-2085 physical, chemical and phytoplankton dynamics of Lake Maggiore, considering the CH2011 climate change scenarios and testing increases and decreases in nutrient loads. Results showed that diminishing mixing intensity would lead to hypolimnetic anoxia regardless of a reduction in nutrient input, unless global GHG emissions were immediately reduced. The total phytoplankton biomass instead strongly depends on nutrient input, so that it would weakly be affected by climate change, yet water warming would cause cyanobacteria to dominate over diatoms.

In a further work on Lake Maggiore by Dueri *et al.* (2009), the 1D version of the finite-difference hydrodynamic model COHERENS (COupled Hydrodynamical Ecological model for REgional Shelf seas; Luyten *et al.*, 1999) was coupled to a contaminant fate module (Jurado *et al.*, 2007) to simulate the water column concentrations of polychlorinated biphenyls (PCBs) in the Ispra Bay, considering exchanges with the atmosphere and the sediments.

Three other papers employed fully original 1D coupled ecological-hydrodynamic models. Vinçon-Leite *et al.* (1995) presented a coupled model of Lake Bourget adopting as state variables water temperature, dissolved mineral P, particulate algal P, particulate zooplankton P and DO. The coupled model is based on the implementation in Vinçon-Leite (1991), adopted also in Vinçon-Leite *et al.* (2014). It allowed reproducing the observed partial winter turnovers leading to low hypolimnetic DO levels, triggering the release of orthophosphate (PO_4) from sediments. Panizzuti and Tartari (1995) used a coupled hydrodynamic-chemical model to simulate the pH evolution in Lake Orta. The model, named ORTAMOD, is composed of two modules: i) the hydrodynamic-chemical driver ORTALAKE, derived from both the MINLAKE model (Minnesota Lake Water Quality Management Model; Riley and Stefan, 1988), and an early version of

the RESQUAL II model (Gulliver and Stefan, 1982); ii) the pH model pHORTA, based on the work by Chapra and Reckow (1983). ORTAMOD showed good results in the simulation of pH in Lake Orta in the late 1980s, before liming was performed to reduce acidification (Calderoni and Tartari, 2000). Joehnk and Umlauf (2001) last introduced a 1D model of Lake Ammer coupling a hydrodynamic driver implementing the k - ϵ turbulence closure and a DO model. The model yielded good results in reproducing the processes leading to the metalimnetic DO minimum, yet a strong influence of calibration parameters was found, limiting prognostic use.

3D models

Hydrodynamic models

Papers employing 3D models have seen an exceptional rise in the last 2011-2020 decade, 24 out of 28 of them having been published in this period. The most used models are Delft3D and ELCOM (now AEM3D), employed in 13 and 11 papers, respectively. Delft3D (Lesser *et al.*, 2004) is an open-source code by the Deltares Institute, while ELCOM/AEM3D (Estuary and Lake COmputer Model; Aquatic Ecosystem Model) has been developed by the University of Western Australia (Hodges *et al.*, 2000). Scheu *et al.* (2018) employed the open-source model SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator) by the Stanford University (Fringer *et al.*, 2006), which solves the RANS equations with the Boussinesq and hydrostatic approximations through a finite-volume approach. Four works instead applied an own solver of the Navier-Stokes equations (Salvadè *et al.*, 1992; Mari *et al.*, 2009; Ambrosetti *et al.*, 2012; Ulloa *et al.*, 2019).

The earliest application of 3D models in the bibliographic corpus is represented by Salvadè *et al.* (1992), who reported the pioneering 3D hydrodynamic modelling studies performed on Lake Lugano. Their first own implementation of the Spraggs and Street (1975) model simply solved the 3D hydrostatic RANS equations of mass and momentum conservation for water at constant density and constant wind stress forcing. However, their ensuing own implementation of the Oman (1982) model was already comparable with current 3D models, solving the 3D hydrostatic RANS equations of mass, momentum and energy conservation with the Boussinesq approximation for density, reproducing baroclinic motions. This latter model was initialised with an observed vertical temperature profile and boundary conditions were given by multiple in-lake stations. Significant limitations were the coarse grid, given the limited computational resources available at the time, the employed finite-difference scheme, leading to strong numerical diffusion, and the rigid lid approximation. In Salvadè *et al.* (1992), simplified models of surface

and internal seiches in Lake Lugano were also presented, solving the harmonic linear equations that characterise such motions (Hutter, 1984). The observed oscillations of both the thermocline and the halocline of the North basin were reproduced through a three-layer internal-wave model, while resonances between the three basins were found for surface seiches. The same harmonic equations for internal seiches were coupled in Cuypers *et al.* (2011) to a passive scalar transport equation, to interpret the observed vertical and horizontal distribution in Lake Bourget of *P. rubescens*, which proliferates in the metalimnion.

The most popular models Delft3D and ELCOM/AEM3D were compared in Dissanayake *et al.* (2019) for Upper Lake Constance against temperature profiles and current velocity and drifter measurements. Almost equivalent accuracy was found between them for the prediction of stratification, internal seiches and surface currents, Delft3D yet attaining slightly better performances. Differences between the models were smaller than those between models and observations, suggesting that the input meteorological parameters have more impact than the different numerical formulations. Regarding those, Delft3D and ELCOM/AEM3D solve in their standard layouts the RANS equations with the Boussinesq and hydrostatic approximations, Delft3D employing in its main hydrodynamic module Delft3D-FLOW a finite-difference approach with an Alternating Direction Implicit (ADI) scheme (Stelling and Duijnmeijer, 2003), while ELCOM/AEM3D adopts a semi-implicit hybrid finite-difference/finite-volume approach based on the TRIM (Tidal, Residual, Intertidal Mudflat) model by Casulli and Cheng (1992). The horizontal components of eddy viscosity and diffusion are parameterised in both models, strongly depending on the mesh resolution, while more accurate closures are used along the vertical. ELCOM/AEM3D uses a mixed-layer approach applied to each vertical stack of cells, derived from the one employed in the 1D DYRESM and GLM models. In Delft3D it is instead possible to choose between fixed vertical eddy viscosity and diffusion values, an algebraic zero-equation model, a k - L one-equation model and a k - ϵ two-equation model, the last most advanced option being used in all the reviewed applications.

Automatic calibration techniques have been successfully employed for the application of Delft3D to Lake Geneva in Baracchini *et al.* (2020), being supported by multi-site temperature profiles and current velocity measurements. However, compromises were made to calibrate water temperature and current velocity independently, simplifying the procedure.

A relevant problem of 3D model applications is the need for spatially distributed boundary conditions. Among input meteorological variables, wind displays the most definite horizontal patchiness and needs the most spatially

and temporally accurate description. In fact, wind inhomogeneities determine the layout of surface currents and of internal waves (Råman Vinnå *et al.*, 2017; Valerio *et al.*, 2017; Amadori *et al.*, 2018). This is especially true for the MLDEPLs, which are surrounded by mountains, leading to strong wind spatial patchiness that adds up to the daily alternating patterns. As single-site measurements are suitable only for small basins, furthermore tending to underestimate on-lake wind stress if done on land (Valerio *et al.*, 2017), and as networks of in-lake wind stations to build spatially interpolated fields have been successfully operated up to now only for limited time inside research projects, as done for few years on Lake Como (Morillo *et al.*, 2009; Laborde *et al.*, 2010, 2012; Copetti *et al.*, 2020) and Lake Iseo (Vilhena *et al.*, 2013; Valerio *et al.*, 2017), the most solid solution to solve wind inhomogeneities are atmospheric models. Works on Swiss lakes have employed the hourly reanalysis data from the MeteoSwiss atmospheric model COSMO (Consortium for Small-Scale Modeling; www.cosmo-model.org), both through its older version COSMO-2 (Bonvin *et al.*, 2013; Razmi *et al.*, 2013, 2014; Råman Vinnå *et al.*, 2017, 2020; Soullignac *et al.*, 2018; Dissanayake *et al.*, 2019; Nouchi *et al.*, 2019; Baracchini *et al.*, 2020; Caramatti *et al.*, 2020) and through the new one COSMO-1 (Baracchini *et al.*, 2020; Caramatti *et al.*, 2020). While COSMO-2 has 2.2 km resolution and data can be retrieved since 2008, COSMO-1 has 1.1 km resolution, data being available from 2016 onwards. These reanalysis products are obtained initialising COSMO every hour with variable fields obtained combining the results from the previous model run with observations (Caramatti *et al.*, 2020). Recent works on Lake Garda (Amadori *et al.*, 2018, 2020; Piccolroaz *et al.*, 2019) and on Lake Iseo (Valerio *et al.*, 2017) instead produced their own distributed meteorological data through the model WRF (Weather Research and Forecasting; Skamarock and Klemp, 2008). This allowed tailoring meteorological data at higher resolutions than COSMO, both in space (0.25 km resolution in Valerio *et al.*, 2017) and time (15 min resolution in Amadori *et al.*, 2018, 2020). Valerio *et al.* (2017) compared the representation of the internal wave field given by ELCOM simulations forced with meteorological data produced with WRF against those obtained with COSMO-2 data provided by the Regional Environmental Protection Agency of Emilia-Romagna (ARPAE). They found that the 2.2 km resolution of the COSMO-2 data leads to an underestimation of oscillatory motions for a lake of the size of Lake Iseo (65.3 km²; Tab. 2) surrounded by complex orography. However, use of WRF requires higher computational resources than the 3D hydrodynamic model, in addition to expertise in computational atmospheric physics to be properly set up.

In all the reviewed papers dealing with 3D models, the initial conditions were defined setting a single surveyed

vertical temperature profile throughout the lake volume and assuming water-at-rest conditions for current velocities. A spin-up period is hence required for internal waves and surface currents to develop in the model, spanning from 2 days (Valerio *et al.*, 2017; Amadori *et al.*, 2018; Piccolroaz *et al.*, 2019) to 25 days (Razmi *et al.*, 2013, 2014). Model spin-up protracts computational times with a dummy early part of the simulation and introduces some approximation, as slow hypolimnetic currents and internal waves in deep lakes have components which result from past motions over time scales longer than the spin-up period. However, appointment of initial conditions in 3D models cannot be sensibly improved, apart from using multiple simultaneous observed vertical temperature profiles to start from an already-deformed thermocline, such measurements yet hardly ever being available.

Distributed data are also needed for the calibration and validation of 3D models, as ordinary lake monitoring performed by periodic sampling at single or few sites per lake is not enough to assess spatial and small-scale temporal variations. As operating networks of in-lake monitoring stations is still problematic, data inferred from satellite images would strongly be beneficial (Soulignac *et al.*, 2018; Nouchi *et al.*, 2019; Baracchini *et al.*, 2020), providing maps of variables such as surface temperature, turbidity and Chl-*a* for a whole lake at intervals of few days. Yet, winter fog and clouds may be an operative problem for some perialpine lakes (Caramatti *et al.*, 2020). Satellite images can also be used together with hydrodynamic models to investigate on the inference of hydrodynamics on biochemical processes, this solution being less demanding than implementing a 3D coupled ecological-hydrodynamic model. On this subject, Soulignac *et al.* (2018) employed Delft3D to understand the hydrodynamic mechanisms leading to the spatial and temporal patchiness of phytoplankton in Lake Geneva observed from satellite images. Nouchi *et al.* (2019) instead combined Delft3D simulations with remote-sensed images and field samples to investigate on whiting events taking place in Lake Geneva, proving that calcite (CaCO₃) precipitation was indeed the cause and finding that the inflowing River Rhône provided the suspended sediments that trigger the process.

Still on the use of indirect field data to support 3D hydrodynamic modelling, Scheu *et al.* (2018) used sediment traps and cores to aid simulations performed with SUNTANS aimed at determining the paths of suspended sediments released by River Toce into Lake Maggiore. A similar approach combining data from traps and cores with Delft3D simulations was followed by Råman Vinnå *et al.* (2020), to identify areas prone to subaquatic landslides in Lake Biel due to the intrusion of sediment-laden River Aare. Underflow dynamics of sediment-laden plumes were also studied for the intrusion of River Rhine

into Upper Lake Constance by Mirbach and Lang (2018), who aimed through ELCOM simulations at determining the influence of plunging riverine water and entrained epilimnetic water on deep-water renewal.

Investigations on lake hydrodynamics through 3D modelling can also benefit from information obtained from public interviews to experienced lake users, *i.e.*, through a citizen science approach. Local knowledge can be used both to validate models, especially as regards surface currents, which would otherwise require extensive field measurements, and to discover specific phenomena to analyse through numerical simulations. In Laborde *et al.* (2012), numerical modelling confirmed knowledge on the surface currents and internal waves of Lake Como gained from local fishermen, their nets being ordinarily displaced by these processes. Amadori *et al.* (2020) extended the interviews to recreational lake users, ferry boat drivers, firefighters and officers of the local environmental protection agency to get a picture of surface currents in Lake Garda. Caramatti *et al.* (2020) used data from newspapers, blogs and social media to supplement governmental information on ice cover in Lower Lake Constance, to validate the results on the reproduction of its annual development obtained from simulations with AEM3D integrated by the Oveysy *et al.* (2012) ice model.

In the comparison between 1D SIMSTRAT and 3D Delft 3D performed in Råman Vinnå *et al.* (2017) on Lake Biel, it was found that the system-wide effects of thermal pollution from River Aare on the vertical thermal structure were identified by both models. However, the extreme local epilimnetic temperature variations, which are needed to estimate the risks for the biota, were identifiable only with Delft3D, which also performed much better in the metalimnion, as it solves the movements of the thermocline. The 3D model further allowed following the path of River Aare inside Lake Biel from the inlet to the outlet, disentangling its interactions with lake circulations and thermal stratification.

Three-dimensional models allowed understanding the relevance of geostrophic effects for the elongated Italian MLDEPLs Lake Maggiore, Lake Iseo, Lake Como and Lake Garda. Deviations in the paths of the plumes of the tributaries were highlighted on Lake Maggiore by Ambrosetti *et al.* (2012), who simulated through an own 3D solver the paths of Lagrangian markers to infer the residence time of lake water, and by Scheu *et al.* (2018). Pilotti *et al.* (2014b) employed a rotating physical model of the northern portion of Lake Iseo to study the deflection operated by the Coriolis force on the entrance of the two main tributaries, River Oglio and the Canale Industriale. The results of the scale model were supported by both 3D simulations with ELCOM and field data. For Lake Como, numerical ELCOM investigations supported by field measurements in Laborde *et al.* (2010) and Copetti *et al.*

(2020) stressed how geostrophic effects deviate the clean-water plumes of the main northern inflows River Adda and River Mera towards the western shore, driving them into the polluted southwestern Como arm. Such beneficial water exchange is further empowered by the main V1H1 and V2H1 internal wave modes, which displace water between the northern and southwestern arms (Guyennon *et al.*, 2014), thus alleviating the nutrient and Chl-*a* gradients in the lake. The support of downward-pointing impellers to these natural mitigation processes occurring in Lake Como was explored in Morillo *et al.* (2009), in which ELCOM numerical simulations were validated through field dye experiments on a pilot impeller. Amadori *et al.* (2018) and especially Piccolroaz *et al.* (2019) underlined through Delft3D simulations supported by field measurements how planetary rotation drives secondary currents in the narrow, deep and steep northern basin of Lake Garda under winter conditions with Föhn winds aligned with the lake structure. These currents make warmer surface water plunge downwards at the western shore, being replaced at the eastern shore by upwelled colder deep water, thus providing deep ventilation.

As a last remark, the computationally efficient hydrostatic approximation, which is suitable for the typical slow vertical motions of lakes and the commonly employed coarse grids (Dissanayake *et al.*, 2019), is used in all the reviewed applications of 3D models, except for two works in which non-hydrostatic effects are explicitly addressed. Vilhena *et al.* (2013) compared the hydrostatic and non-hydrostatic (Wadzuk and Hodges, 2009) versions of ELCOM against field observations for Lake Iseo, focusing on non-linear internal waves. They found out that after storm events a relevant amount of lake energy is moved from basin-scale low-frequency linear internal waves to small-scale high-frequency non-linear ones. The dissipation processes of these non-linear waves are intrinsically non-hydrostatic and are balanced by numerical diffusion in hydrostatic models. In Ulloa *et al.* (2019), the RANS simplification adopted in all the other 3D papers was removed together with the hydrostatic approximation, performing a numerical experiment with an own Large Eddy Simulation (LES) non-hydrostatic solver on an ideal trapezoidal prismatic basin shaped after the Lake Alpnach basin of Lake Lucerne. Such simplified LES model allowed gaining an insight on Benthic Boundary Layer (BBL) currents not possible with RANS models. In fact, the RANS scheme fails at small scales, especially near the bottom, as the logarithmic wall law assumed in RANS models does not hold for baroclinic motions. Three-dimensional RANS models should further include modified turbulence models to account for the effects of stratification on the turbulence field, as done by SUNTANS, in which the Canuto-A stability function (Canuto *et al.*, 2001) is used

to parameterise the effects of stratification on vertical mixing in the Mellor-Yamada level 2.5 turbulence model (MY2.5; Mellor and Yamada, 1982) used to compute vertical eddy viscosity and diffusivity, horizontal components being parameterised (Scheu *et al.*, 2018). In LES, energetically relevant turbulence is directly solved, thus including the effects of stratification.

Coupled ecological-hydrodynamic models

Only 2 works among the 28 papers dealing with 3D models employ coupled ecological-hydrodynamic models. In both cases, the hydrodynamic drivers are not coupled to complete biogeochemical modules reproducing nutrient cycles aimed at ecosystem modelling, as common in 1D applications. In Mari *et al.* (2009), an own hydrodynamic model based on a volume-conservative finite-element approach, solving the hydrostatic Boussinesq RANS equations, was coupled to a population dynamics model without any chemical and biological background, to reproduce Lagrangian larval transport and sessile adult-stage reproduction of an ideal species in Lake Garda. In Bonvin *et al.* (2013), the Delft3D model of Lake Geneva developed in Razmi *et al.* (2013, 2014), there used to assess the hydrodynamics and residence time in the Vidy Bay under different conditions, was coupled with an own photolysis model. The study aimed at assessing micropollutant contamination risk for the local drinking water intake from a wastewater outfall (see Saha *et al.* (2011) for a work over the same subject in Upper Lake Constance, employing hydrodynamic ELCOM simulations; see also Schwefel *et al.* (2018), in which the Razmi *et al.* (2013, 2014) Delft3D hydrodynamic model of Lake Geneva was applied to infer the representativeness of the hydrodynamic conditions experienced during a field campaign).

0D ecological-only models

Twenty papers inside the bibliographic corpus adopted 0D ecological-only models. Phosphorus budget models are the most represented, with 6 works. Rossi *et al.* (1986) applied a model with three vertical box interactive layers to a bay of Lake Lugano. The description of the P cycle included dissolved inorganic, dissolved and particulate organic P and their transformation into the inorganic dissolved form. The model was used to evaluate the mean P residence time in the lake compartments and the total phosphorus (TP) turnover time in the ecosystem, in addition to estimate the P abatement in the lake in response to input load reductions. Schauser *et al.* (2004) presented the SPIEL (Sedimentary Phosphorus In Eutrophic Lakes) model, aiming at simulating the diagenesis of P within the sediments of eutrophic lakes. SPIEL is structured in modules, in-lake restoration interventions such as oxidation with DO or nitrate, precipitation with iron or aluminium,

sediment capping and hypolimnetic withdrawal being reproducible by activating a specific module for each of them. The model was calibrated and validated for Lake Sempach, for which a sensitivity analysis of SPIEL was later presented in Schauer *et al.* (2006). Bryhn *et al.* (2010) developed and tested the dynamic model Mero-LakeMab on Lake Bourget, with the purposes of reconstructing the P loading history and forecasting TP concentrations under different climatic and hydrological scenarios. Simulations suggested that: (1) TP load decreased by about 88% between the early 1980s and the late 1990s; (2) the effects of future temperature warming on the yearly mean TP concentrations would be small compared to the effects of changes in the TP load; (3) future decrease in the lake inflow discharge would not affect TP concentrations markedly. Müller *et al.* (2014) examined data from the monitoring of 4 eutrophic Swiss lakes (including the MLDEPLs Lake Hallwil and Lake Sempach) which have undergone re-oligotrophication in the last 25 years, revealing that both net sedimentation rates and export rates of P increased as the in-lake concentrations decreased. These findings highlighted that the P concentration in eutrophic lakes could in some cases decrease more than linearly with a reduction in external load, *i.e.*, faster than predicted by the applied traditional Vollenweider (1975) eutrophic-state-based model. Lepori and Roberts (2017) used a model derived from Nürnberg (1998) and investigated how reductions in external P load triggered a decline in Lake Lugano P and Chl-*a* concentrations. During the 1983-2014 study period, nutrient management within the watershed approximately halved external P load, yet the responses of in-lake P and Chl-*a* concentrations also reflected variations in internal load and food-web structure.

Omlin *et al.* (2001a, 2001b) introduced the process-based model BELAMO (Biogeochemical and Ecological LAke MOdel), developed for Lake Zürich and implemented inside the AQUASIM framework (Reichert, 1994). In the first work, a preliminary sensitivity analysis on model parameter identification was performed. Plankton growth parameters were found to be the most difficult to be properly identified, while those linked to the dynamics of dissolved chemical variables could be much more easily defined. In Omlin *et al.* (2001b), the structure of BELAMO is first described. The model calculates horizontally averaged substance and organism concentrations along the stratified water column, these being shaped by a parameterised vertical mixing, making use of fixed vertical diffusion coefficients. Sedimentation, inflows, outflows and biogeochemical processes at the sediment-water interface are included. The chemical module reproduces the DO, P and N cycles, whereas the biological one includes the dominant species *P. rubescens*, a generic phytoplankton group and an herbivore zooplankton group. The calibrated model was able to reproduce

key features of nutrient and DO vertical profiles and of phytoplankton-zooplankton interactions in Lake Zürich over several years, but not to predict occasional blooms. Dietzel and Reichert (2012) further used BELAMO as case-model to study the generation and propagation of systematic errors in complex deterministic models, using the long-term input data from Lake Zürich.

Two other works deal with statistical approaches to simulate and predict phytoplankton dynamics, focusing on the proliferation of potentially toxic cyanobacteria species. Gallina *et al.* (2017) studied the impact of climate change on *P. rubescens* in Lake Geneva. Extreme hot air temperature events were used as a proxy of future climate and Multi-Adaptive Regression Splines (MARS) were adopted to model and predict future changes in *P. rubescens* biomass. The outcomes suggested a strong increase in the concentrations of this cyanobacterium, air temperature warming leading to high spring inoculum concentrations, thus triggering an outbreak during the summer. Derot *et al.* (2020) instead adopted machine-learning (ML) techniques as an alternative to process-based models to reproduce the development of harmful algae. Predictions were performed pairing two ML models with a long-term learning database of algal blooms spanning 34 years.

Primary production is modelled without any chemical background in two further papers. Finger *et al.* (2013) analysed 28 years of ¹⁴C assimilation rates, as well as other biotic and abiotic parameters, such as global radiation, nutrient concentrations and plankton densities in Lake Lucerne, to determine the effects of re-oligotrophication on primary productivity. They used a simple model implementing a productivity-light relation, through which they estimated a continuous series of primary production, interpolating the gaps between field observations. The uncertainty of the model was assessed through Monte Carlo simulations. Results underlined that nutrient management within the watershed has successfully improved water quality. However, while nutrient concentrations have decreased by more than an order of magnitude, primary production has decreased only slightly, varying significantly from year to year due to meteorological conditions. Franchini *et al.* (2017) proposed an improvement to existing mathematical interpolation models that calculate cumulative (*i.e.*, seasonal or annual) primary production rates from instantaneous (*i.e.*, hourly) sampled production values. This was performed employing photosynthetic parameters estimated from solar irradiance and TP-adapting equations previously used in marine studies. The algorithms were calibrated and validated through the 1983-2014 series of primary production measured in Lake Lugano.

Two other papers relate with food-web models. Both studies deal with Lake Annecy and used models imple-

mented inside the Ecopath with Ecosim framework (Christensen *et al.*, 1992). Janjua and Gerdeaux (2009) studied trophic interactions in Lake Annecy using 14 food-web functional groups. The resulting food-web parameters showed that Lake Annecy is a mature and relatively stable ecosystem. Lemaire *et al.* (2020) improved the model of Janjua and Gerdeaux (2009) to assess potential impacts of strong variations in young-of-the-year (YOY) perch biomass on the food web. The results indicated that strong variabilities in the abundance of YOY perch had little effects on the main food-web flows and pathways because of the capacity of the predators to feed on different prey, yet they could induce significant variations in the food-web properties and organisation.

The remaining contributions employing ecological-only models cannot be grouped together. Baudo (2002) attempted to fit the history of pollution and recovery of Lake Orta to the ecological theory of resilience. The Lake Orta ecosystem was perturbed by the onset of pollution in the 1920s, settling in another stable state characterized by very low water pH (Panizzuti and Tartari, 1995). A folded surface scheme reveals that after a restoring event, such as the liming of the whole lake (Calderoni and Tartari, 2000), an ecosystem would not merely revert its pathway, but it would evolve in a similar (but never completely identical) to completely different way, showing hysteresis. The observed variations of phytoplankton, zooplankton, benthos and fish in Lake Orta were further investigated applying a stochastic exponential population growth model. Enz *et al.* (2002) used a population dynamics model, implemented inside the STELLA framework (Costanza *et al.*, 1998), to evaluate mortality factors for whitefish in Lake Hallwil. They used as input variables the number of whitefish larvae stocked annually and the mean age of gillnetted whitefish, while data on annual whitefish yield and year-class strength (YCS) were used for model validation. Results showed that warmer and sunnier weather conditions in May negatively influenced whitefish yield and YCS, likely because gas supersaturation resulting from intense DO production by algae during warm sunny weather causes lethal-gas-bubble syndrome in whitefish larvae. Buerge *et al.* (2003) presented a study in which caffeine was used as a chemical marker for water surface pollution by domestic wastewaters in Lake Greifen (Switzerland) and MLDEPL Lake Zürich. They carried out systematic caffeine measurements in the influents and effluents of wastewater treatment plants (WWTPs) and in lake surface waters. A model reproducing caffeine concentrations, including the processes of flushing, biodegradation and indirect photodegradation by reaction with HO[•] radicals was implemented inside the AQUASIM framework (Reichert, 1994). Vertical mixing was described by time- and depth-dependent turbulent diffusivity coefficients, estimated with the heat budget

method from monthly temperature profiles. Their results showed that WWTPs efficiently reduced caffeine concentrations by 81-99.9%. Moschet *et al.* (2013) carried out a study in Lake Constance aimed at evaluating the exposure to micropollutants (MPs) from a large catchment. After an in-depth field analysis and a modelling exercise of the input loads of MPs from the watershed, they applied the MASAS substance budget model (Ulrich *et al.*, 1995) to predict the long-term trends of in-lake concentrations. The model considers the flushing of the lake, the water exchanges between epilimnion and hypolimnion and the direct photolytic degradation. A comparison of MASAS predictions with lake measurements showed good results for almost all MPs. Possible mitigation options were also evaluated, a post-ozonation step upgrade in the major WWTPs leading to significant reductions in the input loads of MPs. Finally, Minella *et al.* (2016) calculated the steady-state concentrations of photoinduced transient chemical species in Lake Garda, Lake Geneva and Lake Iseo through the APEX (Aqueous Photochemistry of Environmentally occurring Xenobiotics) photochemical model (Bodrato and Vione, 2014). Alterations in water chemistry due to climate change are expected to produce very heterogeneous photochemistry patterns among the studied lakes, depending on changes in dissolved organic C concentrations and water alkalinity.

DISCUSSION

The exponential increase in time of modelling studies of the MLDEPLs evident from the reviewed bibliographic corpus suggests a growing interest in quantitative approaches forecasting the outcomes of management actions and climate change. Such growth has been supported by the constant improvement of computational resources, allowing more complicated problems and environments to be modelled and more scenarios to be considered, thus raising the potentialities of modelling tools. German and Austrian MLDEPLs other than Lake Constance and Lake Ammer are not dealt within the reviewed bibliographic corpus, so that future modelling investigations to expand the available knowledge on them represent a priority.

The recent outbreak of papers employing 3D models has been allowed by their execution now being possible in ordinary workstation computers. At the same time, 3D models can solve the spatial heterogeneities of the limnological processes occurring in large deep lakes, in which rapidly displacing surface phytoplankton patches are common (Kiefer *et al.*, 2015), in response to wind-driven currents and the spatial heterogeneity of environmental conditions (Huang *et al.*, 2014; Cyr, 2017). This is especially relevant in multi-basin lakes (Salvadè *et al.*, 1992; Copetti *et al.*, 2020). These phenomena are potentially fully represented by 3D coupled ecological-hydrodynamic

models employing a complete ecosystem module. Yet, their application has been to date made difficult, to the point that the reviewed bibliographic corpus does not include any work in which they are employed, while several examples exist with 1D hydrodynamic drivers. Complete ecosystem modules nevertheless already exist for the most used models Delft3D (Delft3D-ECO module; Los *et al.*, 2008) and ELCOM/AEM3D (CAEDYM module – Computational Aquatic Ecosystem DYnamics Model; Hamilton and Schladow, 1997).

A first obstacle to the use of 3D coupled complete ecological-hydrodynamic models lies in model calibration. In fact, the computational times needed to perform 3D simulations are not yet small enough to realistically allow performing manifold preliminary runs for parameter optimisation, as is instead possible with 1D models, at least for commonly available workstation computers. Huge reductions in computational times could be obtained if model execution were moved from the computer processor (CPU – Central Processing Unit) towards the graphics card (GPU – Graphics Processing Unit), allowing in ordinary computers an extensive parallelisation of the numerical code which is otherwise possible only in HPC (High Performance Computing) cluster units. At the moment, it seems that the Deltares Institute is moving the first steps towards the GPU implementation of Delft3D (Buwalda, 2020). The computational constraint is especially relevant for 3D coupled complete models, as huge non-linear, highly site-specific parameter spaces with multiple levels are included in the biogeochemical modules, requiring a multitude of preliminary simulations for calibration. With such complicated parameter interdependencies, automatic calibration techniques can hardly be applied despite their constant improvement, as the problems which Baracchini *et al.* (2020) highlighted calibrating automatically a 3D hydrodynamic-only model with mutually dependent water temperature and current velocity fields would enormously amplify. Trial-and-error time-consuming expert-knowledge manual calibration may then be the only option, being already tiresome for coupled 1D models (Fenocchi *et al.*, 2019). Considerable calibration difficulties were in fact reported in a sample application of ELCOM-CAEDYM to the 5.25 km²-wide Italian perialpine Lake Pusiano (Carraro *et al.*, 2012).

Moreover, long-term observed series of a high number of chemical and biological variables should be provided for accurate calibration and validation of coupled complete ecological-hydrodynamic models, being them of 1D or 3D nature. To evaluate the continuous response of models, which allows reproducing short-term physical and biochemical phenomena, data should also be available at high frequency, *i.e.* at a daily to hourly interval. Even if the long limnological tradition characterising the perialpine region guarantees the existence of some of the longest series of

limnological data for some MLDEPLs, such as Lake Maggiore (Fenocchi *et al.*, 2019), available data from periodic sampling are often limited to single locations and to on average monthly frequencies. As such, they are not sufficient for the complete calibration and validation of 1D models on the temporal side and of 3D models on both the temporal and spatial side. Installation of networks of high-frequency monitoring buoys to be eventually managed by the local environmental protection agencies rather than depending on research projects alone has been recently started on Lake Como, Lake Lugano and Lake Maggiore inside the SIMILE Interreg project (Tiberti *et al.*, 2021). Ongoing difficulties in buoy maintenance and data management were highlighted. Most of these problems are not present in the floating laboratory LÉXPLORE platform installed on Lake Geneva (Wüest *et al.*, 2021), which allows complete on-site maintenance and control of monitoring sensors, in addition to countless additional research possibilities compared to the use of buoys, yet with much higher costs and a greater visual impact. Use of satellite images could then provide a relevant low-cost help (Pinaridi *et al.*, 2015), even if not all the needed environmental variables can be retrieved, subsequent images are spaced apart by few days and only the surface photic layer is represented, leaving out the metalimnion and hypolimnion. Still on the issue of distributed data, obtaining high-resolution wind fields to feed 3D models, which is vital to obtain realistic surface current and internal wave fields (Råman Vinnå *et al.*, 2017; Valerio *et al.*, 2017; Amadori *et al.*, 2018), has only recently been made possible for the MLDEPLs thanks to the use of small-scale meteorological models such as COSMO (www.cosmo-model.org) and WRF (Skamarock and Klemp, 2008).

The same high number of fixed parameters employed by complete ecological modules represents a further problem, as it induces stationarity (Trolle *et al.*, 2008a, 2008b). This limits the applicability to future projections, as variations in the species aggregates and thus in the ecological succession cannot be simulated (Burger *et al.*, 2008; Fenocchi *et al.*, 2019, 2020). In this regard, advanced statistical modelling approaches involving ML techniques do not offer any advantage over process-based models for long-term prognoses, while providing good results for short-term studies (Gallina *et al.*, 2017; Derot *et al.*, 2020). In fact, their base is purely parametrical and machine-knowledge on the processes driving the evolving ecosystem is not available to the models (Vinçon-Leite and Casenave, 2019).

In principle, coupling a hydrodynamic model to an ecosystem module reproducing primary production can improve the accuracy of hydrodynamic simulations themselves (Hamilton and Schladow, 1997). In fact, a time-dynamic estimation of the light extinction coefficient as function of algal population and particulate substance

concentration can be straightforwardly passed to the hydrodynamic driver (Rinke *et al.*, 2010), as done for example in GLM-AED2 (Hipsey *et al.*, 2013). Still on the links between the biogeochemical module and the hydrodynamic driver, a relevant shortcoming of coupled 1D and 3D ecological-hydrodynamic models is the missing capability to reproduce the precipitation of CaCO_3 , a frequent phenomenon in the MLDEPLs (Nouchi *et al.*, 2009). As a matter of fact, to the knowledge of the Authors, all available models represent solutes in the water column through a single salinity conservative variable. Calcite precipitation can be triggered by phytoplankton blooms occurring under heatwaves providing the nucleation cells and is thus expected to occur more frequently in the future. This phenomenon leads to a further stabilisation of the water column in addition to that predicted by available models, as salinity is effectively transferred to the already denser hypolimnion, accelerating the transition towards meromixis (Salmaso *et al.*, 2003). The implementation of calcite precipitation in numerical models should take into account both the occurrence of CaCO_3 supersaturation and of the triggering event, which could be of various nature (Nouchi *et al.*, 2019), the two not being contemporaneous (Koschel *et al.*, 1983).

Even if 1D models have proved themselves able to reproduce the mixing dynamics of lakes over broad ranges in latitude, climatic zones and morphometric properties (Bruce *et al.*, 2018), their application to large deep lakes will always seem a bit of a stretch, as both practical and theoretical considerations would push towards the use of 3D models. An example is the missing reproduction of internal waves, the main kinetic energy source in deep inland waters, whose effects are at best parameterised, as done by GLM (Hipsey *et al.*, 2019) and SIMSTRAT (Goudsmit *et al.*, 2002), which leads to largest errors occurring in the metalimnion (Răman Vinnă *et al.*, 2017). However, the 1D approach still represents a viable compromise between the representation of physics and the computational load for ordinary workstation computers, and as such it has been applied in several studies performing long-term prognostic simulations on the MLDEPLs. Notably, 1D models have proved themselves able to reproduce the oligomictic thermal regime of most of the MLDEPLs, in which full overturns occur only after cold and windy winters (Ambrosetti and Barbanti, 1999), allowing the simulation of their evolution towards meromixis with climate warming (Valerio *et al.*, 2015; Fenocchi *et al.*, 2018). When undertaking these long-term simulations on oligomictic basins, it is essential to perform continuous runs from the present day to the future (Valerio *et al.*, 2015; Fenocchi *et al.*, 2018, 2020) and not reproduce isolated future periods, at worst simulating each year separately. In fact, while the latter approach could be used for dimictic lakes, in which every year the vertical

temperature profile is reset twice when the water column passes through the 4 °C isotherm of maximum density, for oligomictic lakes it would lead to neglecting the annual carryover of heat stored in the hypolimnion between full turnovers. The casual occurrence of the latter also makes relying on single runs to assess the future evolution of the thermal structure insufficient, the statistical analysis of manifold realisations with random meteorological data series allowing a much more solid understanding of the possible outcomes (Fenocchi *et al.*, 2018, 2020).

Among papers employing 0D ecological-only models, the strong presence of models focusing on the P budget should be pointed out. This high attention is due to the role played by this nutrient in limiting algal growth and thus governing productivity. Large interest has also been devoted to the proliferation of *P. rubescens*, which in recent years has increasingly dominated the phytoplankton assemblage of many MLDEPLs. As a matter of fact, the occurrence of blooms of harmful cyanobacteria is of prime importance for risk assessment and management, as it affects the use of lakes for drinking and recreational purposes (Ibelings *et al.*, 2003).

Last, local knowledge has proven itself a promising support to lake modelling activities in the MLDEPLs, providing an experienced perspective on processes occurring in complex natural systems (Laborde *et al.*, 2012; Amadori *et al.*, 2020; Caramatti *et al.*, 2020).

CONCLUSIONS

This review paper has revealed a growing interest in modelling approaches to understand the functioning and evolution and support the management of the MLDEPLs. Studies applying 3D hydrodynamic models have seen an exceptional rise in the last decade, echoing the curiosity on the physical causes triggering the biochemical heterogeneities observed in the MLDEPLs, especially in multi-basin ones. However, coupling of 3D hydrodynamic drivers with ecological modules directly reproducing the patchiness phenomena is still hampered by: i) difficulties in obtaining multi-station ecological datasets with adequate temporal frequency for model calibration and validation; ii) computational times not being yet small enough to perform the manifold runs needed for accurate calibration. Several applications of 1D coupled ecological-hydrodynamic models to long-term forecasts of the impacts of climate change and of management actions on both lake physics and ecology have instead already been published, aided by the low computational burden and relative ease of use of 1D models. Ecological-only models, neglecting the underlying physics, have inferior predictive power, as they are parameterised to work under physical conditions close to the calibration ones, yet they can provide rapid and usually effective answers for watershed managers.

Future improvements in computational power and optimisation, in the understanding of ecosystem processes, leading to a reduction in model parameterisation, and in automatic calibration techniques are expected to bring about further ease of application and improved performances for 3D coupled ecological-hydrodynamic models. The combination of numerical modelling with remote sensing, in addition to high-resolution in-situ monitoring performed through permanent stations rather than limited to the ordinary periodic sampling, could lead to important improvements in 3D model calibration and validation, especially as regards the reproduction of algal blooms. Nevertheless, this integrated approach needs multidisciplinary contributions to be carried out effectively. The combination of such methods would allow scientists to fill the shortcomings of individual fields, to gain an integrated knowledge of the MLDEPLs.

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