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LéXPLORE: A floating laboratory on Lake Geneva offering unique lake research opportunities

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Abstract

Environmental sciences depend heavily on observational data. Successful studies of ecological processes in lakes require in-situ data that cover the relevant temporal scales from milliseconds to entire seasons. Temporal and spatial coverage requirements represent a non-trivial challenge in lake sciences, which have traditionally used sampling campaigns conducted from research vessels or anchored moorings. These come with various logistical tasks and impose constraints on data coverage. An open water platform can overcome many of these limitations by providing continuous access and a wide range of analytical capabilities in direct contact with the lake environment. A consortium of five partner institutions constructed a 10 × 10 m, open-water, multipurpose platform on Lake Geneva (Switzerland/France) for a broad range of limnological research. The LéXPLORE platform, anchored since February 2019 at a position reaching 110 m depth off the lake's north-shore, provides workspace for a large number of instruments and up to 16 staff working in parallel on individual or integrated multidisciplinary projects. The safe, dry and protected floating laboratory offers direct access to the lake environment for high-sensitivity, high-throughput analyses including those which might advance sensor technology. The platform provides flexible workspace for both high-resolution measurements and investigations of larger-scale external forcing. It thus supports multidisciplinary empirical research in limnology, atmospheric sciences, and remote sensing. This article describes the platform and how it will advance aquatic sciences. The large number of projects that have already requested access to the platform demonstrate the efficacy and necessity of the LéXPLORE concept.

This article is categorized under:
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KEYWORDS

datalakes-eawag.ch, environmental monitoring, freshwater ecosystems, in-situ sensors, remote sensing

1 | INTRODUCTION

Aquatic systems processes occur over a wide range of time scales, from sub-seconds to decades. These define the frequency, density, and duration requirements of scientific measurements. Historically, collection methods imposed significant constraints on the coverage and resolution of limnological data. Early and ongoing fieldwork (Forel, 1892) depended on boats for collecting surface and water column samples. These sampling campaigns faced logistical challenges and only provided a discrete and often incomplete picture of the lake environment. Development of electronics and sensors in the late 20th century allowed for sampling by multiparameter profilers and fixed-position moorings. These, along with Earth observation satellite data gave a more expansive picture of lakes but have uncovered many new questions about how the systems function.

Autonomous monitoring of aquatic systems has deployed communications and data science advances primarily in moored buoys and platforms. The freely drifting Argo-floats ocean system (Kerut, 1980) is a classic example of an autonomous system that continuously transmits open ocean data via satellite links. Improved, off-the-shelf communications technology allows deployment of automated lake buoys which can perform long-term measurements with programmed or remotely controlled sensors. Several lake platforms have been deployed (Box 1) in order to collect comprehensive datasets (Hamilton et al., 2015). Automated buoys however do not provide space for lab equipment and personnel. Here we show that an open water platform can overcome these limitations. The vision for LéXPLORE was to provide (a) space for instrumentation, (b) laboratory-like working conditions, (c) close and continuous proximity to the lake environment, (d) the possibility to perform in-situ experiments, and (e) a facility for developing and testing new sensor technology. LéXPLORE will also create novel opportunities for combining advanced in-situ sensors with traditional lab analyses in an integrated, interdisciplinary research environment.

An open water research platform requires safe surroundings to protect instruments from other lake activities, such as fishing, transportation, and recreation. Close proximity of the sensors to the platform simplifies instrument operation, maintenance, and data transfer. The platform itself should provide safe and spacious working conditions including a shelter, personal facilities, and a motion-dampened workspace. Operating in direct contact with the lake environment, the platform laboratory is especially useful for using instrument components that are not sealed in watertight apparatus. The platform size should accommodate a team of researchers (or even multiple teams) and thus supports interdisciplinary research. A large pontoon mass reduces buffeting and movements to levels suitable for stable atmospheric measurements and optical remote sensing, which require fixed or at least controlled positioning for precise observations.

This publication introduces the LéXPLORE platform (Figure 1) recently installed on Lake Geneva (Switzerland/France), lists its advantages compared with pre-existing platforms and discusses ongoing and future research that LéXPLORE can facilitate.

2 | LéXPLORE PLATFORM REALIZATION

The facilities listed in Box 1 demonstrate the feasibility of an operational field station on Lake Geneva and provided guidance for development and design. Careful study of these systems evolved into a list of design specifications. These included (a) stability and ability to withstand a 100-year storm (winds of 140 km/h with 1.5 m significant wave height

BOX 1 Active platforms on lakes

Instrumented, moored buoys, platforms, and permanent monitoring facilities have been developed and deployed at various global localities. The following list of five representative examples describes the range of active stations and how they vary substantially in terms of research objectives and instrumentation. This list is obviously incomplete.

MÜGGELSEE MONITORING STATION – IGB BERLIN: This automated research and monitoring station (www.igb-berlin.de/en/muggelsee-monitoring-station) has operated since the 1970s on the small, shallow Müggelsee (Germany). It collects meteorological, physical and biological (plankton) data in real time in order to investigate the ecological impacts of climate and environmental changes on aquatic communities and biodiversity. This station serves both national and international observational programs (Schmidt et al., 2018).

AQUAPROBE – EAWAG: This automated lake monitoring station (www.aquascope.ch/) on Greifensee (Switzerland) provides continuous (24 h), high-frequency measurements on phytoplankton and zooplankton at 3 m depth along with environmental monitoring data (multiparameter profiles, weather station, and automated nutrient sampling). Data streamed in real-time are used to investigate plankton biodiversity and dynamics. Plankton monitoring consists of scanning flow cytometry (www.cytobuoy.com) and observations by the newly developed Aquascope, an underwater high-resolution, dual-magnification imaging microscope (Orenstein et al., 2020; Pomati et al., 2011).

ERKEN LABORATORY – UPPSALA UNIVERSITY: This program has a long history of monitoring physical, chemical and biological conditions on Lake Erken and more recently, on Lake Mälaren and surrounding rivers. Monitoring has been performed manually since 1940 and with automated high-frequency sensor technology since 1988. The present Erken Monitoring Program (www.ieg.uu.se/erken-laboratory/) measures physical and chemical variables, plankton composition, greenhouse gas fluxes and both inflow and outflow water quality (Pettersson, 2012). The station is part of the Swedish Infrastructure for Ecosystem Sciences, which monitors diverse habitats and climatic zones to ensure long-term data coverage (www.fieldsites.se/en-GB).

LAKE GEORGE SMART SENSOR NETWORK: While not a singular platform, this project consists of a network of 12 weather stations, 4 vertical profilers, 12 tributary stations, and several current profilers (https://www.jeffersonproject.rpi.edu/lake). As a collaboration between Rensselaer Polytechnic Institute, IBM Research, and the FUND for Lake George (The United States), the network monitors water flows and water quality in order to understand human impacts and identify mitigation strategies (Gilbert, 2018).

GREAT LAKES OBSERVING SYSTEM: This project covers the entire Great Lakes System of North America. The network continuously monitors biological, chemical, physical, and meteorological parameters using a large number of anchored observational buoys (www.glos.us; www.uwm.edu/glos/). Data is freely available to scientists, water managers, government and the public via an on-line data portal (Read et al., 2010).

and 0.5 m/s water flow), (b) heavy structure to minimize motion, (c) spatial layout allowing adequate equipment installation and lab bench space necessary for parallel working conditions, (d) a sheltered laboratory for working with non-weatherproof equipment, preparing samples, conducting IT tasks and providing protection for severe weather and overnight campaigns, and finally, (e) space for moonpools that directly access the lake surface both inside and outside the cabin. Site location specifications were (a) a distance far enough offshore to ensure open water conditions, (b) positioning above depths that represent a substantial part of the hypolimnetic water column, and (c) a location that addressed concerns of other lake stakeholders. The final location was negotiated with the granting governmental authorities, professional fishermen, recreational anglers, the public ferry, water police, the local harbor operator, sailing association, and a local conservation NGO.

The LéXPLORE design emulated existing and past platform designs (Box 1) especially those of the oceanographic Floating Instrument Platform (Fisher & Spiess, 1963) and the WAVES Tower on Lake Ontario (Birch et al., 1976). The latter installation consists of a bottom-mounted tower at the western end of Lake Ontario. Built in 1975 and powered by a shore-based underwater cable, the tower rests 1.1 km offshore at a local depth of 15 m, where it can intercept wind fetches of 1–300 km. The bi-level design of the tower consists of an 85 m^2 open grating upper deck to minimize flow distortion and a lower walkway 3.6 m above the lake surface. The tower allows for

FIGURE 1 Side view of LéXPLORE from the south with the town of Pully in the background. The image shows the sheltered laboratory and exterior meteorological instruments (a), solar panels (b), on roof and towards south, two A-frames (c), the outdoor moonpool (d) with electrical winch (e), support frame for lifting loads (f), and the structure maintaining a thermistor chain (g). Blue anchor winches with cables for positioning rest at all four corners (h) and are mounted with navigation lights (i). The two doors access the toilet (k) and the laboratory (l). Battery banks and diesel-generator rest inside the pontoon-hull. The yellow buoys delineate the safety perimeter (j) for instrument protection. Reprinted with permission from Florian Bentlee, Stuttgart, Germany

high-quality wave and wind measurements that capture directional fetch-limited frequency spectra of wind-generated waves (Donelan et al., 1985).

Five companies participated in design and construction of LéXPLORE. The main tasks consisted of hull construction, anchorage of the platform and the installation of the protective perimeter. The platform was built on a nearby dock and anchored after its completion on 19th February 2019 at 570 m off the north shore at a local depth of 110 m. Financial resources were provided by the five LéXPLORE partner institutions, (a) the Swiss Federal Institute of Technology, Lausanne (EPFL; www.epfl.ch/research/domains/limnc/), (b) the Swiss Federal Institute of Aquatic Science and Technology (www.eawag.ch/), (c) the University of Geneva (www.unige.ch/forel/en/), (d) the University of Lausanne (www.unil.ch/idyst/), and (e) CARRTEL INRAE-USMB (www6.lyon-grenoble.inrae.fr/carrtel/). Box 2 summarizes LéXPLORE's technical specifications.

Besides the physical platform on the lake, data management is a crucial component of LéXPLORE (Box 3). There are two types of data: (a) monitoring data (core dataset), which are freely available for download at www.datalakes-eawag.ch and (b) project-specific data curated by project leaders. The monitoring data include continuous meteorological parameters and currents, as well as temperature, oxygen and photosynthetic-active-radiation (PAR) and multi-parameter profiles (Appendix S1; www.lexplore.info/available-dataset/). Ongoing projects use project-specific equipment and instrumentation, some of which are listed in the Appendix S1. We encourage research teams to make all data publicly available when projects end, although final decisions and responsibility for data access lie with project leaders and funding agencies. Since the beginning of operations (February 2019), 30 projects have applied to use LéXPLORE, which are listed in Appendix S2. In addition to being technically and scientifically feasible, all projects must comply with LéXPLORE operational and safety policies (www.lexplore.info/current-projects/).

3 | RESEARCH OPPORTUNITIES

The research partnership established between the five institutions supporting LéXPLORE enables a broad range of future research projects. Relative to existing platforms, LéXPLORE stands out in terms of its instrumentation and

BOX 2 LéXPLORE platform technical features

The LéXPLORE platform (Figure 1) consists of a 10 × 10 m steel pontoon with a vertical dimension of 1.5 m and a minimum of 1 m freeboard above the water surface. The light and maximum displacements are 35 and 47 metric tons, respectively, with a maximum permitted load of 5 tons including 16 staff. The multichambered pontoon hull consists of eight individual compartments, which are connected at their tops for wiring, however their large volumes guarantee that in case of leakage, only one compartment would be flooded. This eliminates risk of foundering. The four edges of the platform include marine winches (Figure 1) connected to 3-ton heavy Delta Flipper anchors installed at horizontal distances of 170–200 m from the platform. Simulations showed that this mooring design would hold the pontoon in place within ∼4 m horizontal dislocation at maximal-expected wind speeds of 140 km/h (Vuyk, 2019).

Electricity is generated on the platform by (a) 45 m^2 of photovoltaic (PV) panels (nominal capacity 8.5 kW) and (b) a back-up soundproof diesel generator (30 kVA). During the first 2 years, the PV panels provided 97% of the electricity (in total 10.8 MWh). The electrical generator supports specific applications and can help bridge multiple sun-free days in deep winter. Figure 1 shows the station's 28 PV panels along its southern edifice and the laboratory roof. The weather-proofed system was installed by certified professionals and meets country-specify safety standards.

The deck hosts the indoor laboratory, two A-frames, a loading dock with a hand-wheel crane (Figure 1) and an outdoor moonpool (1.5 × 1.5 m, Figure 2(b)) equipped with an electrical KC crane for profiling, water sampling or other deep-water assays. The deck also includes a water closet with a toilet and sink (Figure 1). The inner compartments of the pontoons hold a battery bank (2000 Ah @ 48 V), the back-up electrical generator, a 1000 L diesel supply tank and a 1000 L blackwater tank. The sheltered laboratory (5.9 × 4.5 × 2.3 m; Figures 1 and 2) includes a heating unit, a fume hood, a small workshop, cabinetry, shelves, a moonpool (1.5 × 1.5 m, Figure 2(d)) equipped with an electrical winch and water pumps for variable-depth water intake and several bunk beds. A control cabinet contains several computers, controllers and dataloggers for platform operation and safety checks. These include a pontoon motion monitoring and video camera system. Computers perform data acquisition from instruments as well as 4G data transmission to remote servers (Box 3).

Water for the toilet and cleaning sink is pumped directly from the lake. Purified water used in analytical procedures needs to be transported to the platform.

A ∼15,000 m^2 safety perimeter (Figure 1) surrounds the platform and protects instruments from drifting fishing nets and boats. The perimeter consists of nine illuminable buoys installed ∼70 m from the platform and anchored by 2-ton bottom weights. Fifty-meter long cables hang between buoys to form a protective curtain that shields scientific equipment. The perimeter allows for undisturbed in-situ measurements and thus forms a critical component of the platform.

accessible workspace. The types of measurements possible on the platform can support interdisciplinary project teams working in parallel on the same question while using different techniques. Below, we describe research efforts, which require interdisciplinary collaboration and long-term high frequency observations that allow investigating ecological phenomena under varying forcing conditions and different scales.

3.1 | Connecting physical and biogeochemical mechanisms of the carbon cycle

A grand challenge facing aquatic biogeochemistry lies in resolving how specific physical, chemical, and biological processes of the carbon cycle act at different temporal and spatial scales (Eglinton, 2015). Many driving mechanisms of the lacustrine carbon cycle occur at time scales much shorter than those addressed by traditional field sampling and laboratory analysis. The analytical limitations of high-frequency measurements have long restrained and even confounded understanding of carbon cycle dynamics in aquatic ecosystems (Hanson et al., 2006; Klaus et al., 2019).

The LéXPLORE platform offers high-frequency automated sensors for different parameters relevant to the aquatic carbon cycle, including pCO_2, UV–visible absorbance and fluorescence, pH, conductivity, and oxygen

BOX 3 DATALAKES—A data management platform for lakes

The LéXPLORE platform with its various monitoring and scientific instruments generates vast quantities of data. Efficient access to and utilization of LéXPLORE data requires dedicated curation. The web-based open access data platform Datalakes (www.datalakes-eawag.ch/) is designed for these needs.

Datalakes serves as a sensor-to-frontend platform for data on any Swiss lake. The software performs continuous acquisition, storage, curation, indexing, patching, visualization, and extraction of lake-related environmental data and products. Datalakes offers a modern, user-friendly online interface with easy-to-use visualization and extraction functions. The platform also seeks to maximize reproducibility and data integrity. Access does not require registration and provides raw data (labeled as Level 0) up to commonly used products integrating information from multiple sensors. As an example, the interface categorizes surface net heat flux (www.datalakes-eawag.ch/datadetail/452) as Level 2 data.

Both the web portal and GIT repository offer access to processing scripts with the intention that the scientific community will adapt, update, and optimize them. To avoid ill-defined reproducibility, changes in processing scripts and methods, Datalakes tracks workflow and performs version control using a Renku platform (www.datascience.ch/renku/). Finally, Datalakes is not confined to LéXPLORE data but rather combines different sources of information. This promotes data visualization and extraction of one-dimensional and three-dimensional hydrodynamic models using remote sensing data from Meteolakes (www.meteolakes.ch/; Gaudard et al., 2019; Baracchini et al., 2020). This GIS-based visualization portal facilitates integration of different data layers generated by remote sensors, in-situ instruments and hydrodynamic models.

(Watras et al., 2015). These carbon cycle parameters are typically under-sampled over seasonal time scales and during episodic events (Natchimuthu et al., 2017). Studies of lake carbon processes have also primarily focused on surface layers where greenhouse gas exchange with the atmosphere occurs. Greater depth-resolved sampling and sensor options available through LéXPLORE allow for higher resolution monitoring of relevant parameters and active boundaries (Perolo et al., 2021). In addition to measuring CO_2-related parameters in a mooring array, LéXPLORE instruments can also detect CH_4 peaks within the oxic water column (Günthel et al., 2019).

As a station equipped with a broad range of instruments (Box 2; Appendix S1), LéXPLORE will help build a more integrated understanding especially of physical mechanisms and biogeochemical processes related to the carbon cycle. Critical questions concerning the role of wind forcing and deep-water upwelling events can be addressed by these approaches (Natchimuthu et al., 2017). Compared with automated buoys (Box 1), LéXPLORE expands both analytical scope and data precision by providing a dry working environment for deploying critically sensitive sensors. These include a UV–Vis spectrometer for high-frequency dissolved organic matter optical characterization (S::CAN Spectrolyzer; Müller et al., 2014) and infrastructure like water-pumps and automated samplers for sequential chemical analyses (e.g., alkalinity, isotopic compositions, and nutrient concentrations at low levels). The floating laboratory facilitates ongoing maintenance and calibration of sensors and immediate conditioning, preparation, and analysis of samples that would otherwise risk alteration during transport or long sampling campaigns.

3.2 | Gas exchange dynamics in response to complex forcing

Dissolved gases are important components of all surface water processes. They figure prominently in biogeochemical cycles and overall ecosystem function in lakes. Surface waters interact with the atmosphere by exchange of gases such as oxygen or greenhouse gases, CO_2, CH_4, and N_2O (Beaulieu et al., 2019; Cole et al., 2007). Advances in understanding of the role that lakes play in the global CH_4 balance has concentrated research activity in limnology. Gas fluxes are driven by gradients of partial pressures and turbulence at the air–water interface. Newer sensors can measure gas partial pressures at a higher resolution such that gas transfer velocities have become critical sources of the remaining uncertainties.

The LéXPLORE platform allows direct and continuous measurements of gas exchange using multiple techniques applied under varying environmental conditions. Accurate estimation of piston velocity is a primary goal for establishing reliable semi-empirical parameterizations (Klaus & Vachon, 2020). Various processes

FIGURE 2 LéXPLORE elements (from top left to bottom right): (a) outdoor work area, (b) outdoor moonpool with electric crane (left) and pump system (right), (c) Wirewalker deployment using an A-frame, (d) partially covered indoor moonpool, and (e) office work area

contribute to uncertainties in piston velocities including (a) lateral and temporal variability of wind forcing, (b) interactions of wind-induced and cooling-induced turbulence, and (c) fluctuations in surface wave-affected gas transfer (Deike & Melville, 2018; Reichl & Deike, 2020). In addition, the scale of vertical and temporal variations in gas concentrations in the upper few tens of centimeters of the water column (Watson et al., 2020) and sub-daily variation in near-surface stratification and gas transfer velocity from intermittent wind, waves, and heat fluxes can obscure detection of forces driving gas transfer. These dynamics demonstrate that both concentration gradients (driving force) and turbulence levels (transfer velocity) vary considerably over short time scales of less than a day. Gas fluxes represent the instantaneous product of these processes and thus vary on the same time scales.

LéXPLORE allows long-term, continuous operation of automated forced-diffusion chambers that measure CO_2 fluxes at the air–water interface (Perolo et al., 2021; Risk et al., 2011). A CO_2 eddy-covariance system mounted on the laboratory roof (Erkkilä et al., 2018; Eugster et al., 2003) can provide flux measurements integrated over larger spatial scales. These direct observations can further constrain turbulence-based models for gas exchange velocities. Surface layer turbulence can be quantified with upward-facing High-Resolution Acoustic Doppler Current Profilers, rising Microstructure Profilers or autonomous profiling Wirewalkers (Rainville & Pinkel, 2001; Figure 2(c)) and (potentially) water-side eddy-covariance measurements (Berg & Pace, 2017). In summary, the LéXPLORE platform offers the necessary infrastructure (Appendix S1) for evaluating gas fluxes over short time scales and a broad range of forcing conditions and lake dynamics.

3.3 | Resolving surface microlayer dynamics from a stable platform

The air–water interface is the first direct and visible contact, when approaching lakes. In spite of its seeming accessibility, the size and variation of the air–water interface poses major experimental challenges in lake sciences (Soloviev &

Lukas, 2013). Surface layers feature distinct dynamic structures down to microscopic scales (<100 μm). These in turn determine physical and biogeochemical processes for the near-surface and beyond (Cunliffe et al., 2013). Electromagnetic radiative transfer notwithstanding, molecular bottlenecks of diffusive and viscose boundaries, themselves governed by adjacent turbulent atmospheric and water layers, determine air–water exchange. Under conditions of strong winds, breaking waves contribute additional turbulent kinetic energy and thereby enhance this exchange (Terray et al., 1996).

An illustrative example of the influence of small-scale features is the up to 0.5°C temperature differential that can develop between the thermal sublayer skin and underlying bulk water, which becomes particularly pronounced under weak wind (Wilson et al., 2013; Irani Rahaghi et al., 2019). This difference exceeds the detection limits of high-resolution satellite radiometers currently used to monitor lakes. Temperature data for inland waters should thus include skin-to-bulk differences (Minnett et al., 2011; Riffler et al., 2015). Establishing relations between the skin and bulk properties or more generally, between the surface microlayer and the turbulent layer beneath, represents a major challenge in limnology. LéXPLORE provides an observational solution for characterizing differences between near-surface boundary layers (Section 3.2). Specifically, LéXPLORE allows continuous sensing by closely-spaced thermistor arrays and highly resolved acoustic Doppler current profiles together with upward fine-structure temperature profiling and automatized water-sampling. These in-situ observations can be complemented by downward-facing airside radiometers and meteorological instruments (Appendix S1), which together enable quantification of dynamics in near-surface layers under variable conditions.

The surface boundary layer also hosts unique biogeochemical processes including the formation of biofilms. These process terrestrial particles (such as pollen in spring) and autochthonous lacustrine organic matter. Surface biofilms modify the physico-chemical characteristics of the air–water exchange for instance by greater heat absorption, which increases the skin-to-bulk temperature gradient (Soloviev & Lukas, 2013) or greater viscosity, which increases lake surface tension (Cunliffe et al., 2011). Biofilm organic matter may influence the absorption of ultraviolet radiation and also by extension, water column penetration of biologically harmful radiation. LéXPLORE provides a unique facility that help scientists investigate biogeochemical and physical interactions that characterize this directly accessible yet difficult to analyze surface microlayer.

3.4 | Seasonal apparent and inherent optical properties for remote sensing applications

Accurate interpretation of satellite-based Earth observation imagery depends on fiducial ground reference measurements of Apparent and Inherent Optical Properties (AOPs and IOPs). Calibration and validation of atmospheric corrections and the resulting water-leaving reflectances require standardized measurements of AOPs and specifically of downwelling irradiance (Ruddick et al., 2019a) and water-leaving radiance (Ruddick et al., 2019b). In practical terms, such measurements are acquired at several marine sites, most notably by the AERONET-OC network (Zibordi et al., 2010), BOUSSOLE (Antoine et al., 2008), and MOBY (Franz et al., 2007). The availability of equivalent calibration data for lakes remains scarce despite efforts by the Committee on Earth Observation Satellite's Radiometric Calibration Network (RadCalNet) or the WATERHYPERNET to establish comparable measurement data for inland waters (Vansteenwegen et al., 2019). Measurements from a stationary-oriented platform like LéXPLORE offer advantages over those collected from a moving boat. IOPs help to rigorously tie AOPs to biophysical parameters such as phytoplankton concentrations, particles and colored dissolved organic matter. Lab analyses and in-situ measurements can also constrain bulk spectral absorption as well as beam transmission and attenuation (Riddick et al., 2015).

LéXPLORE operation in open water settings allows deployment of the automated Thetis profiler (Minaudo et al., 2021) adjacent to the platform (Figure 3). This profiler acquires bulk IOP measurements at high frequencies and high vertical resolution (Appendix S1). The tool can capture relatively poorly understood diel and vertical variations in IOPs that influence a wide variety of aquatic processes including primary production (Figure 3), whiting, grazing, and intrusion of riverine suspended particles (Minaudo et al., 2021). Using these novel measurements as inputs to radiative transfer models will yield simulated AOP results showing water-leaving or top-of-atmosphere reflectance. These outputs can be compared with spectroradiometer measurements acquired in-situ by Thetis, with those acquired by LéXPLORE surface instruments, or with satellite observations. Dual closure of water-leaving reflectance obtained from measured and simulated AOP based on measured IOP improves accuracy and reduces uncertainties associated with ground measurements typically used for vicarious calibration (Werdell et al., 2018). LéXPLORE thus provides fiducial reference measurements for the calibration and validation of atmospheric correction methods.

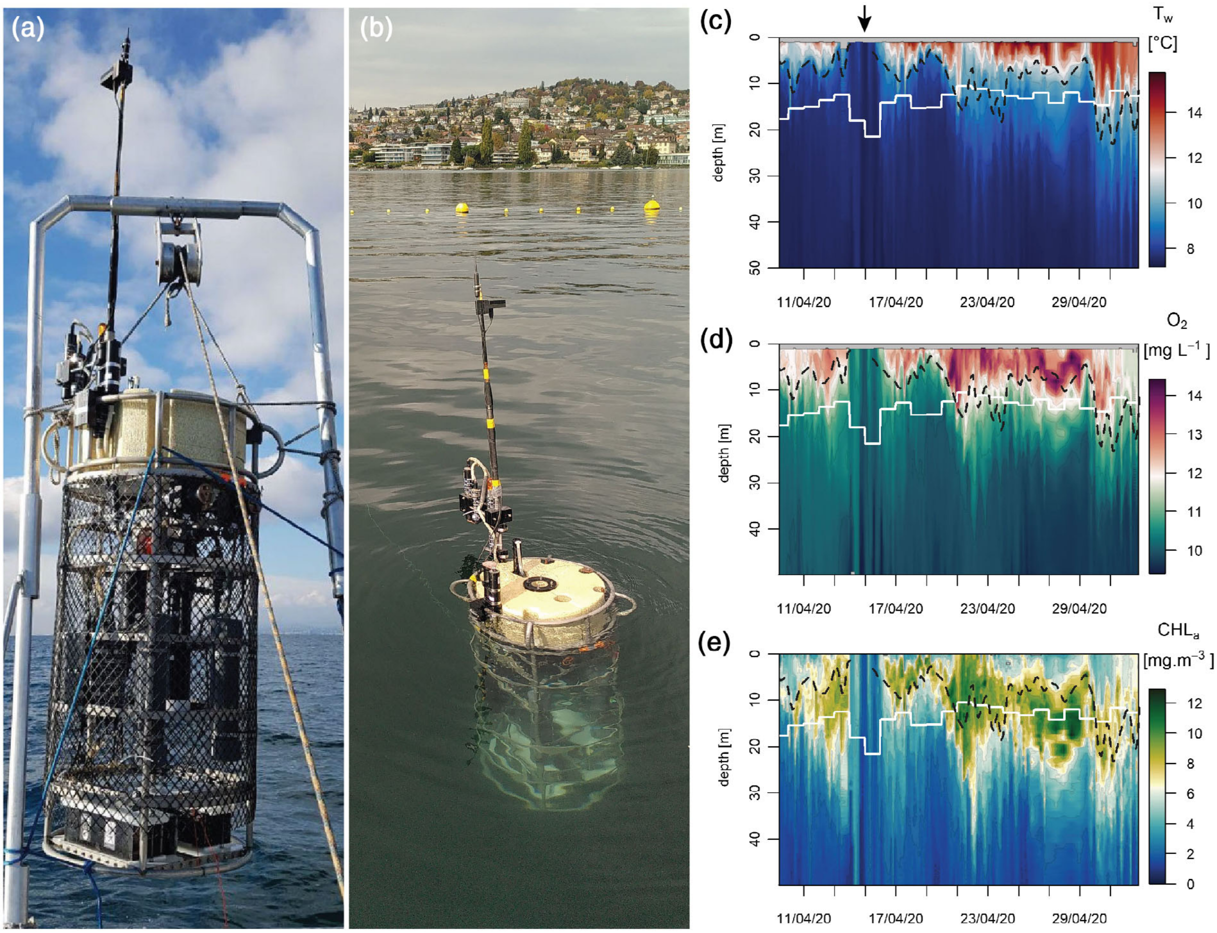

FIGURE 3 Thetis profiler measurements at LéXPLORE: Thetis deployment with various sensors inside the cylindrical black-meshed rack (a) and Thetis rising and breaching the surface with its antenna installed above the bright-yellow buoyancy body (b). The antenna operates via FreeWave radio technology. The three panels show examples of vertical temperature (c), oxygen (d), and chlorophyll-a (e) data series collected by Thetis in the upper 50 m of the water column near LéXPLORE at a resolution of ~3.0 h. Black-dashed and white lines, respectively, indicate the thermocline and euphotic depths. Thetis can also acquire electrical conductivity, hyperspectral absorption and attenuation, backscattering and fluorescence at discrete wavelengths, PAR and hyperspectral up-welling and down-welling radiations (Appendix S1). These exemplary profiles show a warming period in April 2020 interrupted by 2 days of wind-driven mixing/upwelling (black arrow in c) and subsequent chlorophyll-a and oxygen accumulation in the epilimnion. Reprinted with permission from Minaudo et al. (2021)

3.5 | High-frequency plankton monitoring under environmental change

Populations and individuals face trade-offs in ecosystems. Species may perform well at certain functions but find themselves at a disadvantage regarding others. Species within a community are shaped not just by the environment but also by both disadvantage and advantage matrices of other organisms (Cadier et al., 2019; Ehrlich et al., 2017; Litchman & Klausmeier, 2008). Predictions of ecological consequences depend on complex webs of interaction but trade-offs in these webs remain difficult to quantify, especially in aquatic communities that resist experimental interventions (Ehrlich et al., 2020). The high-frequency in-situ monitoring capabilities of LéXPLORE can address some of these limitations. Together with Pomati et al. (2011), we are developing a combined CytoBuoy flowcytometry and AquaScope image analyzer to automate phytoplankton and zooplankton monitoring (Box 1). Combined with novel machine-learning techniques for automated data analysis, these tools can monitor species abundances and environmental conditions over short time scales. Observations can inform studies on environmental interdependence and growth cycles (Thomas et al., 2018). These new approaches can also enable process-based forecasts on how lake communities respond to environmental changes on time-scales from weeks to decades.

Environmental dependencies in trophic interactions also pose significant challenges for traditional lake monitoring. Abiotic factors can impose nonlinear effects on the physiology and growth of individual species (Thomas et al., 2017; Uszko et al., 2017) which in turn influence the growth of interacting species, especially predators (DeLong & Lyon, 2020). Complex feedbacks can arise from multiple species occupying different trophic levels and interacting within the environment (Luhring et al., 2018). Evaluating interacting environmental dependencies is critical for understanding and predicting how ongoing warming and oligotrophication will affect lake ecosystem function. Current factorial lab experiments are investigating how species respond to changes in multiple environmental dimensions. These are coupled to model simulations that predict how effects propagate to higher trophic levels. High-frequency observations from LéXPLORE will help validate model predictions through monitoring of multiple interacting trophic levels. Observations during extreme meteorological events can provide important constraints on model predictions of how perturbations and temperature–food relationships will shape the future Lake Geneva ecosystem. Continuous monitoring using LéXPLORE is critical in capturing data from rare and multidimensional ecosystem events.

3.6 | Long-term studies of fish population dynamics

LéXPLORE offers unique opportunities to research fish population dynamics and species diversity. Both local and global fisheries studies require information on population dynamics, recruitment, and food web interactions (Cheung et al., 2009). The platform facilitates sampling and analysis of individuals for traits, maturity, parasitism, and genetics. These investigations also require high quality environmental background data (Olmos et al., 2020). LéXPLORE data (Box 3; Appendix S1) and collaborative frameworks can thus support classic ongoing or novel fisheries studies.

In addition to shifts in plankton communities, trophic networks (Section 3.5) and biogeochemical processes (Section 3.1), reoligotrophication of Lake Geneva has helped restore iconic threatened species such as whitefish (*Coregonus* sp.; Lynch et al., 2015; Straile et al., 2007) and Arctic charr (*Salvelinus alpinus*; Caudron et al., 2014). However, these species now face additional threats from increasing temperatures, modified riverine flows and changing wind patterns during critical development phases (Kelly et al., 2020; Mari et al., 2021; Nõges et al., 2018). Core datasets (Box 3; Appendix S1) and plankton studies (Section 3.5) from LéXPLORE will support investigations on the temporal coupling between the emergence of fish larvae and the phenology of plankton, or the risk of so-called match–mismatch phenomena (Cushing, 1990). This synchronism plays a key role in fish recruitment and therefore the size of the fishery. Recruitment depends strongly on short-term weather phenomena such as sudden and pronounced upwelling events (Baracchini et al., 2020). For example, spring storms can lower the surface temperature by more than 10°C in less than 24 h. This can kill perch larvae (*Perca fluviatilis*) which lack the ability to take refuge in warmer zones. High-frequency water column data will help constrain key parameters and impacts of these events. Toxic algal blooms (Platt et al., 2003), microplastics (Parker et al., 2021), and new organic pollutants (Corsolini et al., 2005) all impact fish communities as well. In addition to addressing these, the LéXPLORE platform can provide samples for genomic studies such as analysis of e-DNA samples (Sales et al., 2021) from different depths or remote hydroacoustic surveys using broadband sounders (Benoit-Bird & Waluk, 2020; Appendix S1). These datasets can help natural resource specialists and scientists manage fish communities and invasive species by assaying larval emergence phenology or species diversity, distribution in the water column, and schooling behavior as a function of biotic or abiotic dynamics.

3.7 | Addressing complex questions by integrated, multidisciplinary approaches

LéXPLORE offers the opportunity for several teams to work simultaneously on different or joint projects. Compared with existing platforms, LéXPLORE stands out in terms of its functionality and flexibility as a workspace which can serve a broad range of complementary measurement applications and research questions. The question of what regulates primary production—one of the first projects initiated on LéXPLORE—is such an example of a prescient, systems-level science question requiring integrated, multidisciplinary approaches. Primary production depends on both vertical distribution and vertical flux of nutrients and algal communities, as well as on carbon cycling and light regimes. As documented by the first LéXPLORE publications, teams working simultaneously and using diverse approaches can build effective lines of evidence to address these questions (Fernández Castro et al., 2021; Minaudo et al., 2021; Perolo et al., 2021).

4 | CONCLUSIONS AND OUTLOOK

Given the inherently variable nature of aquatic systems, effective scientific investigations require long-term observations at high vertical and temporal resolution. To address these needs and overcome limitations imposed by traditional monitoring by boat, mooring, and automated buoys (Box 1), a consortium of five partner institutions constructed a multipurpose platform for performing a broad range of scientific observations on Lake Geneva. The LéXPLORE platform provides a workspace for a large number of instruments and up to 16 staff working in parallel or on different projects (Box 2). The dry, protected laboratory offers direct access to the lake environment for high-sensitivity, high-throughput measurements including development of novel sensor technology. In addition, the floating laboratory offers a range of possibilities for student projects and field courses, as well as education/outreach activities for the public.

The LéXPLORE platform represents unprecedented analytical access to a large, dynamic lake environment experiencing reoligotrophication under conditions of a changing climate. LéXPLORE combines complex instrumentation and lake environment access. The station offers diverse analytical opportunities from lake in-situ microscopy of plankton communities to long-term, multiparameter measurement of local atmospheric dynamics. Since anchoring of the platform in February 2019, 30 projects (Appendix S2) have made use of LéXPLORE. Initial research projects indicate that LéXPLORE is an effective facility for making major scientific contributions. The greatest effect of LéXPLORE is its community-building role, as field-based scientists meet and exchange, and thereby stimulate interdisciplinary studies. We encourage lake researchers to consider how such an equivalent platform might serve their research and also welcome any inquiries from scientists interested in using LéXPLORE.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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DATA AVAILABILITY STATEMENT

All data related to LéXPLORE is freely available at: https://www.datalakes-eawag.ch/

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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