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The Observatory on LAkes (OLA) database: Sixty years of environmental data accessible to the public

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ABSTRACT

Lakes are essential ecosystems that provide a large number of ecosystem services whose quality is strongly impacted by human pressures. Optimal uses of lakes require adapted management practices which in turn rely on physico-chemical and biological monitoring. Long-term ecological monitoring provides large sets of environmental data. When such data are available, they have to be associated to metadata and to be stored properly to be accessible and useable by the scientific community. We present a data informatics system accessible to anyone who requests it. Maintained online since 2014 (https://si-ola.inrae.fr), it is originated from the Observatory on LAkes (OLA). It contains long-term data from 4 peri-alpine lakes (Lakes Aiguebelette, Annecy, Bourget, Geneva/Léman) and 24 high-altitude lakes of the northern French Alps. We describe the generated long-term data series, the data type, the methodologies and quality control procedures, and the information system where data are made accessible. Data use is allowed under the condition of providing reference to the original source. We show here how such a platform clearly enhances data sharing and scientific collaboration. Various studies referring to these data are regularly published in peer-reviewed journals; providing *in fine* a better understanding of lakes' ecosystems functioning under local and global pressures.

INTRODUCTION

While lake water represents less than 0.01% of the total water on Earth (Shiklomanov, 1993), it provides a disproportionately high number of ecosystem services, such as water provisioning, fish resources, biodiversity support, climate buffering, scenic and cultural services. Any alteration of lake's water quality has wide-ranging ecological and societal implications. In many ways, human societies depend on healthy aquatic ecosystems, and conversely, ecosystems depend on human pressures.

Humans have influenced lake ecosystems for thousands of years, both locally and regionally, and impacts on the functioning of lakes often lead to alterations of water quality and modifications of ecosystem services. The most striking example is eutrophication: after industrialization and introduction of fertilizers and domestic pollutants, major changes in nutrient loads occurred in lakes, leading to increased primary production and frequent associated dysfunctions such as hypoxia and Harmful Algal Blooms (Le Moal *et al.*, 2019). When the first symptoms of eutrophication have appeared, scientists and stakeholders promptly highlighted the need for the implementation of systematic water quality monitoring, and, at best, this type of survey began in the late 1950s.

Data collected for water quality monitoring can be used for scientific purposes and contribute to the global data collection needed for better evaluating the impacts of long-lasting changes such as climate change. Long-term data that allow to detect changes in lake ecosystems are also essential for achieving an integrated understanding of how aquatic biological populations and communities interact and to develop and test ecological theories. Long-term monitoring also help establishing reference conditions in order to identify the magnitude of changes between past and present conditions (Kaiblinger *et al.*, 2009). Long term ecological research (LTER) programs have been established in several regions such as North America and Europe over the last decades to facilitate adapting environmental policies in watersheds and protect terrestrial and aquatic resources for future generations.

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Database URL: https://si-ola.inrae.fr

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Such programs are either national (*e.g.*, in France: Zone Ateliers and Analysis and Experimentation on Ecosystems [AnaEE France]; in the USA: Long Term Ecological Research [LTER]) or involved in international networks (*e.g.*, AnaEE Europe, Europe LTER, International LTER [ILTER] see Mirtl et al. 2019). These programs aim to facilitate interactions and collaborations within the multidisciplinary community of researchers such as the Global Lake Ecological Observatory Network -GLEON- (Rose *et al.*, 2016).

Storage of long-term environmental raw data is crucial and it is essential to associate to them meta-information about data traceability. Indeed, protocols are highly susceptible to change over time because of technological improvements or natural adaptation of ecosystems. A clear description of those raw data and how they have been collected is crucial to interpret and re-use them. Consequently that information on data acquisition have to be documented in metadata which must be associated to raw data. Moreover, it is necessary to develop platforms that provide a persistent access to this information. The observatory OLA (Observatory on LAkes) offers such a structure.

The observatory OLA (https://www6.inrae.fr/soere-ola_eng/) was created by the research unit CARRTEL (INRAE-USMB), an alpine research center devoted to the study of limnetic systems and associated food webs. It focuses on lakes of the northern French Alps and covers the region between 45°32' and 46°26'north. This region has been particularly affected by growing human populations and activities during the last decades. Human populations were concentrated primarily around the largest lakes (Aiguebelette, Bourget, Annecy and Geneva), where densities were particularly elevated — more than 1000 inhabitants per km² in many places. In the 20th century, the need to protect these precious aquatic resources became crucial because of the ecological, social and economic importance of these four lakes. Therefore, an ecological monitoring started in the 1960's as soon as the first signs of important eutrophication occurred (Jacquet *et al.*, 2014a; Montuelle and Clemens, 2015; Tab. 1). These monitorings are still ongoing today and are funded through various administrative entities, representing several municipalities neighboring the lakes (see Supplemental data S1 for details).

OLA provides high-quality scientific data for understanding and modeling the ecological functioning of lakes. Data are publicly available and are regularly used in scientific studies. An information system (IS) accessible at https://si-ola.inrae.fr gives access to the data. In this paper, we briefly describe the analytical methods for the main parameters, the database content, rules for using the data, IS data storage and the website interface.

Data available in the database

The efficient partnership between scientists and local stakeholders allowed the collection of physical, chemical and biological data from 1957 on Lake Geneva (also called Lake "Léman"), 1966 on Lake Annecy, 1974 on Lake Aiguebelette and 1987 on Lake Bourget. More recently, since the late 90s, 24 small high-altitude lakes situated on a latitudinal gradient in the French Alps were included in the observatory, and are since then monitored. Studying these lakes, considered as 'pristine' and highly sensitive to climate change, opens perspectives on the impacts of global change on lake functioning. The location and intrinsic physical characteristics of the largest lakes monitored in the framework of OLA are shown in Tab. 1 and Fig. 1. Samples are collected from the middle of the lake above its deepest point. Detailed description of all sampling stations can be found at https://si-ola.inrae.fr and in Tab. 2.

ACQUISITION OF BIOLOGICAL DATA

Taxonomic composition of phytoplankton community

The water sample for phytoplankton taxonomic identification and counting is collected within the first 20 m (0-10 or 0-18 m, depending on the lake and year) using an integrated sampling bottle. Samples are preserved with Lugol and then are kept in a dark and cool place until microscopic observations are performed. The Utermöhl technique (Utermöhl, 1958), standardized at the European level (CEN, 2006), is used. Briefly, after the settling of a known volume of sample in a microscopic chamber, algal counts and determinations are carried out under an inverted microscope at x64 magnification using specialized literature (for instance, the various volumes of the *Süsswasserflora von Mitteleuropa* edited by B. Büdel, G. Gärtner, L. Krienitz and M. Schagerl). Results are expressed in biovolume per volume of water ($\mu L.m^{-3}$) or in biomass

Tab. 1. Limnological characteristics of the main lakes monitored in the OLA observatory.

Lake	Volume (km^3)	Renewal time (years)	Max depth (m)	Watershed surface (km^2)
Geneva	89	11.3	310	7395
Bourget	3.6	9.0	145	560
Annecy	1.12	3.8	82	251
Aiguebelette	0.116	3.1	70	59

per volume of water considering that phytoplankton density is 1 kg.L^{-1} (µg.L^{-1}). A database of species biovolumes (Rimet and Druart, 2018) is used to obtained these results. Over more than 50 years, this biovolumes' database has been regularly updated to include species observed in the alpine lakes in France (Lakes Geneva, Annecy, Bourget and Aiguebelette) and also in high-altitude lakes in the French Alps (Feret *et al.*, 2017) and in various other French lakes.

Simultaneously, picocyanobacteria are examined in Lakes Annecy, Bourget and Geneva from samples taken at 6 discrete depths since 2003 (see details in supplemental data S2); these data will be included in the IS in the forthcoming years.

Primary production and Chl *a*

Primary production and Chl *a* are measured at 9 discrete depths (0, 1, 2.5, 3.5, 5, 7.5, 10, 15 and 20 m) in Lake Geneva (two times a month the entire year except once a month from December to February). Primary production has been measured using the ^{14}C method (Steemann-Nielsen, 1952) with the incorporation of $NaH^{14}CO_3$

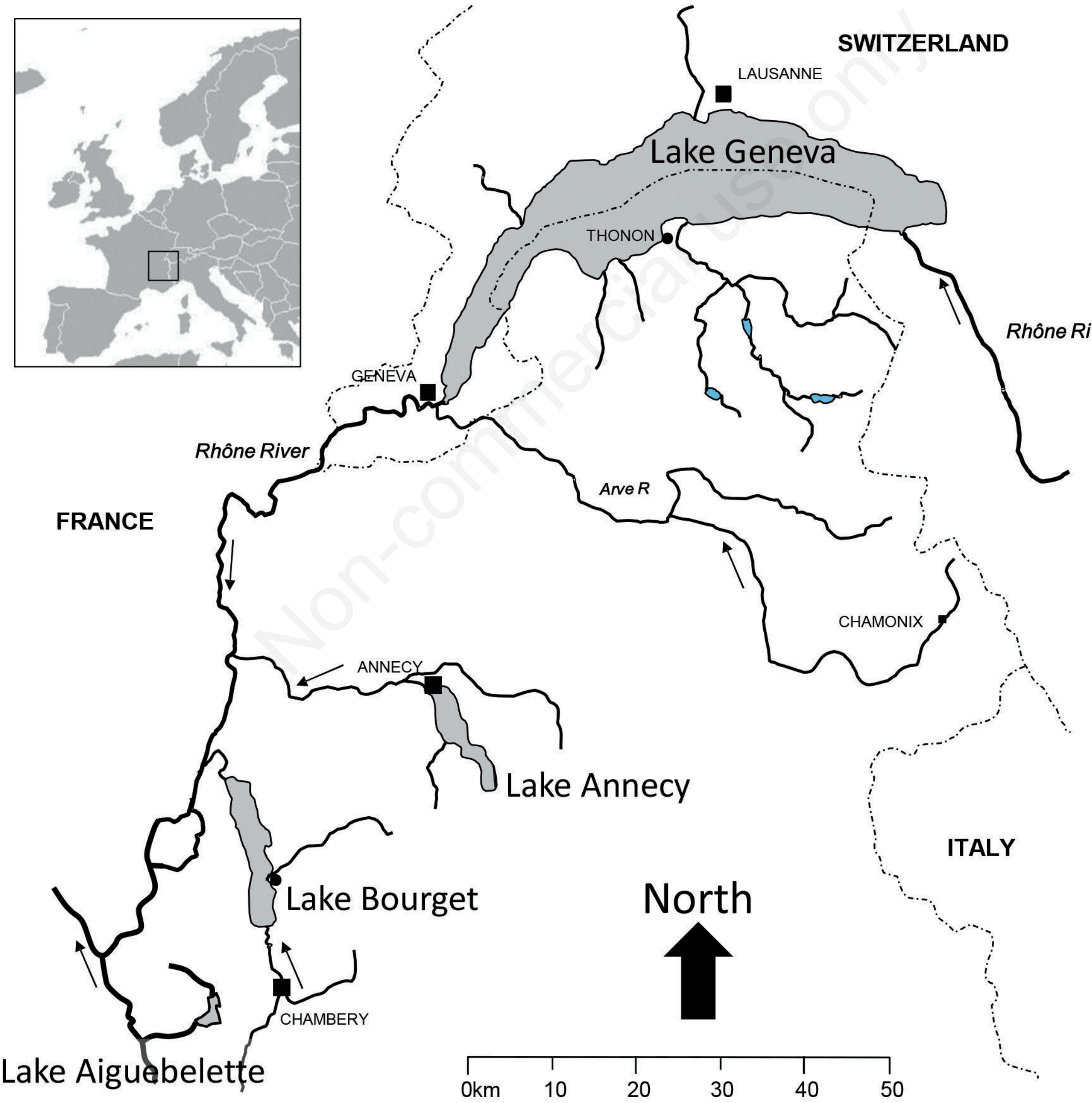

Fig. 1. Location of the large peri-alpine lakes monitored in the OLA observatory. Arrows indicate the flow of the main rivers.

from 1971 to 2012 (Pelletier, 1983). Since 2012, measurements of primary production are carried out using an isotopic method (incubation with ^{13}C sodium bicarbonate whose incorporation into the biomass is measured by isotope mass spectrometry). Measures of primary production are expressed in µg C/L/h. Chlorophyll *a* is analyzed using spectrophotometry after extraction into 90% acetone (ISO 10260: 1992). Chlorophyll *a* discrete measurements are completed with vertical profiles measures obtained with multiparameter probes.

Zooplankton

Zooplankton is sampled with a vertical tow from 50 m to the surface using a 200-µm plankton net for crustaceans and a 64-µm plankton net for rotifers. Samples are fixed in the field using 5% buffered formaldehyde.

Crustacean identification and counts are carried out in a subsample of a known volume of the net sample using a light microscope at x10 magnification. The identification books of Amoros (Amoros, 1984) and Dussart (Dussart, 1967, 1969) are used to distinguish species. Larger organisms (*Leptodora kindtii* Focke and *Bythotrephes longimanus* Leydig) are identified using the same procedure at x4 magnification. Final results are given in number of individuals per square meter.

Samples dedicated for observing rotifers are processed following the Utermöhl technique (Utermöhl, 1958). A subsample of known volume is allowed to settle in a microscopic chamber, and counts and determinations are carried out using an inverted microscope at x16 magnification. The identification books of Stemberger (Stemberger, 1979) and Voigt and Koste (Voigt and Koste, 1978a, 1978b) are used to distinguish species. Results are given in number of individuals per square meter.

Tab. 2. Complete list of the lakes and sampling stations integrated in the OLA.

Type	Name of lake	Name of sampling station	Latitude	Longitude	Altitude (m)
Large lake	Aiguebelette	Point a	45.55066	5.00900	390
Large lake	Annecy	Grand lac	45.87270	6.16453	447
Large lake	Annecy	Petit lac	45.81748	6.22140	447
Large lake	Bourget	Point B	45.75583	5.86000	231
Large lake	Léman	Shl2	46.45345	6.59423	372
High-lake	Anterne	Sampling point 1	45.99063	6.79889	2063
High-lake	Arpont	Sampling point 1	45.31580	6.77683	2672
High-lake	Aumar	Aumar : sampling point 1	42.84250	0.14972	2192
High-lake	Blanc du Carro	Sampling point 1	45.42000	7.12668	2753
High-lake	Bresses inférieur	Centroïd	44.15812	7.24204	2458
High-lake	Bresses supérieur	Centroïd	44.15932	7.24406	2501
High-lake	Brévent	Sampling point 1	45.92906	6.82739	2127
High-lake	Corne	Sampling point 1	45.22490	6.07870	2098
High-lake	Cornu	Sampling point 1	45.95837	6.84954	2275
High-lake	Cos	Sampling point 1	45.23250	6.07890	2183
High-lake	Izourt	Izourt : sampling point 1	42.68805	1.49777	1645
High-lake	Jovet	Sampling point 1	45.75697	6.73199	2173
High-lake	Lauzanier	Sampling point 1	44.3791	6.87234	2280
High-lake	Malrif	Centroïd	44.82292	6.86922	2580
High-lake	Merlet Supérieur	Sampling point 1	45.36040	6.64023	2447
High-lake	Mont Coua	Sampling point 1	45.31740	6.63899	2666
High-lake	Muzelle	Sampling point 1	44.95050	6.09722	2099
High-lake	Noir du Carro	Sampling point 1	45.42140	7.12491	2750
High-lake	Pavé	Centroïd	44.98770	6.32588	2846
High-lake	Pétarel	Centroïd	44.80214	6.16875	2090
High-lake	Pisses	Centroïd	44.72245	6.37941	2515
High-lake	Plan Vianney	Sampling point Edytem	44.95750	6.04333	2250
High-lake	Pormenaz	Sampling point 1	45.96254	6.79460	1947
High-lake	Rabuons	Sampling point 1	44.26970	6.98250	2501
River	Dranse	Defaut dranse – main tributary of Lake Léman	46.38350	6.50744	388

PHYSICAL AND CHEMICAL DATA ACQUISITION

In situ measurements

Transparency, using a Secchi disk, is systematically measured following the international standard ISO 7027. Probes are used to measure depth (pressure), pH, conductivity, oxygen concentration, turbidity, *in situ* chlorophyll *a* fluorescence and photosynthetic active radiation. In recent years, the most commonly used probes were CTM214 FO and CTD009 (Sea and Sun Technology©).

Water samples are collected at discrete depths for subsequent chemical and physical laboratory analyses. Sampling is performed using bottles such as the Freeflow bottle (Hydrobios©) or the integrated sampling bottle (Hydrobios© IWS bottle). In past years, other kinds of bottles were used, including the Niskin bottle for sampling at discrete depths and the Pelletier bottle for collecting integrated depth samples (Pelletier and Orand, 1978).

Chemical and physical laboratory data

In the laboratory, water samples are filtered immediately through Whatman© GF/F filters (0.7-µm nominal pore size) and then stored at 4°C in high-density polyethylene plastic bottles or amber glass bottles until analyses, which are performed within 48 h after collection. A large range of physical and chemical analyses are carried out following international or national standards. Chemical procedures follow rigorous quality assurance and control to ensure the quality of obtained analytical data. Tab. 3 shows the major analyses performed.

Total suspended matter is determined using an ultra-micro balance (XP2U; Mettler Toledo©). Major cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) are determined using flame (acetylene/air) atomic absorption spectrophotometry (AA240FS; Varian©) following NF 90-020. Lanthanum is added as a matrix modifier to minimize interference. Major anions (Cl^-, NO_3^- and SO_4^{2-}) are quantified using ion exchange (861 Advanced Compact ion chromatograph; Metrohm©) with chemical suppression following ISO 10304-1.

An automatic titrator (Basic Titrino 794, Metrohm ©) with a glass electrode is used to perform successive pH measurements. Temperature corrections are systematically applied when performing lab measurements of the conductivity (ISO 10523:2008). Total alkalinity is obtained using potentiometric titration (ISO 9963-1).

A UV-vis spectrophotometer (Cary 50 scan; Varian©) is used to determine total phosphorus and orthophosphate based on sulfuric acid digestion and a molybdenum blue method (EPA 365.3). Ammonium is determined based on an indophenol blue method (ISO 5664:1984), and nitrite ions are determined using a diazotization method (ISO 6777:1984).

Total nitrogen is determined using chemiluminescence after high-temperature digestion and catalytic postcombustion using an ElementarVario© TOC/TNb coupled with a chemiluminescence detector (APNA-370; Horiba©). Total inorganic nitrogen (ammonium and nitrate ions) is calculated as the difference between total nitrogen and or-

Tab. 3. Physical and chemical analyses carried out in the laboratory. References to the standard methods and to the main principles are given.

Parameters	Standard	Principle
pH, Conductivity	ISO 10523:2008	Potentiometric and conductometric measure
Alkalinity	ISO 9963-1	Potentiometric determination
Total suspended matter	EN 872:2005	Filtration
Dissolved oxygen	ISO 5813:1983	Iodomitric method
Total and dissolved organic carbon	EN 1484:1997	Heated-Persulfate oxidation, Non-dispersive infrared measure
Particulate carbone and nitrogen	ASTM D2579-93e1	CHN elemental analyzer (High-temperature combustion method, gaz chromatography, thermal conductivity detector)
Ammonium	ISO 5664:1984	UV-Visible spectrometer
Nitrite	ISO 6777:1984	UV-Visible spectrometer
Nitrate, chloride, sulfate	ISO 10304- 1	Ion chromatography
Total nitrogen	EN 12260:2003	High temperature digestion and catalytic post combustion, chemiluminescence measure
Orthophosphate, total phosphorus, particulate phosphorus	EPA 365.3	UV-Visible spectrometer
Silica	NF T 90-007	Discret Chemistry Analyzer
Majors cations (sodium, potassium, calcium, magnesium)	NF 90-020	Atomic Absorption Spectrometry
Chlorophyll-a	ISO 10260 : 1992	UV-Visible spectrometer

ganic nitrogen (EN 12260:2003). Total and dissolved organic carbon are measured using a non-dispersive infrared detector coupled to an Aurora 1030W carbon analyzer, applying a heated persulfate oxidation method (EN 1484:1997). Dissolved organic carbon is determined from filtered (muffled Whatman© GF/F filter) samples. Particulate organic carbon and nitrogen are analyzed applying a high-temperature combustion method (ASTM D2579-93e1) with a gas chromatograph equipped with a thermal conductivity detector (Flash 2000; Thermoscientific©). Biogenic silica is analyzed using a Smartchem 200 Discrete Analyzer (WESTCO Scientific Instruments©), applying NF T90-007.

DATA STORED IN THE IS: FOCUS ON A SELECTION OF LONG-TERM LIMNOLOGICAL DATA

Tab. 4 gives an overview of the data available in the IS. The longest series of data are available for Lake Geneva (going back to 1957 for chemical parameters). The most recent series are available for the high-altitude lakes. A detailed description of the data is available at https://si-ola.inrae.fr/

From such data, the responses of lakes to local and global pressures have been described, as for instance the effect of global warming on water temperature (O'Reilly *et al.*, 2015), thermal structures (Kraemer *et al.*, 2015), lake mixing, oxygen availability (Foley *et al.*, 2012), plankton communities and fisheries (O'Reilly *et al.*, 2003). Local and global pressures deeply modify alpine lake functioning and biodiversity, as testified by recent paleo-reconstructions showing multi-level responses in biodiversity facing eutrophication and warming (Perga *et al.*, 2015).

Here we selected some of these long-term data to illustrate some of the scientific advances they recently provided. Supplemental data 2 and 3 show complementary data collected for other biological compartments (fish and picophytoplankton) that will be included soon in the OLA-IS.

Tab. 4. Temporal distribution of the data available in the information system (white: no data, grey: data available in the information system).

Lake	Measures	50ies	60ies	70ies	80ies	90ies	2000	2010	Present
Aiguelebette	Chemical par.			1974					
	Multipar. probe			1974					
	Phytoplankton					1998			
	Chlorophyll				1989				
Annecy	Chemical par.		1966						
	Multipar. probe		1966						
	Zooplankton					1994			
	Phytoplankton					1996			
	Chlorophyll					1990			
Bourget	Chemical par.					1999			
	Multipar. probe						2003		
	Zooplankton					1995			
	Phytoplankton					1995			
	Chlorophyll				1987				
Geneva	Chemical par.	1957							
	Multipar. probe	1957							
	Zooplankton	1959							
	Phytoplankton			1974					
	Chlorophyll			1976					
High	Chemical par.					1992			
Altitude	Multipar. probe							2014	
Lakes*	Zooplankton							2015	
	Phytoplankton					1998			
	Chlorophyll							2015	

**High altitude lakes encompass:* Anterne, Arpont, Aumar, Blanc du Carro, Bresses inférieur, Bresses supérieur, Brévent, Corne, Cornu, Cos, Izourt, Jovet, Lauzanier, Malrif, Merlet supérieur, Mont Coua, Muzelle, Noir du Carro, Pavé, Pétarel, Pisses, Plan Vianney, Pormenaz, Rabuons.

Interannual dynamics of phosphorus in deep peri-alpine lakes

Lakes Geneva, Bourget, Annecy and Aiguebelette are typologically similar but they have been impacted differently by local anthropogenic pressures. Restoration of these lakes, after phosphorus pollution several decades ago, provides nowadays exemplary cases of successful restoration of trophic status in a world where freshwater eutrophication is increasing globally (Le Moal *et al.*, 2019). Lakes Geneva and Bourget, and to a lesser degree, Annecy and Aiguebelette, underwent rapid eutrophication during the 60s and 70s as a result of development of nutrient point sources, mostly untreated domestic effluent discharges. The temporal series of total phosphorus concentrations in Lake Geneva from 1957 to 2017, in Lake Bourget from 1999-2017, in Lake Annecy from 1966 to 2017 and in Lake Aiguebelette from 1974 to 2017 are shown in Fig. 2.

Phosphorus maxima observed in the data were reached during the late 70s in Lake Geneva and during the 90s in Lakes Annecy and Aiguebelette. The maximum phosphorus concentration in Lake Bourget during the 80s is also well known but not included in the database (Perga *et al.*, 2015). Effective measures for reducing the phosphorus load in the 70s resulted in strong decreases in phosphorus concentrations in the four large alpine lakes. Re-oligotrophication processes continue today (Jacquet *et al.*, 2014a).

Long-term chloride concentration in Lake Geneva

Chloride ion concentration in Lake Geneva increased continuously from 1973 to 2017 (Fig.3). The annual average concentration reached 10.31 mg Cl^-/L. The contributions of various tributaries to the lake largely explain this trend (Klein, 2016). Chloride concentration reflects a growing utilization of chemical chlorine-based products in the industrial sector (metallurgy and pharmaceutical sectors) and the application of deicing salt during winter (Gumy and De Alencastro, 2001). These data have been used to consolidate a database of 529 lakes in Europe and North America (Dugan *et al.*, 2017b); the associated study predicts that many lakes could exceed the aquatic life threshold criterion for chronic chloride exposure (230 mg L^{-1}), stipulated by the US Environmental Protection Agency (EPA), in the next 50 years if current trends do continue (Dugan *et al.*, 2017a).

Temporal dynamics of phytoplankton and zooplankton in Lake Geneva

Over the last 50 years, the abundance, taxonomic structure and phenology of phytoplankton communities have changed (Anneville and Leboulanger, 2001; Anneville *et al.*, 2005, 2010, 2018; Rimet *et al.*, 2009; Jacquet *et al.*, 2014c) because of decrease in phosphorus concentrations, warming in water temperature and change

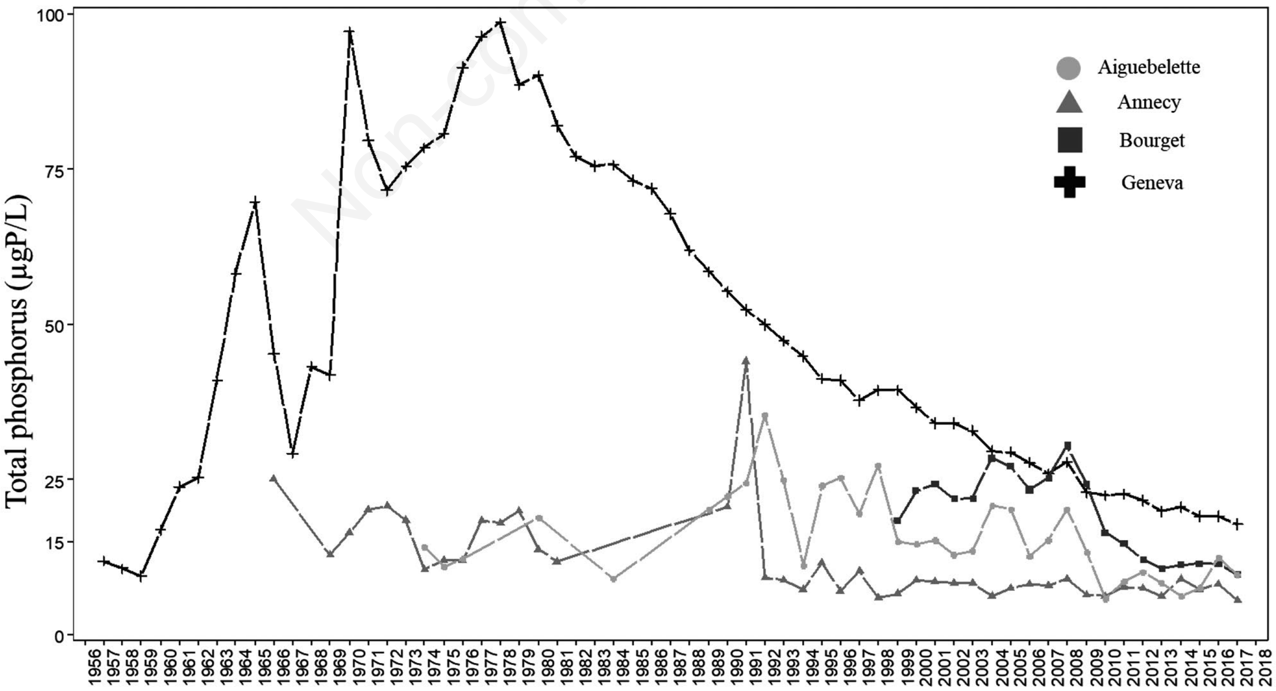

Fig. 2. Interannual dynamic of total phosphorus in the large alpine lakes: Aiguebelette (1974-2017), Annecy (1966-2017), Bourget (1999-2017) and Geneva (1957-2017).

in the thermal stratification dynamic. Except in Lake Geneva (Fig. 4), phytoplankton biomass has systematically decreased with phosphorus concentration. The unexpected trend in phytoplankton biomass observed in Lake Geneva is explained by a decrease in zooplankton grazing (Tadonleke *et al.*, 2009), a change in phytoplankton taxonomic composition and an increase in phytoplankton biomass during winter and spring as a result of temperature increases during these seasons (Anneville *et al.*, 2018). Moreover, the abundance and taxonomic composition in zooplankton gradually changed with time because of decreases in food quality (Anneville *et al.*, 2007 showed a shift from herbivorous to carnivorous copepods), changes in thermal conditions (Molinero *et al.*, 2007) and trophic status (Molinero *et al.*, 2006), and increased fish predation (Nõges *et al.*, 2018).

Changes in phytoplankton composition

Long-term monitoring of phytoplancton in Lake Geneva is one of the longest time series in the world (Fig. 5). It shows deep changes in its biomass and moreover on its taxonomic composition from the 70ies to nowadays. These changes were mostly controlled by bottom-up factors, such as nutrient level. For instance, the decrease of Dinophyceae from 1974 is mostly due to *Ceratium hirundinella,* a species preferring eutrophic epilimnia (Reynolds *et al.*, 2002) and which is nowadays quite rare in Lake Geneva phytoplankton compared to 40 years before. On the other hand, some species known to prefer oligotrophic waters and which have mixotrophic capacities (Padisak *et al.*, 2009), mostly belonging to the Chrysophyceae (*e.g. Dinobryon* spp., *Kephyrion* spp., *Chrysolykos planktonicus*) showed an increase in their biomass and are common in the summer epilimnion of the last decade, whereas they were absent in the 70ies. Inside the diatom class, some species have disappeared, like *Stephanodiscus binderanus,* a centric usually observed in eutrophic waters, and have been replaced by species like *Cyclotella costei,* characterizing re-oligotrophication stage in Lake Geneva (Rimet *et al.*, 2009). Global warming has an impact on lake stratification and phytoplankton composition; it is the case with *Mougeotia gracillima,* a filamentous Zygophyceae which showed higher biomass in the metalimnion after year 2000, sometimes blooming when a thick layer of the epilimnion is stratified (Tapolczai *et al.*, 2015).

Such changes in the phytoplanktonic structure and biomass have also been observed in Lake Bourget. During almost 20 years, the toxic and filamentous cyanobacteria *Planktothrix rubescens* developed and bloomed (representing between 20% and more than 50% of the algal biomass each year) despite efforts to reduce phos-

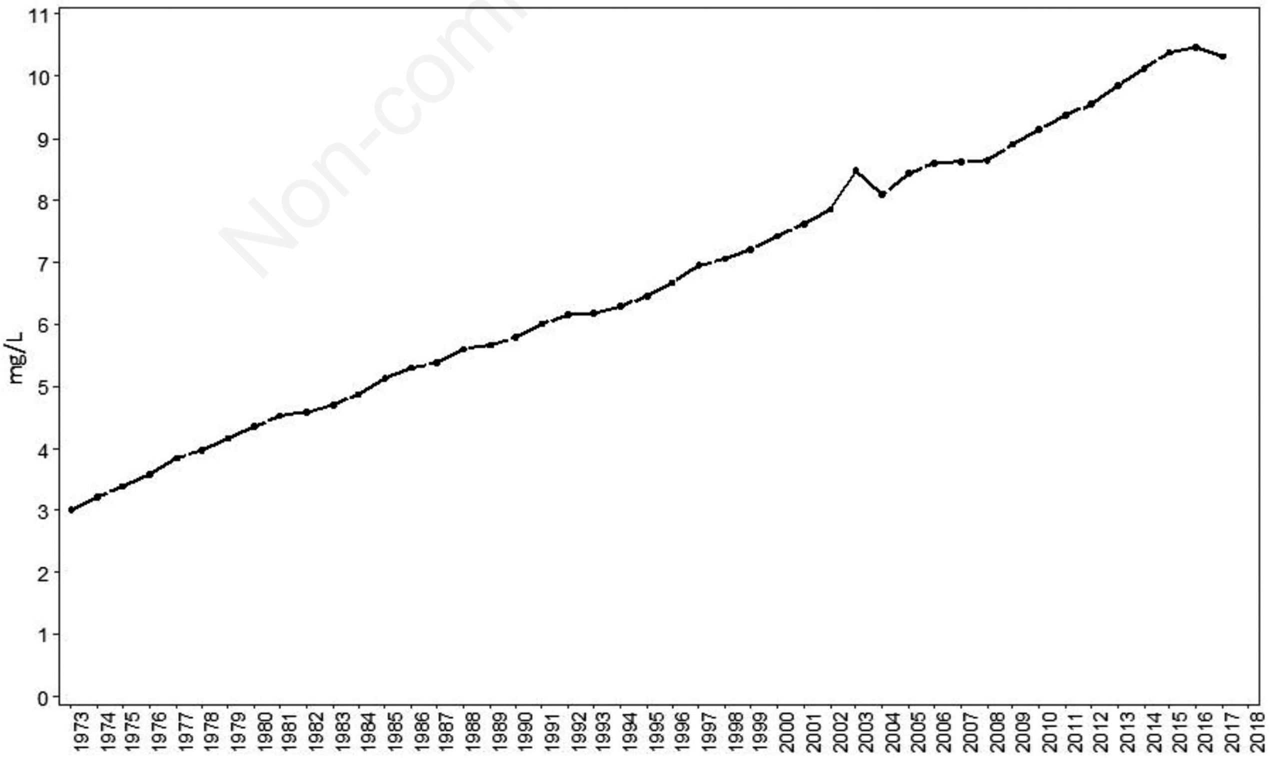

Fig. 3. Interannual dynamic of chloridein Lake Geneva between1973 and 2017.

phorus loading since the early 1980's. Between 1996 and 2009 blooms occurred and persisted while the lake was mesotrophic. By the end of 2009, however, a conjunction of events occurred so that the cyanobacterium disappeared. Interactions among nutrients, light availability, temperature and water column stability as well as zooplankton grazing could be identified as important factors for explaining bloom collapse (Jacquet *et al.*, 2014b). In parallel, as for the Lake Geneva, mixotrophic algal species and picophytoplankton groups have significantly increased during the last decade in response to the re-oligotrophication and the disappearance of *P. rubescens*. It is noteworthy, however, that 2016 and 2017 constituted again two years where the species raised again despite nearly oligotrophic conditions (Jacquet *et al.*, 2018).

INFORMATION SYSTEM STRUCTURE

The OLA-IS is built around generic components offering common functionalities to various observatories dedicated to a variety of environmental topics (lakes, grasslands, forests and crops) (Schellenberger *et al*., 2019b; https://doi.org/10.15454/QJJJZU). However, several features dedicated specifically to lakes were added (specific datatype modules), making the OLA-IS specific (Schellenberger *et al*., 2019a; https://doi.org/10.15454/VBWYWG). The OLA-IS was written in Java as a Maven project and is divided into several lake datatype modules. The OLA database was designed according to a relational model (Monet et al., 2020a, https://doi.org/10.15454/OHXVJY) managed by PostgreSQL Release 12. Technically, the database has been designed to make the modeling as generic as possible so that each type of data (for instance: phytoplankton data type, probes data type, *etc.*) is modeled in the same way. In addition, the metadata tables are the same regardless of the type of data studied.

The web interface is based on the JSF framework, and Primefaces, Spring and Hibernate graphics components libraries complement the technologies. The IS is accessed online through an apache server (https://si-ola.inrae.fr).

The interface provides information on the available data and states the Terms of Use (ToU) as stipulated in the data access license (Monet *et al*., 2020b, https://doi.org/10.15454/HHN2GA). Both the interface and the data content (variable names, units, etc.) are available in English and French.

The interface proposes extraction by data type. For each data type, the user can choose the lake, the time period and the desired variables. After extraction is complete, the user can download the data as text (.cvs) files. Online notifications show the user if the extraction is in progress or completed, and this does not imply the user

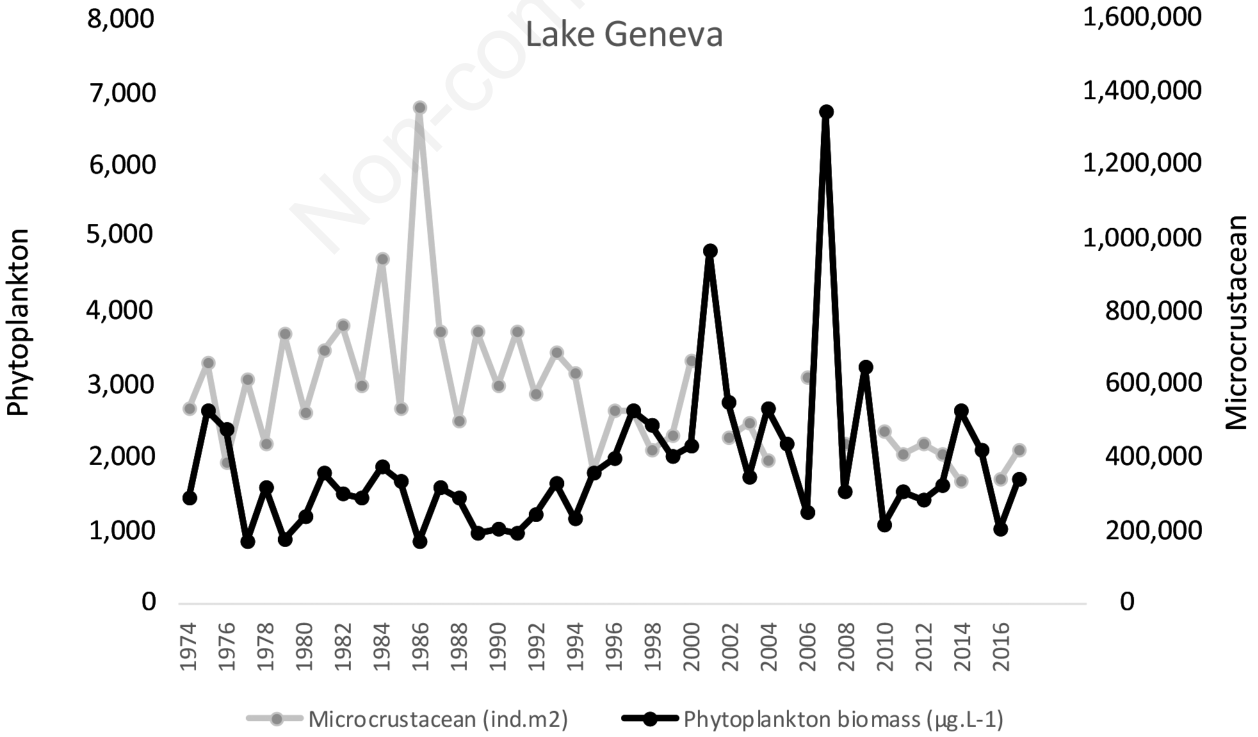

Fig. 4. Interannual dynamic of phytoplankton (µg.L^{-1}) and microcrustacean (ind.m2) biomasses in lake Geneva.

must remain logged in. Another interface, restricted to administrators, enables management of the users, the rights granted to them, and control, deposit and publication of validated data.

OLA is part of the French national research infrastructure Anaee-f . Anaee-f works to publish its metadata and its data through the use of the semantic web (https://www.anaee-france.fr/en/infrastructure-services/

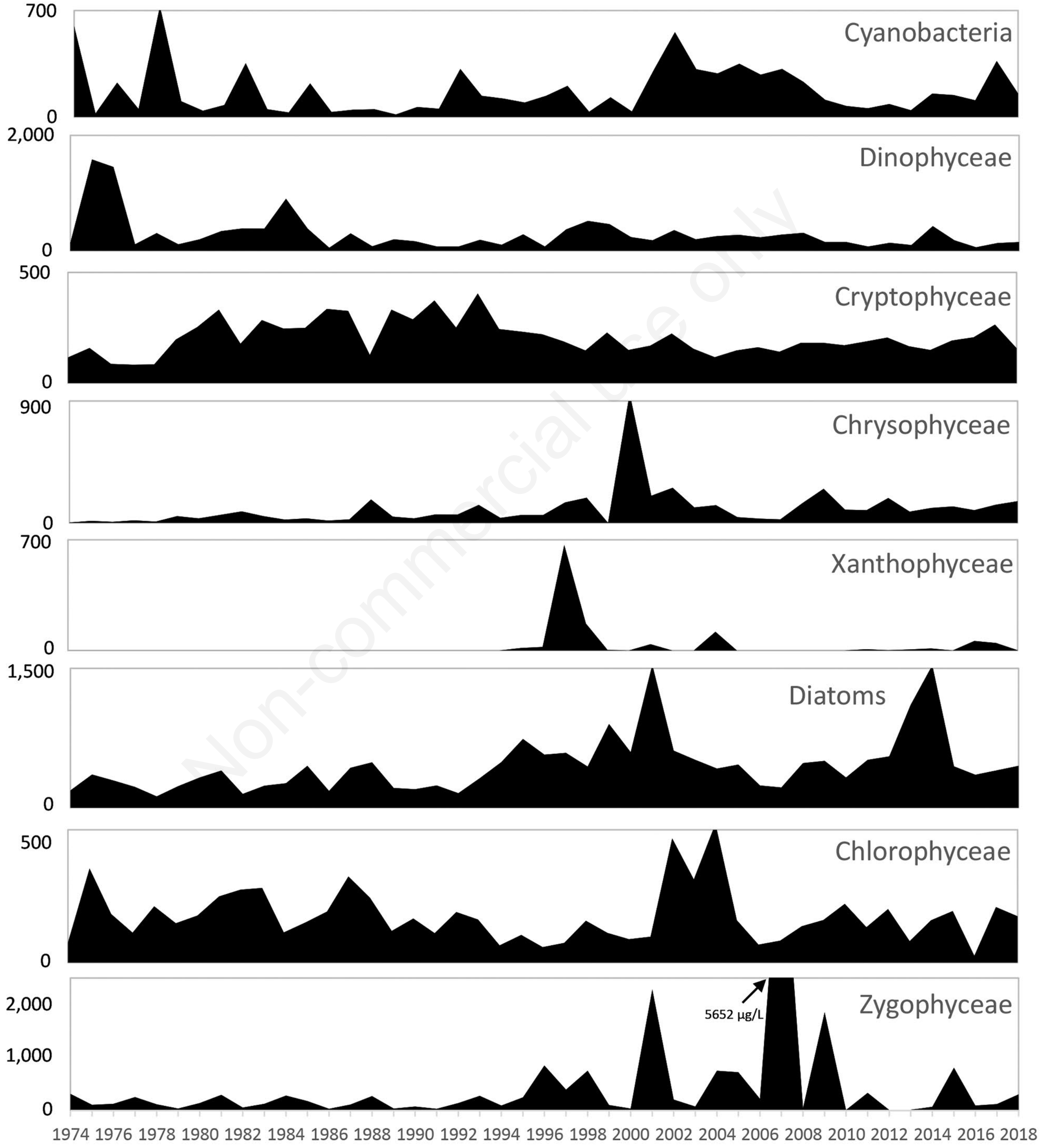

Fig. 5. Taxonomic composition of lake Geneva phytoplancton expressed in biomass (µg/L) from 1974 to 2018 (each value is an annual mean of the water column integrated phytoplankton samplings carried out 2 times a month except once a month between December and February).

modelling-and-data/semantic-reference-framework). OLA fits in with this perspective and uses the vocabulary of thesaurus Anaee-F, data are semantically annoted using the AnaEE-F (http://agroportal.lirmm.fr/ontologies/ANAEETHES and OBOE ontologies (Madin *et al*., 2007). In this way, OLA IS is developed according to FAIR Data principles (Findable, Accessible, Interoperable, Re-usable) (Clobert *et al*., 2018; Pichot, 2017, Wohner *et al*., 2019).

DATA MANAGEMENT PLAN

Development and implementation of adapted policies and processes are essential to maintain the integrity, security and usability of the data. Data validation, data access and sharing policy are important component of the data management plan.

Quality control

The OLA-IS contains only curated data. All along the data collection, from field sampling to data archiving, rigorous quality controls are carried out (Fig. 6). These data follow a controlled vocabulary included in the AnaEE - France thesaurus (Clastre *et al.*, 2018).

DATA ACCESS AND SHARING POLICY

Before downloading and using the data, a user must register on the SI, agree to the GCUs and formulate the data request. The data request is evaluated by the OLA scientific committee (scientists of the research unit CARRTEL). Once the request is validated, the user is provided a login which allow to enter the OLA-IS for a period of three months and download the data. Access to the IS and the GCUs is available at https://si-ola.inrae.fr/. The GCUs describe the rights and obligations of the user when using the data provided by the OLA-IS. Data are accessible free of charge via registration on the website and compliance with the GCUs. The data are protected under copyright law, and compliance with the GCUs will not change this. All the data stored in the OLA-IS are usable by any applicant, under the condition of providing reference to the original source of the data in any communication by indicating the lake(s) studied, as given in the GCUs and by citing the present paper:

Rimet *et al*. (2020) *The Observatory on LAkes (OLA) database: Sixty years of environmental data accessible to the public.*

Furthermore, the user is asked to transmit to the OLA-IS manager a copy of the work wherein the downloaded data were analyzed and valorized. The GCUs expire after a period of five years after which the user must destroy the data. The user must formulate a new request in case the data are required for a new project. Data cannot be shared or stored in another public database.

CONCLUSIONS AND PERSPECTIVES

Since the OLA-IS was created in December 2014, an average of more than one peer-reviewed publication providing limnological data from the OLA has been accepted monthly. More than 55 publications have been referenced on Google Scholar from 2015 to 2018. This also corresponds to the monthly data demands received through the OLA-IS website. It is obvious that this website and IS fuel data-sharing and scientific collaborations between environmental scientists. Proof of this is found in large international co-authorships of several papers that include OLA data. Examples are Sharma *et al*. (2015), where several tens of scientists studied surface lake temperatures, Taranu *et al*. (2015), where cyanobacteria increases along with nutrient concentrations were studied on a large temporal and spatial scale, and Leach *et al*. (2018), where the relative importance of light and thermal stratification were found to be key drivers of deep chlorophyll maxima structure in a variety of lakes. Other examples include studies of the impact on stratification and response to climate change of lake morphometry (Kraemer *et al.*, 2015), the rise in chloride concentrations in European and American lakes (Dugan *et al.*, 2017b), or the widespread diminishing anthropogenic effects on calcium in freshwaters because of industrial acid depositions (Weyhenmeyer *et al.*, 2019).

However, even if the OLA-IS is an excellent platform for data accessibility, the inclusion of new types of data must be scheduled. Some of these new types of data are related to technological evolutions that enable high-throughput data (DNA high-throughput sequencing and high-frequency sensors) to be accessed. Until now, biological analyses have been carried out under microscopes (*e.g.*, for phytoplankton and zooplankton), requiring experts trained in taxonomical recognition. An alternative is DNA barcoding (Hebert *et al.*, 2003) and high-throughput-sequencing, which enables rapid analyses of many environmental samples at lower costs compared to the involvement of specialized analysts. This method was tested on mock communities of algae (Kermarrec *et al.*, 2013) and then on natural algal communities (Vasselon *et al.*, 2017; Rivera *et al.*, 2018). It also enables global assessments of protist diversity, including rare biosphere (Taib *et al.*, 2013) and small eukaryotes whose taxonomy remains still not well-established (Lepere *et al.*, 2008; Mangot *et al.*, 2013). Therefore assessments of diversity are enlarged compared to the restricted diversities observable using optical devices. Such methodologies can also be applied to fish (Pont *et al.*, 2018) and macroinvertebrates (Elbrecht *et al.*, 2017), also providing promising results. The OLA lakes are already studied using metabar-

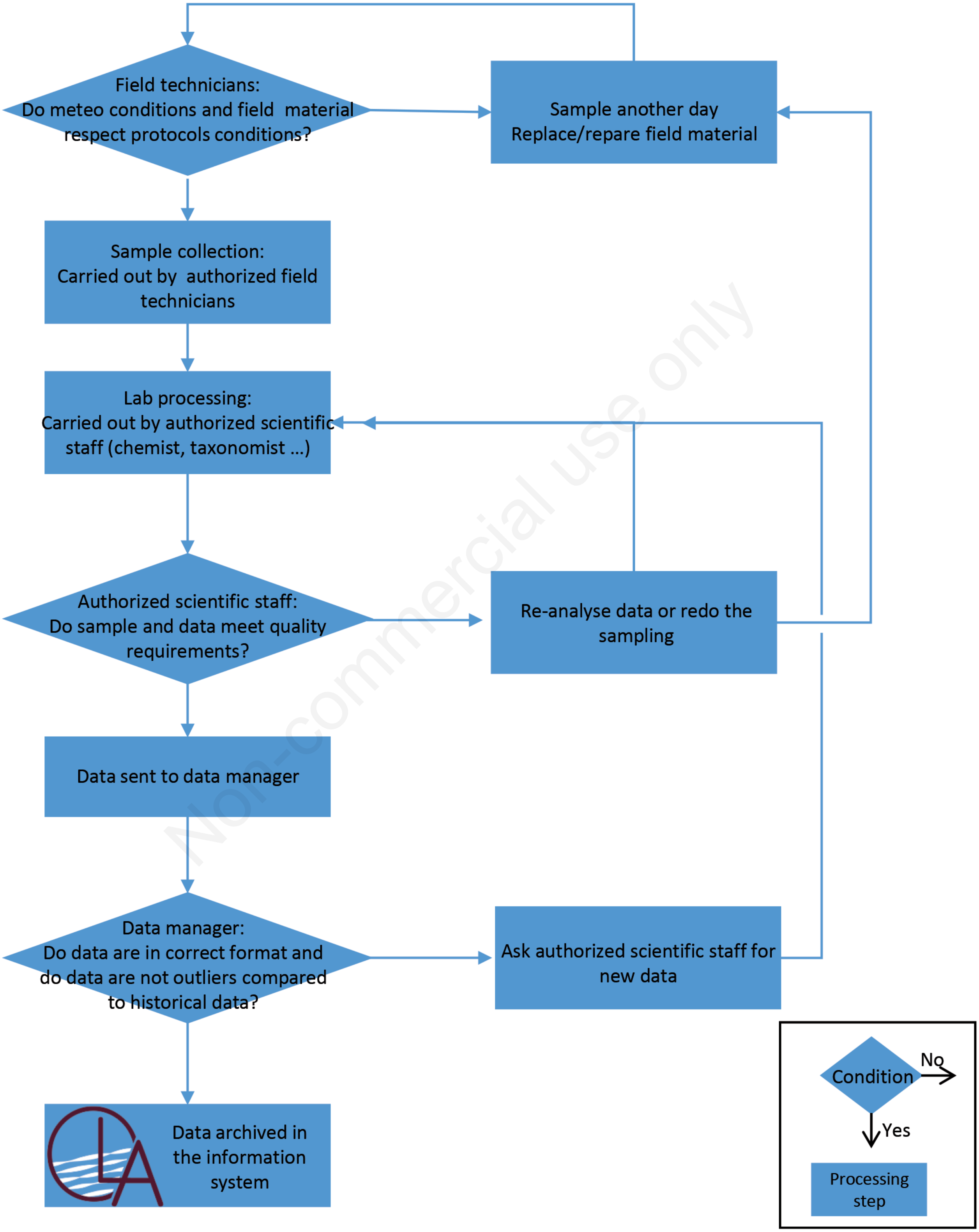

Fig. 6. Simplified flow chart for data validation and curation before integration in the OLA information system.

coding for algal communities (Rivera *et al.*, 2018; Rimet *et al.*, 2018; Lefrançois *et al.*, 2018), global protist diversity (Lepere *et al.*, 2008) and fish (Civade *et al.*, 2016). Therefore, genomic data storage in the OLA-IS must be envisaged. However, the quantity of data stored will increase several orders of magnitude with the changes from classical to these more sophisticated methods (Keck *et al.*, 2017), and informatics solutions will be required.

High-throughput data storage (and accessibility) also presents an imminent challenge related to the development and storage of data from high-frequency sensors. Recent technological developments have increased the number of variables monitored in lakes using automatic high-frequency sensors (Marcé *et al.*, 2016). To facilitate posterior data handling and interpretation, it is critical that an interface as the OLA-IS provides storage capacity and sharing access for this type of data, given it is becoming essential in near-future limnological surveys.

Monitoring additional matrices and habitats in lakes and their integration into the OLA-IS are already envisaged. For instance, data on fish populations, picocyanobacteria and new sampled habitats such as the littoral zone, are now routinely collected and are planned to be archived in the OLA-IS whose architecture allows to host new data. Therefore, integrating high-throughput data (DNA and sensors), new sampling sites and matrices into the OLA-IS would considerably enrich and diversify this database, offering thus new opportunities to enlarge scientific collaborations.

To conclude, the OLA-IS success was made possible by three items. First thanks to the quality of its data and the presence of experts in different fields (taxonomy, chemistry, physics). Second, thanks to the traceability of the data, since metadata are associated to each data, detailing the protocols of acquisition, the material used and the responsible persons. Finally, thanks to the permanence and accessibility of the IS made possible by the commitment of the regular staff dedicated to its maintenance

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