Water Research 172 (2020) 115529

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Meteolakes: An operational online three-dimensional forecasting platform for lake hydrodynamics

Theo Baracchini [a], Alfred Wüest [a, b], Damien Bouffard [b, *]

[a] Physics of Aquatic Systems Laboratory (APHYS) — Margaretha Kamprad Chair, ENAC, EPFL, 1015, Lausanne, Switzerland
[b] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters — Research and Management, 6047, Kastanienbaum, Switzerland

ARTICLE INFO

Article history:
Received 22 July 2019
Received in revised form
9 January 2020
Accepted 20 January 2020
Available online 21 January 2020

Keywords:
Lake modelling
3D hydrodynamics
Information dissemination
Real-time monitoring
Forecasting
Data assimilation

ABSTRACT

Environmental management depends on high-quality monitoring and its meaningful interpretation. The combination of local weather dynamics, regional anthropogenic stresses and global environmental changes make the evaluation of monitoring information in dynamic freshwater systems a challenging task. While the lake ecosystems gather many complex biogeochemical interactions, they remain constrained by the same physical environment of mixing and transport. It is therefore crucial to obtain high-quality physical system insight. Three-dimensional hydrodynamic models are perfectly suited for providing such information. However, these models are complex to implement, and their use is often limited to modellers. Here, we aim to provide model output via a user-friendly platform to a broad audience ranging from scientists to public and governmental stakeholders.

We present a unified approach merging the apparently diverse interests through meteolakes.ch, an online platform openly disseminating lake observations and three-dimensional numerical simulations in near real-time with short-term forecasts and data assimilation. Meteolakes is scalable to a broad range of devices, modular and distributed, hence allowing its expansion to other regions and hardware infrastructures. Since 2016, the platform has continuously provided timely synoptic lake information to more than 250,000 users. This web-based system was built not only to provide guidance to scientists in the design and analysis of field experiments and to foster interdisciplinary lake studies, but also to assist governmental agencies and professionals in the long-term policy and planning of water resources management. Finally, our system aimed at promoting awareness and understanding of the complexity of lakes and providing information to the public through user-friendly interfaces. This article details the design and operation of such a platform and its products. Applications are demonstrated by examples of a recent upwelling and a storm event. Both cases illustrate how Meteolakes help scientists in their quest for process understanding as well as water professionals and civil society in providing specific warnings.

1. Introduction

Successful environmental management depends on high-quality monitoring. Such information is relevant for the entire management chain from the definitions of environmental goals to planning, implementation, enforcement and finally to efficiency control. A touchstone of effective management is the ability to convert monitoring to meaningful information and actions. The complex dynamic response of water bodies to external forcing often hampers any straightforward interpretation of monitoring data. External forcing always comes as a combination of long-term global environmental changes, local anthropogenic influences and short-term weather dynamics. In lakes, a lack of anticipation of those responses can lead to management inefficiency and additional costs as well as compromising long-term quality targets. The combined costs related to eutrophication in the US freshwater systems amounts to $2.2 billion per year (Dodds et al., 2009). Long-term eutrophication-related issues lead to emergency interventions in response to harmful algae blooms. A well-known example was the drinking water shutdown on August 2nd 2014, in the vicinity of the City of Toledo (Lake Erie), affecting more than 500′000 consumers (Carmichael and Boyer, 2016). Besides the need to predict at short time scales, the development and evolution of harmful algae (Paerl et al., 2011) and - more generally - to prevent

* Corresponding author. Eawag, Seestrasse 79, 6047, Kastanienbaum.
E-mail address: damien.bouffard@eawag.ch (D. Bouffard).

https://doi.org/10.1016/j.watres.2020.115529

human exposure to critical substances and pathogens (Brookes et al., 2004), there are many other environmental risks and human activities requiring attention (i.e. management of heat extraction, water level, flooding, leisure and professional boat navigation and related storm hazards).

The challenge is that biogeochemical processes are driven by an incommensurable number of reactions. Yet, they are all subject to the same physical environment. It is therefore crucial to first establish a high-quality representation of the hydrodynamics that is the transport and mixing governed by advection-diffusion equations. Furthermore, physical and biogeochemical processes are usually spatially structured (Bouffard et al., 2018), hence traditional in-situ monitoring may lack representativeness due to its limited spatial coverage (Kiefer et al., 2015; Soulignac et al., 2019). This brought to the fore the need for new monitoring programs (Hering et al., 2015), using novel approaches in combining numerical simulations and remote sensing observations (Vörösmarty et al., 2015).

The adoption of one-dimensional hydrodynamic models is growing at a rapid pace (Gaudard et al., 2017; Gaudard et al., 2019; Bruce et al., 2018; Kirillin et al., 2011), while three-dimensional (3D) models, beyond the expert users, have been limited in their applications due to complexity and tedious calibration. Those latter models are currently the only source of information able of resolving physical processes at the large variety of spatio-temporal scales involved in lake dynamics. The results of the combination of direct observations and numerical simulations can be disseminated in a timely and comprehensive manner by operational forecasting systems. As of today, a limited number of operational systems with an integrated data-model approach exist to monitor inland waters. The most notable is undoubtedly the Great Lakes Operational Forecast System (GLOFS, https://tidesandcurrents.noaa.gov/ofs/glofs.html) initiated more than 25 year ago (Schwab and Bedford, 1994) that provides nowcast and forecast guidance of various physical characteristics, such as water levels, temperature, currents and ice cover, for the five North American Great Lakes (Chu et al., 2011; Anderson et al., 2018). Other platforms have been developed such as the online lake modelling tool FLake-Global (http://www.flake.igb-berlin.de/model/run), a platform for the one-dimensional estimation of temperature and mixing conditions in any shallow freshwater lake at seasonal scale (Kirillin et al., 2011), the open-access platform Simstrat (https://simstrat.eawag.ch/) for high-frequency lake modelling and statistics data sharing for scientists and practitioners (Gaudard et al., 2019), the 3D monitoring and forecasting tool WIS-CAST, applied to a mid-sized lake for a duration of three months (Kimura and Wu, 2018), or the 3D hydrodynamic model for Lake Constance (Bodenseeonline; https://www.lubw.baden-wuerttemberg.de/wasser/bodenseeonline). Nevertheless, the number of online lake operational systems remains limited, particularly when compared to the widespread use and development of meteorological and coastal ocean systems (Kourafalou et al., 2015).

In this study, we present a near real-time monitoring and forecasting system for lakes with its online platform, meteolakes.ch. This platform aimed at a paradigm shift in how lakes are studied and monitored by providing the following possibilities: (i) an unified user-friendly data visualisation platform for citizens, water professionals and scientists, (ii) an open access to the model output (for historical and forecasting data); and (iii) an uncertainty quantification of model output through data assimilation. These requirements warrant an optimal dissemination of data (open access to the data), facilitation of short-term decision-making (user-friendly visualisation) and possible use of the output data (uncertainty quantification). Meteolakes processes and disseminates past, present and future spatial information derived by harnessing the combined potential of in-situ measurements, space-borne remote sensing observations and numerical simulations to create a dynamic synoptic view of the entire lake. Operational since 2016, the system provides open access to lake environmental information to up to thousand daily visitors concerning recreational activities, hazard warnings, risk assessment and scientific phenomena. Besides the short-term interests, such information is used for long-term planning and management decisions. This article provides an overview of Meteolakes, its technical design and implementation, observational and modelling components. Finally, data products are showcased through two examples of notable meso-scale physical phenomena, including a strong upwelling and a storm event, which affected commercial and recreational activities in and around the lake.

2. Methods

Meteolakes is a unified solution benefitting all interested in lakes. The platform gathers into a single system the apparently disconnected objectives of public and governmental stakeholders. For this purpose, we designed an online data platform, including an Application Programming Interface (API), and real-time data processing chains, to openly distribute modelled key hydrodynamic variables with a state of the art uncertainty quantification through data assimilation and a complete spatio-temporal coverage of the lake, in near real-time with short-term forecasts. Meteolakes ultimately combines lake hydrodynamic simulations, in-situ measurements and remote sensing observations. This section provides an overview on the data composition and acquisition scheme, the computational framework, key model components and the online interface.

2.1. Platform components

The flowchart shown in Fig. 1 summarizes the system processes and key tasks, software and hardware components. The following subsections briefly describe the main components of the web-based platform. Currently, hydrodynamic processes in four lakes are available on Meteolakes: Lake Geneva, Lake Zurich, Lake Biel, and Greifensee. Yet, the system can be scaled-up to include additional others lakes. Moreover, the architecture of the platform allows porting this system for worldwide applications by adding support for the local meteorological weather forcing. In the absence of national weather products, the latter can be achieved using European Centre for Medium Range Weather Forecasts worldwide high-resolution (9 km) atmospheric products (ECMWF HRES). For sake of simplicity, we focus here on Lake Geneva only.

2.1.1. Study site

Lake Geneva (locally Le Léman) is the largest freshwater lake of Western Europe (maximum depth, surface area and volume of 309 m, 580 km^2 and 89 km^3, respectively). It is located between Switzerland and France (46.458 °N, 6.528 °E), in the perialpine region at an altitude of 372 m. The mean hydraulic retention time is 11.4 years, with its main tributary, the Rhône River located at the Eastern end accounting for 75% of the water flow entering the lake (average (1986–2013) of 184 m^3/s). Lake Geneva has a dam-operated/regulated outflow, located at the western end in Geneva. Complete deep convective mixing occurs only every 5 to 10 winters in Lake Geneva (Schwefel et al., 2016). Average wind speeds above the lake are in the range of 1–2 m/s and currents reach speeds of ~0.3 m/s on windy days (with wind speeds > 5 m/s).

2.1.2. Hydrodynamics computations

Delft3D-FLOW – The open-source modelling suite Delft3D-

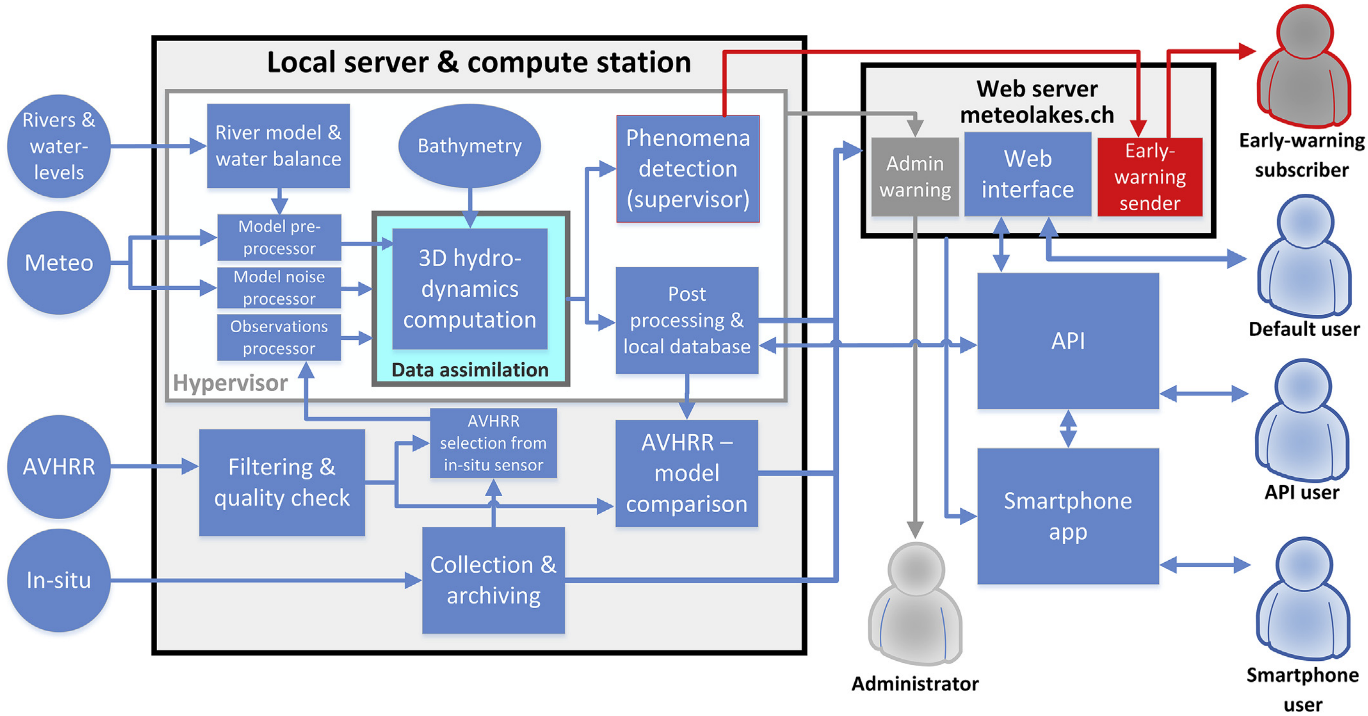

Fig. 1. Flowchart of system processes and overview of key tasks, software and hardware components. Input data are shown on the left under the circle symbols (e.g. "Rivers & water levels" for observed river discharge and temperature; "Meteo" for meteorological forcing; "AVHRR" for Advanced Very High Resolution Radiometers from environmental satellites; and "In-situ" for lake observations). Data are quality checked and pre-processed to be used as model input (meteorological, rivers and water levels data) or for data assimilation with Ensemble Kalman Filtering (satellite data). Model output are then post-processed and all data and models results archived on the local server. Furthermore, results are available through three different interfaces: (1) a web interface, (2) the API and (3) a smartphone application. Finally, subscribers can receive early-warning e-mails to selected processes automatically detected by the supervisor (red arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

FLOW (Deltares, Netherlands) has been used for this system platform. Detailed hydrodynamic numerical model description can be found in the Delft3D-FLOW manual (Deltares, 2015).

This model has been extensively calibrated and validated for Lake Geneva (Bouffard et al., 2018; Baracchini et al., 2019a, 2019b, Soulignac et al., 2018, 2019). The current setup includes a 450 m horizontal grid resolution and 100 unevenly distributed (from 20 cm at the surface to several m in the hypolimnion) vertical z-layers (layers are horizontal and do not follow the lake bed) with a time stepping of 1 min. Subgrid processes are parameterized with the κ-ε turbulence closure model. The model has initially been started from an in-situ temperature profile taken at the deepest location in January 2015 and has been running continuously since then. The model is forced by a time-varying set of two-dimensional meteorological data (see below) and by the river inflow data of the main tributaries (see below).

Meteorological forcing – MeteoSwiss COSMO-1 and COSMO-E products (MeteoSwiss, 2019a, 2019b) are used as meteorological forcing. Seven variables are extracted from those files by the model pre-processor (Figs. 1 and 2): wind speed, wind direction, solar radiation, air pressure, cloud cover, relative humidity, and air temperature. COSMO-1 products are provided on a 1.1 km grid with hourly resolution. COSMO-E provide hourly forecasts over 120 h, at a reduced spatial grid resolution (2.2 km). Model hindcasts are forced with COSMO-1 reanalyses, while Meteolakes daily forecasts are forced by COSMO-E forecasts.

Rivers forcing and water levels – River data consists of discharge and water temperature collected at 10 min intervals by the Federal Office of the Environment (FOEN). Water level measurements are collected in real-time and sent daily from the FOEN File Transfer Protocol (FTP) server. Water levels allow a hydrological budget closure and modelling of lake water level changes. Once received, the files are corrected with various integrity checks, including removal of duplicates, removal of incoherent observations, and inference of missing data. The system then forecasts the next 4.5 days of river temperature and discharge based on hybrid models for river temperatures (Toffolon and Piccolroaz, 2015) and statistical models (Marques et al., 2006) for the other parameters (flows and water levels). More details on the entire procedure and the hydrological budget are available in appendix A. This entire processing is monitored by the hypervisor (Fig. 1), which warns the administrator via e-mails when encountering missing or incoherent data and solution selected to circumvent the problem.

2.1.3. *Remote sensing monitoring*

The space-borne Advanced Very High Resolution Radiometer (AVHRR) sensor has been selected as the operational remote sensing data source. Its moderate spatial (1 km) and high temporal (10 overpasses per day) resolution enables the real-time monitoring of the lake surface water temperature (LSWT) and meso-scale to basin-scale lake dynamics. The partnering Oeschger Centre at the University of Bern has an operational data downlink from satellites, which facilitated the access to the data. The AVHRR LSWT retrieval process, with locally adapted Split Window coefficients for Lake Geneva, is described in Lieberherr et al. (2017) and Lieberherr and Wunderle (2018).

The AVHRR information is transferred to Meteolakes local database using a FTP server for additional screening and comparison with the model. The filtering on Meteolakes local server (Fig. 1) includes removing pixels with quality levels lower than 4 (Lieberherr and Wunderle, 2018). Data is then mapped to the model grid, compared with its corresponding model LSWT field, and

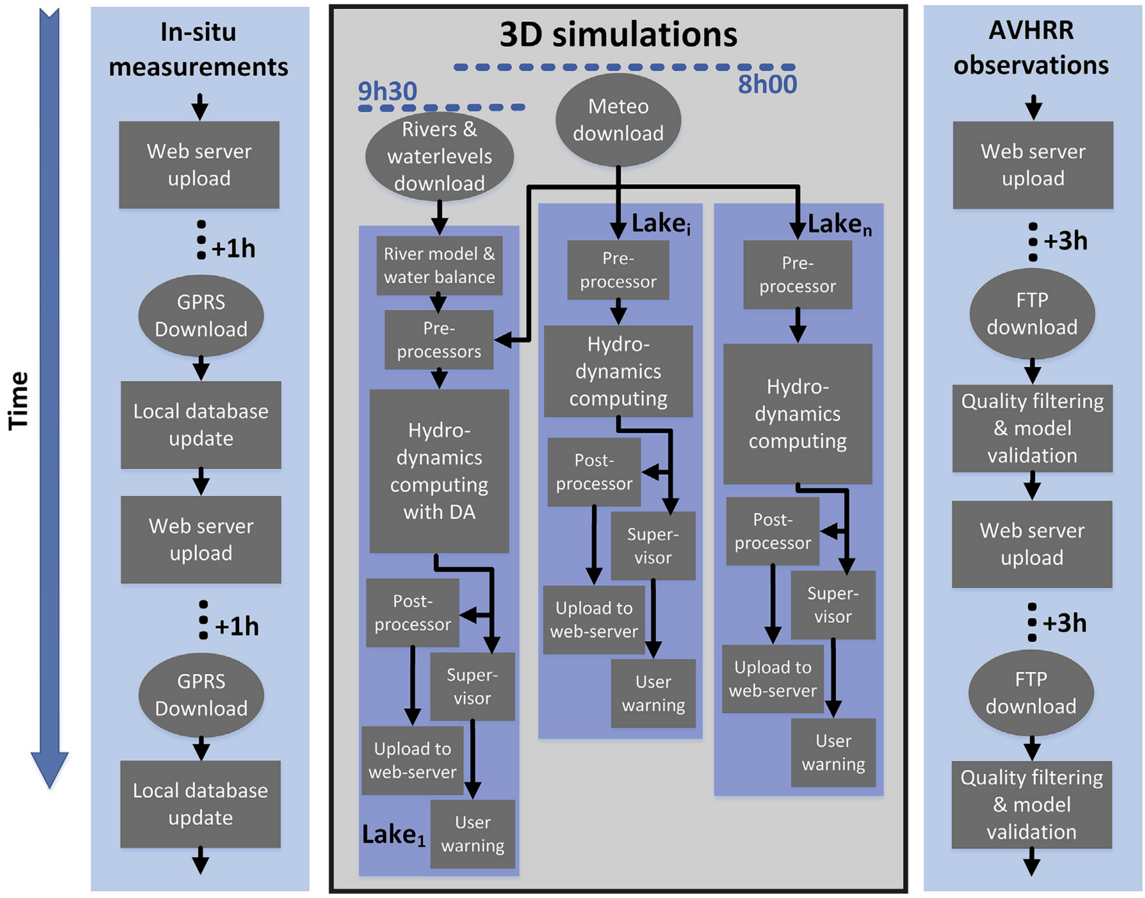

Fig. 2. Daily workflow and automated main tasks performed by the background system. Routines for the numerical simulations (centre square), in-situ measurements (left) and remote sensing data (right) are schematized. In-situ and remote sensing data is recursive (routines triggered every 1–3 h). Once meteorological and river data received, the hydrodynamic simulations are started. Due to a slight delay for the river data delivery, the simulations start earlier for lakes not requiring river data. The varying size of some boxes (e.g. pre-processor, hydrodynamics computing) indicates different lake-specific computational demands. The supervisor is Meteolakes early-warning system.

uploaded via FTP to Meteolakes web server. The AVHRR skin temperature is directly compared with the model bulk temperature and no skin-to-bulk conversion is applied in this current version due to the non-trivial parameterization when both wind and convective processes play significant roles for the near-surface turbulence. Differences due to skin effects can thereby be expected. The update of the local database and comparison with the model is performed every 3 h (Fig. 2).

2.1.4. In-situ monitoring

A small nearshore permanent station, located in shallow waters off the town of Buchillon, has been instrumented with various meteorological and in-water sensors. Those include thermistors located at 1 m and 35 m depth, and two radiometers (Heitronics Pyrometer KT15II) measuring lake skin temperature. Meteorological observations include air temperature, solar radiation, wind speed and direction, humidity, dew point, and air pressure. A programmable Campbell Scientific controller with data-logger and a GPRS module ensures real-time transmission of the data as well as modification of the setup when needed. The data collection and update of the local database is performed on an hourly basis (Fig. 2) and uploaded online on meteolakes.ch. All measured data are shared publicly on the web platform.

2.1.5. Data assimilation

Forecast uncertainties and more robust hindcasts are achieved by implementing a data assimilative operational model. Such an upgrade is needed to make optimal use of satellite-based surface information (Drusch et al., 2009) and in-situ data. The application of advanced data assimilation techniques with data from various sources across multiple spatio-temporal scales is rare (van Velzen and Verlaan, 2007). It is however needed to effectively quantify and reduce the uncertainties of data products capable of providing actionable guidance and enabling risk-based decision-making (Coccia and Todini, 2011; Pappenberger et al., 2007, 2008; Thielen et al., 2009; Weerts et al., 2011). In this study, a data assimilative ensemble approach has been implemented to optimally combine the three information sources in an operational context. The approach aims at quantifying and reducing system uncertainties, while accounting for both observational and model errors. Technical details and the development of the open source tools are described in Baracchini et al. (2019a). The same procedure, developed for Lake Geneva, is used in this study. We briefly describe here the real-time operations and information flow of such a method.

An Ensemble Kalman Filter with 20 members is used to combine LSWT with the hydrodynamics computations. The AVHRR data candidate for assimilation is filtered using the real-time in-situ monitoring station (Section 2.1.4). The thermistor located at 1 m depth selects satellite images with a temperature mismatch lower than 1 °C compared to the bulk temperature at 1 m (Fig. 1). This allows to circumvent translating the satellite skin temperature into water bulk temperature in addition to providing its uncertainty estimates. As described in Baracchini et al. (2019a), a localization scheme with a 15 km cut-off distance is used. Model uncertainty is accounted for through the addition of spatio-temporally correlated noise into the wind fields. COSMO-E statistical products, containing the wind standard deviation, are used to define the wind noise properties (Model noise processor, Fig. 1). A maximum of one satellite image is assimilated per day, with a maximum of five images per week to ensure the operational requirements. Our approach aimed at being operational and the upper limit of assimilated images is so far constrained by operational computational resources with the goal to provide output in < 6 h. Hence, we arbitrarily limited the amount of information being assimilated.

2.2. Computational framework

Meteolakes model computations and data processing are performed on a local server (Fig. 1). The machine comprises two Intel Xeon E5-2697v4 with 256 GB of error-correcting code random access memory, and a RAID-1 configured storage solution. While the system has been built to be computationally easily distributed, so far all numerical simulations are performed on this machine.

The 3D hydrodynamic simulations are run daily (Fig. 2). Every day, the system computes the hydrodynamics of the lake starting arbitrarily from the previous Sunday at 00h00, using COSMO-1 gridded surface meteorological reanalysis and tributaries observations. Model restart conditions are generated on Sundays by a computation comprising the entire previous week and using reanalysis forcing. Forecasts from the previous day are overwritten the next day by the new nowcast cycle. Thereafter, those daily computations perform a 4.5 days hydrodynamic forecast using the COSMO-E products and river forecast model (Section 2.1.2).

The automation of the processing tasks related to the numerical modelling is performed by PowerShell scripts triggered by the Windows Task Scheduler at ~8h00 in the morning (Fig. 2, middle panel). The river model, model pre-/post-processors, and supervisor are coded in MATLAB and are called by the PowerShell scripting. The pre-processor formats river and meteorological data into Delft3D-FLOW input files. The post-processor creates netCDF and CSV model output files by extracting and saving only specific fields (e.g. temperature, flow velocity, grid information) at a reduced spatial resolution to optimize storage load and the online user experience. Finally, the supervisor analyses model results to automatically detect configured physical processes of interest. In the current version, monitored physical processes include upwelling (by k-means clustering), high surface flow velocities, and out-of-bounds cold/warm waters at various depths. The supervisor acts as an early-warning system by sending information (e-mails with text and image detailing the intensity and location of the event) to a list of subscribers via the Meteolakes web server.

2.3. Web interface

Meteolakes includes two pathways for data dissemination with different target users. The majority of users interact with Meteolakes through its online interface, meteolakes.ch. Here, the main objective is to provide immediate comprehensive interactive lake information on the website. Advanced users, however, request data with the API, which provides the users that information in a simple format.

A smooth web navigation is critical to have the proposed monitoring system widely adopted by the civil society and lake professionals. Meteolakes online interface benefits from Web 2.0 concepts, with in particular, optimized user-data interaction, and intuitive information exchange through simple and responsive designs. Moreover, the meteolakes.ch web interface has been built with platform and display scalability in mind, for a seamless experience on a broad range of devices (smartphone, computer, and tablet).

Advanced users can generate URL links, which are interpreted by the server running the developed back-end application. The API extracts the desired dataset from the model netCDF output files and send it back to the user in formatted CSV files. Detailed explanations on how to use the API and available data can be found directly on meteolakes.ch at the following link: http://meteolakes.ch/#!/data. Both interfaces are detailed in Appendix B.

3. Products and application examples

3.1. Meteolakes

In this section, we provide an overview of the Meteolakes online products. We start by describing the various interface elements, followed by examples on how such elements can be used for practical assessments of physical phenomena. Two examples are presented: an upwelling and a storm event with high local currents.

An illustration of meteolakes.ch homepage is presented in Fig. 3. Two animated maps show the LSWT of Lake Geneva on the left and currents on the right, computed by the Delft3D-FLOW hydrodynamic model for the time indicated in the top panel. Several drop-down menus are available in the upper navigation bar. One can select the lake (currently four), the year (starting in 2009), the week and depth of interest. The hydrodynamic interface displays weekly periods. For each moment, the absolute time and the position in the time-frame slider are shown to the user. The time-slider is blue for forecasts and grey for the past. In addition to basic functionalities such as zoom and displacement, the maps can be clicked to obtain time-series at selected locations (Fig. 4). For systems with data assimilation (e.g. Lake Geneva), the time-series will further show the uncertainty of the model by displaying the min and max of all ensemble members as shown in Fig. 4. The temperature map has two additional tabs, providing a visualisation of temperature over depth at predefined transects along the main axes of the lake. They allow the visualisation of stratification and mixing. The flow velocity map has a secondary tab enabling a particle-tracking mode. When this mode is selected, the user has the possibility to release particles online at any spatial location (on the horizontal plane and over depth), and to follow their trajectories. Particles are treated as passive tracers, they are only advected horizontally by the user-defined model layer and are not impacted by vertical mixing nor settling. Finally, at the bottom of the web page (Fig. 3), a navigation bar allows access to the in-situ measurements, the remote-sensing validation, the API documentation and various additional system information.

Figs. 5 and 6 are examples of respective in-situ measurements and remote sensing observations as displayed on meteolakes.ch. Fig. 5 shows the water temperature at 1 m depth (blue), 35 m depth (red) and radiometric skin temperature (orange) measured at the Buchillon station. For in-situ measurements, the user has the possibility to define a period of interest (starting late 2016); this data is available in near real-time (maximum delay of 1 h). Seven additional atmospheric variables are available (not shown here). Remote sensing observations and a comparison with the modelled LSWT are also available in near real-time through the "*Remote Sensing*" tab (Fig. 6). It is worth noting that although the AVHRR data (upper right plot) have been filtered based on its quality flags (Section 2.1.3), no skin-to-bulk conversion is applied and the data is directly compared with model surface bulk temperature (upper left plot). Fig. 6 provides a spatial (lower left plot) and a temporal (lower right plot) overview of model deviations with respect to the AVHRR skin temperature. The temporal evolution is shown by displaying the median difference (blue dot), along with the 10th and 90th percentiles of those offsets (green bars) for each image-model comparison. It is possible to cycle through this temporal

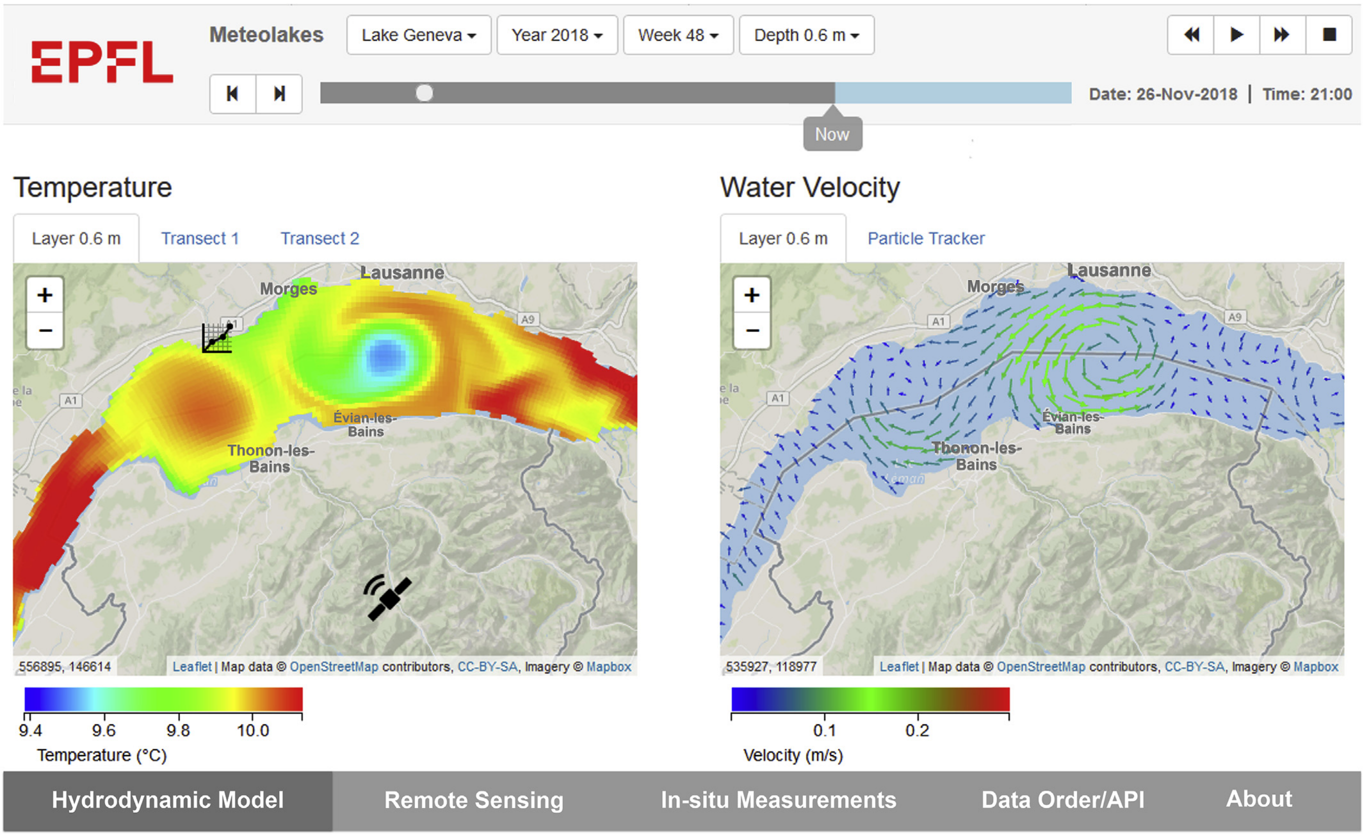

Fig. 3. Online interface as viewable on meteolakes.ch. Simulated temperature (left map) and currents (right map) in Lake Geneva at 0.6 m depth for the time as indicated on the top right. The time-slider is blue for forecasts and grey for the past. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

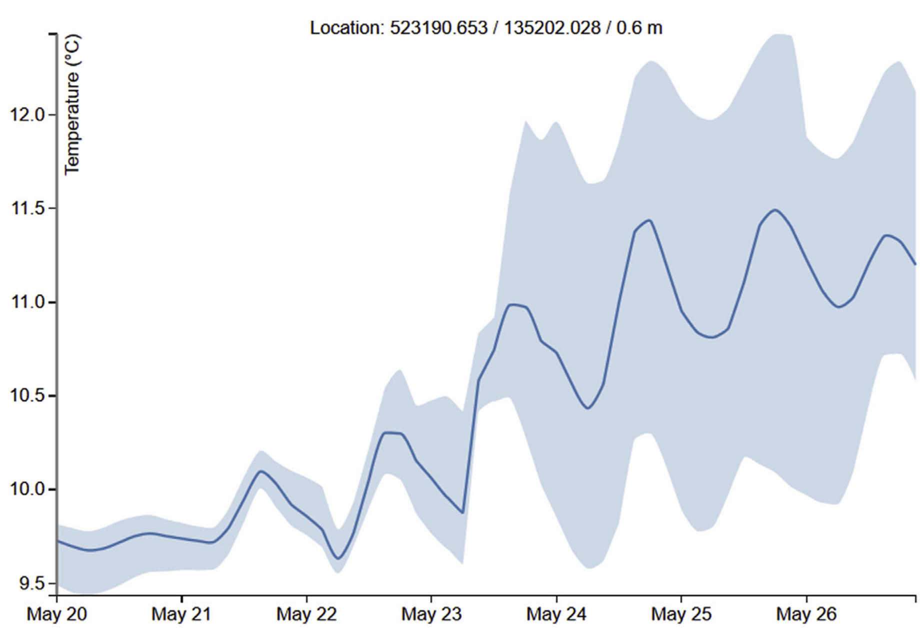

Fig. 4. Time-series of temperature in 2019 as displayed online when the user clicks on a point of interest. The confidence interval represents the uncertainty of the system through the min and max of the ensemble members at the point of interest for the given seven days period. For this particular week, two satellite images have been assimilated (22^{nd} and 23^{rd} of May at 6h00), visible by a significant reduction in uncertainty.

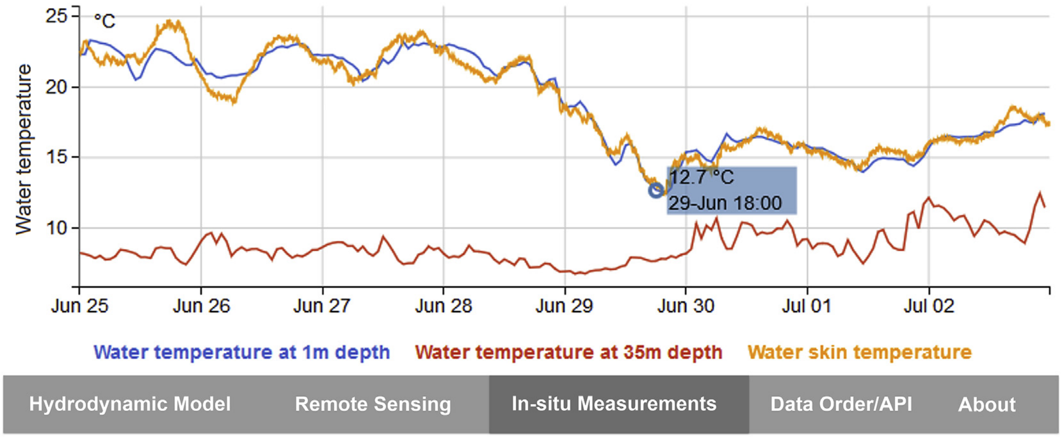

Fig. 5. Example of measured in-situ data as displayed in the "*In-situ Measurements*" tab. Water temperature at 1 m depth (blue), at 35 m depth (red) and radiometric skin temperature (orange) at the Buchillon station in June/July 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

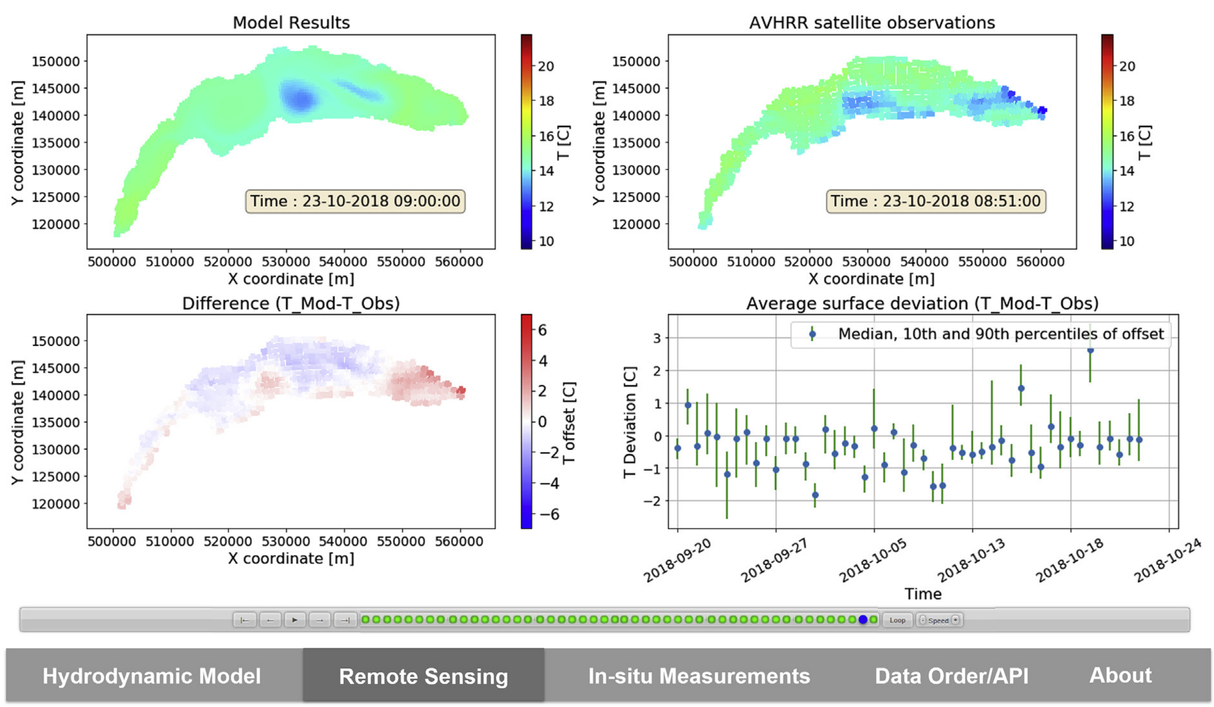

Fig. 6. "*Remote Sensing*" tab: Model results (upper-left) are compared in real-time with AVHRR skin-temperature observations (upper-right). Bottom-left plot shows the difference between the two datasets and bottom-right plot depicts the temporal evolution of those differences (here for one month prior to the shown snapshot). Only one satellite per day (and maximum 5 per weeks) are used for data assimilation. Other satellites data can be used for model and satellites observations comparisons.

comparison to visualize each satellite image and corresponding model snapshot.

3.2. Upwelling event

On 29th June 2017, a large upwelling was forecasted for the western basin of Lake Geneva. Fig. 7 shows modelled temperature before (left plots) and during (right plots) the event. Left plots show a rather uniform and warm (21 °C) LSWT on 30th June with a stratified profile and a thermocline around 15 m depth. Less than two days later, the surface shows a large horizontal thermal gradient resulting from a strong westerly wind event with LSWT 10 °C colder on the western part of the lake compared to the main basin. The bottom-right plot indicates that the stratification has been broken in the western basin, with a full upwelling of hypolimnetic water up to the surface. The signature of the upwelling and following basin-scale internal waves oscillations are also evident at the Buchillon station (Fig. 5) from in-situ measurements located some 10 km away from the main upwelling zone. There, LSWT dropped on June 29th immediately followed by a temperature rise both at the surface and at 35 m depth due to gravitational adjustment through the propagation of internal Kelvin waves (Bouffard and Lemmin, 2013). Such full upwelling did not only affect the lake but also the outflow water for millions of downstream residents as evidenced by the measured and modelled temperature at the outlet of Lake Geneva (Fig. 8). In Fig. 8, both model and observation were in good agreement (timing and intensity, RMSE = 0.8 °C) and showed a 12 °C drop in temperature in the

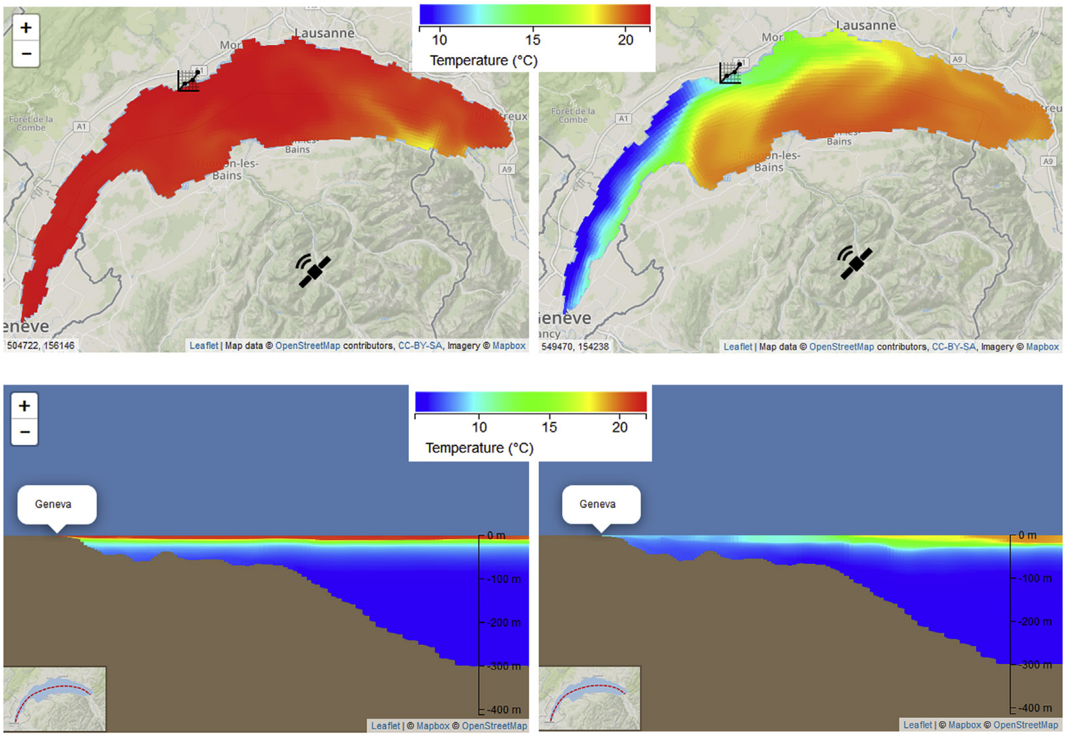

Fig. 7. Modelled upwelling in late June 2017 as displayed by meteolakes.ch. Left water column on 28th June 2017 at 15h00, right water column on 30th June 2017 at 9h00. The upper row shows the surface temperature and the lower row temperatures along a transect centred in the western basin. The graph icon (upper row) corresponds to the location of the in-situ station Buchillon.

downstream water over 2 days. The uncertainties are not shown in this figure as the event occurred before the operational data assimilation scheme was implemented. Looking at the meteorological forcing, which created the upwelling event, we found that it is the result of long-lasting winds blowing from South-West.

The consequences of upwellings for the lake ecosystem and the downstream water remain poorly investigated. One reason is the lack of monitoring tools for meso-scale processes and the difficulty to conduct specific field measurements to track transient phenomena such as the illustrated event. Open access forecasting systems such as Meteolakes can help planning field measurements and open new opportunities for understanding such processes and monitoring their magnitude and spatial extent. In this study, a diagnostic system to automatically detect and warn users has been developed. The method is based on a k-means clustering method, splitting the LSWT in two clusters. When the centroid difference of those clusters is larger than 4 °C, an alert is triggered by the supervisor (Figs. 1 and 2). In the case of Lake Geneva, the developed early-warning system allowed the subscribers to closely monitor such events during the course of two years (2017 and 2018), by being warned about possible occurrences up to four days in advance. Using a similar approach (i.e. comparing a lake model grid point with outlet river temperature measurements), we observed and modelled 6 and 16, respectively, upwellings with a sudden drop of surface temperature by more than 5 °C (respectively 2 °C) at the Eastern end of Lake Geneva between April and November 2016.

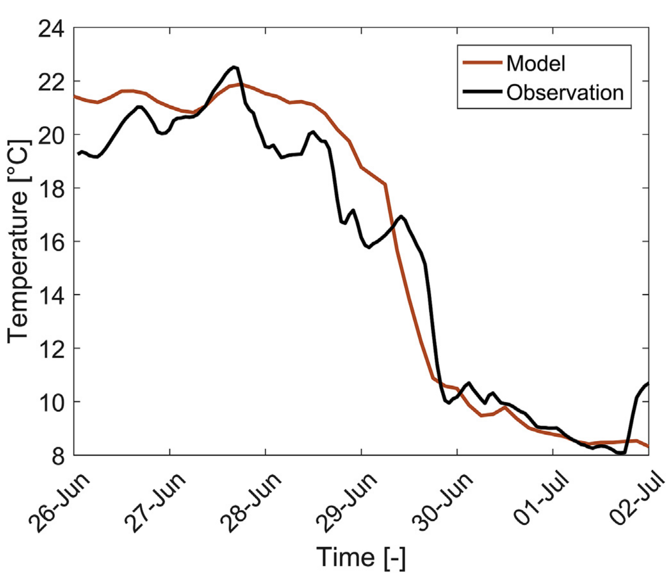

Fig. 8. Time-series of the late June 2017 upwelling event. River Rhône temperature from the lake outflow in Geneva (black line) is compared to the temperature of a near-outlet model surface grid point (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. Storm-induced lake currents

Lake forecasting systems are also relevant for predicting the dynamic effects of extreme storms. The sudden high-speed wind event from 6th August 2018 is an illustrative example for the application of such predictive approaches. Fig. 9 illustrates the surface currents as a result of a spatially localized North-Eastern coastal wind event. Timing was critical as the storm lasted less than 3 h, as shown by the plots before (upper-left), during (main plot) and after (upper right) the event. Surface flows 3 h before the event were in the range of 0.2–0.3 m/s. During peak intensity at 18h00, currents reached 0.8 m/s in the red patch of Fig. 9, before returning to 0.2–0.3 m/s 3 h later. The inset in Fig. 9 shows the devastating wind waves in Vevey Harbour on the North-Eastern shore.

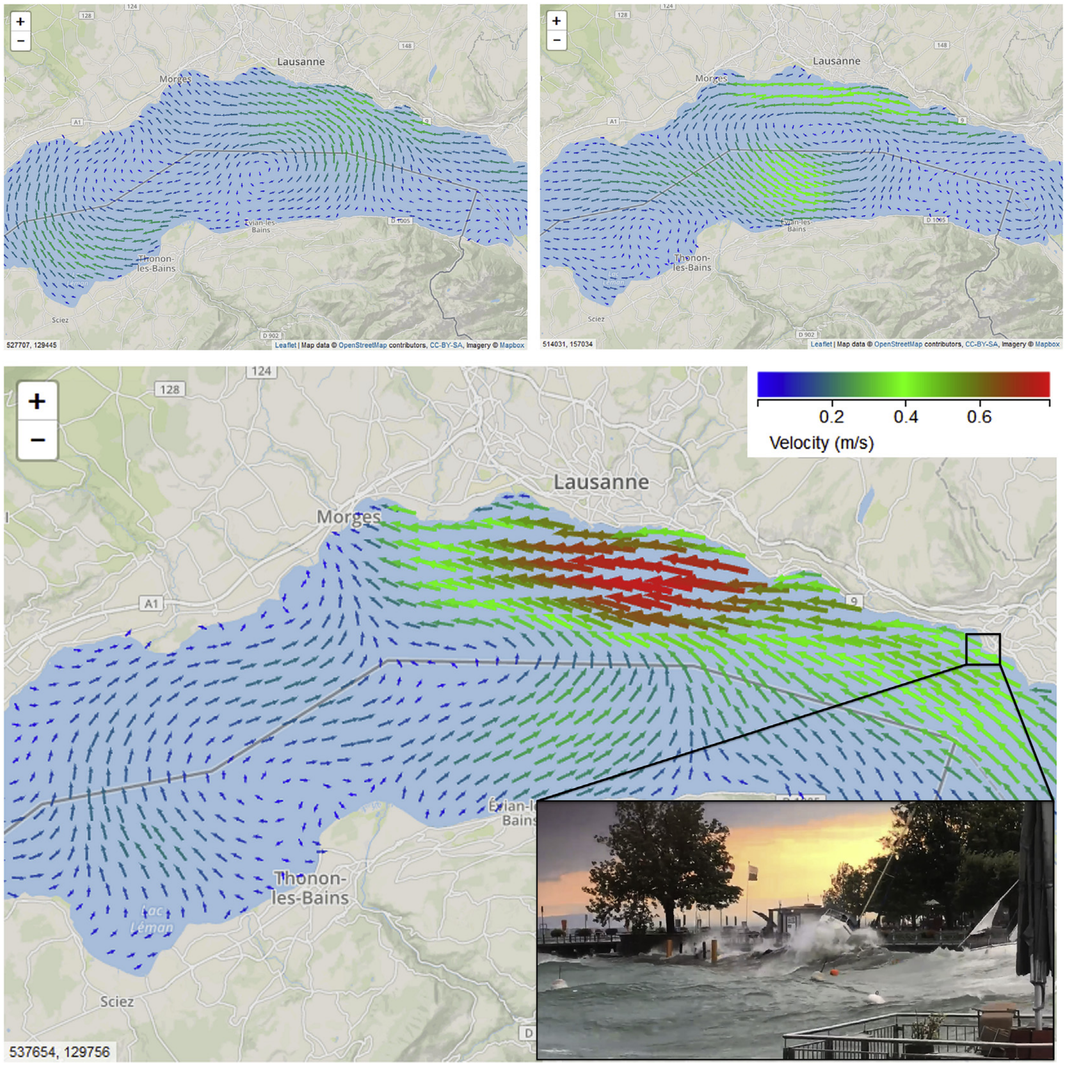

Fig. 9. Surface water velocity field of the main basin from meteolakes.ch for the 6th August 2018 at 15h00 (upper left), 18h00 (lower plot) and 21h00 (upper right). The inset image (extracted from a footage by D. F. Rimaz) shows two boats smashed against the shore in Vevey Harbour during the event.

While two physical phenomena are described in this study, other processes with significant implications for the biogeochemistry of the lake are visible on the platform. For instance, gyres have been found to structure the lateral dispersion of primary productivity (Soomets et al., 2019) as a result of the Coriolis force and subsequent strong up-/down lifts of the thermocline. Those structures are repeatedly observed in Lake Geneva (Bouffard et al., 2018; Kiefer et al., 2015). We refer the reader to meteolakes.ch in order to visualize two of those events: (1) November 3rd, 2015 (week 45 on Meteolakes), and (2) December 3rd, 2018 (week 48), visible in Fig. 3. In that regard, we found that these recurrent gyre systems are the response of a prevalent North-Eastern wind and that they decay within weeks after those wind patterns dissipate.

4. Discussion

Platform acceptance — Since its deployment mid-2016, Meteolakes has provided lake information to more than 250′000 users. Its usage reached an average of ~1000 daily visitors in mid-summer 2019. The platform demonstrated its effectiveness in disseminating both 3D model results and lake observations from satellites and in-situ sensors. Analysis of logging data showed that 51% of connexion logs come from smartphones, 41% from computers and 8% from tablets with 78% of the traffic originating from Switzerland. This device log distribution indicates that we created a scalable and responsive interface to distribute lake data. We distinguish three categories of users from the platform: (i) civil society, (ii) lake professionals, and (iii) scientists. Comments posted on the Android application and articles in newspapers indicate that the civil society has positively received and used the web-based platform, with main interests in lake temperature and currents for recreational activities (navigation, swimming). This category of lake users is also characterised by a strong seasonal variability with most activity over the summer period. Lake professionals, such as fishermen, contribute to a regular stream of visits independent of the season.

Platform applications - The web-based interface allows the visualisation of vertical transects or any horizontal layer to detect zones of interest such as dynamic areas with strong temperature gradients. The possibility to display near-future currents and lake temperature at specific coordinates is also used by beach operators on their respective websites. The upwelling event and associated 12 °C temperature drop illustrated on Figs. 7 and 8 show the importance of monitoring and predicting lake surface nearshore temperature. Warning messages related to storm conditions on the lake, as shown on Fig. 9, are also particularly relevant for lake professionals. Finally, the possibility to interactively add passive tracers at selected coordinates and water depth, and thereby evaluate the dispersion of pollutants, is expected to help drinking water intake operators in case of contamination. The practical benefit of the web-based platform regarding dynamic pollution tracking has not yet been evaluated. Finally, the use of Meteolakes by scientists is now well established. Two approaches can be distinguished: first, such a model allows putting the in-situ and satellite information into a basin-scale context. This approach has contributed, for instance, to the interpretation of negatively correlated remotely sensed temperature and chlorophyll areas which ultimately result from upwelling and basin-scale internal waves propagation lifting the thermocline and deep chlorophyll maxima upward (Bouffard et al., 2018). Similarly, the use of archived modelled data helped in identifying the source and the spatial distribution of a remotely sensed calcite precipitation event (Nouchi et al., 2019). Further investigation of such transient processes will require specific in-situ measurements. The forecasting mode of Meteolakes is currently used for identifying areas warranting the deployment of in-situ sensors in a similar way as suggested by Baschek et al. (2017). A global upscale of the platform is finally technically possible but would require large computer resources. Such global scale approaches are nowadays done with 1D model (Woolway and Merchant, 2019) and cannot account for spatially varying physical processes such as basin-scale internal waves, upwelling and Ekman pumping or gyre circulations all affecting the biogeochemical responses of the trophogenic surface layer.

Impacts of the platform are observed by three different types of stakeholders. First, the online system guides scientists in the design and planning of field campaigns and opens new frontiers for research on interdisciplinary processes. This is particularly relevant for transient dynamic phenomena such as upwellings, gyres or biogeochemical events (such as algae blooms, Wynne et al., 2013; whiting events, Nouchi et al., 2019), which are difficult to observe using in-situ observations without *a priori* knowledge. Second, lake-related professionals such as fishermen, beach operators, rescue organisations, drinking water facilities and engineering consultants access information for diverse reasons. Third, hundreds of citizen use Meteolakes on a daily basis for recreational activities (such as navigation and swimming) or to discover the beauty of lake dynamics related to distinct weather events.

5. Conclusions

Like most environmental systems, lakes are undergoing various stresses from global and local influences, seriously compromising the ecosystem services they provide. Given that a large part of humanity lives near freshwater bodies, reactions to extreme weather events can have drastic economical and human costs. Our current view of the problem is based on reanalysis of historical data and hindcasts. While such classical approaches have provided tremendous amount of information, many challenges are clearly unreachable with such frameworks. Specifically, we are currently poorly prepared to react to short-term transient events such as localized pollution, harmful algae bloom, upwelling events or storms. Furthermore, such episodic features with localised influence are often difficult to study. The coverage of those scales is only achieved by the combination and timely distribution of three types of information: (i) in-situ measurements, (ii) remote sensing observations and (iii) model simulations.

Here, we have developed a new web-based operational modelling platform allowing scientists, lake professionals and citizens to easily access historical, current and short-term forecasting of lakes dynamics. This platform is a step toward merging apparently disconnected interests of environmental-aware citizens, professionals and scientists interested in the fundamentals of the system. Practically, the challenge is solved by providing an effectively functioning and interactive scalable interface together with an efficient archiving approach allowing open access to data and a forecasting mode. Importantly, data assimilation of remotely sensed lake surface temperature allows quantifying the temporal and spatial evolution of the model uncertainty. The presented platform Meteolakes has provided spatio-temporal lake temperature and currents to more than 250′000 visitors over the last three years and has been featured in numerous local media, public events, and museum exhibitions. Meteolakes propose a new way of disseminating model results through a modern approach, combining (i) integration of in-situ observation, remotely sensed data and hydrodynamic models, (ii) a user friendly web-based visualisation of results for a broad audience from scientists to citizens, and (iii) open access to model output with uncertainty quantification provided by data assimilation, and (iv) operation forecast. We believe that the combination of all these criteria combined into a platform for the first time with Meteolakes is a necessary condition for the community to make major progress in science. Meteolakes is not a static platform. Instead, the concept of Meteolakes is that new features can be installed over times (other lakes, more post processing capabilities, other in-situ observation). Yet, the goal to advance in science will remain to engage scientists via Meteolakes in a more transparent and communicative way to openly provide access to model data with uncertainty quantification for all.

Author contributions

TB, DB and AW designed the platform and contributed to its dissemination. TB implemented and maintained the system operations since 2016. TB prepared the manuscript with contributions from DB and AW.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Data - The authors are grateful to the different institutions that provided the data used in this paper: the Federal Office of Meteorology and Climatology (MeteoSwiss) for meteorological data, the Federal Office of the Environment (FOEN), for the river discharge and water levels data of Lake Geneva and the Oeschger Centre of the University of Bern for the AVHRR data. All these data are provided in real-time by those organisations and are not the property of the authors of this study.

The authors would like to thank Stephane Restani, Roman Zoller, Martin Zoller, Guillaume Ulrich and Daniel Forte-Marques for their helpful contributions to the development of Meteolakes. We acknowledge Sébastien Lavanchy, for his work on the Buchillon mast sensors and their maintenance. Finally, we would like to thank the users for the outstanding array of feedback we received and their helpful suggestions. It strongly contributed to the expansion and maintenance of Meteolakes. With this article, we want to honour our young colleague and dear friend, Adrien Gaudard, who was involved in an earlier development of the hydrodynamic model for Lake Geneva, and who unexpectedly passed away during preparation of this publication.

Funding: this work was supported by the European Space Agency's Scientific Exploitation of Operational Missions element (CORESIM contract No.: AO/1-8216/15/I-SBo). The funding source had no further specific involvement in this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2020.115529.

Appendix

A. River data and hydrological budget closure

Flow and temperature are provided in real-time for the Rhône River (inlet and outlet, Fig. 2). Lake water levels are collected ~4 km East from the Buchillon station, along the shore at 10 min intervals. Finally, the data (FOEN) also contains 4.5 days forecasts of the Rhône River inflow based on MeteoSwiss COSMO-E products.

After the daily download from the FOEN FTP server, the data passes various integrity checks. The filtering includes removal of duplicates, removal of incoherent observations, and inference of missing data. Specifically, timestamp are checked to identify duplicate data and out of physically prescribed range data are scanned and automatically remover. Finally, inference of missing data and 4.5 days forecast of the outflow are estimated by singular spectrum analysis forecasting (Marques et al., 2006) using the first four principal components. When both the lake outflow and inflow from the Rhône River measurements and forecasts are available for the computational period, the contributions from the remaining rivers are generated by the river model. Two methods have been implemented in Meteolakes: the first one considers a constant lake volume and the difference of the outflow with the Rhône inflow is spread among the remaining three tributaries. The second method, currently used on the platform, aims at reproducing the water level variations of the lake and therefore requires additional data (water levels measurements). In this method a Gaussian filter is first applied to the observed water level time-series to remove the high-frequency signature from surface seiches. The water levels time-series then undergoes singular spectrum analysis forecasting to generate the next 4.5 days of forecasts. For each time-step *i*, the missing flow ($Q_{i,m}$) is given by:

$$Q_{i,m} = Q_{i.\ out} - Q_{i,Rhône(in)} + A(H)\frac{dH_i}{dt_i} \tag{A1}$$

With $Q_{i,out}$ the outflow from Lake Geneva (Fig. 2), $Q_{i,Rhône(in)}$ the inflow from the Rhône, A the surface area of the lake as a function of its water level H, and *dH* the change in lake water level during time-step dt_i. The remaining flow $Q_{i,m}$ is then distributed among the three remaining rivers, based on the flow contribution over the past 20 years. Cases of negative values are accounted for and mitigated. Additional filters ensure the remaining flow is coherent. Finally, river temperature is needed to drive the model. For the Rhône, real-time measurements are used, however for the remaining rivers or Rhône temperature forecasts, a physical model is operated. From the work of Toffolon and Piccolroaz (2015), it is possible to estimate the river temperature as a function of air temperature and discharge. This is achieved with the following integration:

$$\frac{dT_{river}}{dt} = \frac{1}{\delta}\left\{a_1 + a_2T_{air} - a_3T_{river} + \theta\left[a_5 + a_6\cos\left(2\pi\left(\frac{t}{t_y} - a_7\right.\right.\right.\right.$$
$$\left.\left.\left.\left.\times\right)\right) - a_8T_{river}\right]\right\}, \tag{A2}$$

$$\delta = \theta^{a_4}, \tag{A3}$$

$$\theta = \frac{Q_{river}}{\overline{Q}_{river}}, \tag{A4}$$

where the eight parameters, a_1-a_8, are obtained through calibration. Written in this form, they avoid having to specify explicitly all geometrical characteristics of the river and specific heat inputs (Toffolon and Piccolroaz, 2015). T_{air} is the air temperature obtained from COSMO-E products, *t* and t_y are the time and the duration of a year (in the same units as *t*), respectively, and $\theta = Q_{river}/\overline{Q}_{river}$ is the dimensionless discharge.

B. Web interface

B1 Online web-application

The AngularJS open-source JavaScript—based front-end framework is used to facilitate the web application development. We make use of various existing libraries and protocols such as the Leaflet map API, asynchronous server-client data transfers, for a spatially enabled and responsive content. To reduce computational load on the server, the vast majority of Meteolakes processing and rendering is performed client-side.

Apache Cordova, a mobile application development framework, allowed wrapping up the CSS, HTML and JavaScript code into a packaged Android application. This enabled a distribution on the Google Play store, without the need to develop a truly native mobile application using platform-specific APIs. Meteolakes Android app can be downloaded at the following link: https://play.google.com/store/apps/details?id=ch.epfl.meteolakes&hl=fr_CH.

The results stored on the web server, which are processed by the web interface or mobile application, are in text-file format. Upon user request, additional results can be displayed (e.g. temperature and flow velocity at different depth). Those are provided directly by the API from model results files located on the local server (Fig. 1).

B2 Application Programming Interface

Following user demands for raw data access and additional spatial information, we developed an API. Meteolakes API is built using the open-source Node.js runtime environment. Node.js allows the execution of JavaScript code outside the browser; in our case, it runs server-side directly on the Meteolakes compute and local server (Fig. 1).

Data requests are made by generating URL links, which are interpreted by the server running the Node.js application. The developed back-end application runs as background task, constantly listening to a port on which the requests are made. When receiving a request, the server will extract in the model netCDF output files the desired dataset and send it back to the user. The data is sent in formatted CSV files. Due to the relatively large size model files can have, we decided to have the API directly interact with the local server computing the hydrodynamic models rather than interacting with meteolakes.ch web server, as the latter would require having significantly more file transfers. More information on how to use the API are available directly on meteolakes.ch at the following link: http://meteolakes.ch/#!/data.

References

Anderson, E.J., Fujisaki-Manome, A., Kessler, J., Lang, G., Chu, P., Kelley, J., Chen, Y., Wang, J., 2018. Ice forecasting in the next-generation great lakes operational forecast system (GLOFS). J. Mar. Sci. Eng. 6, 123.

Baracchini, T., Chu, P.Y., Šukys, J., Lieberherr, G., Wunderle, S., Wüest, A., Bouffard, D., 2019a. Data assimilation of in-situ and satellite remote sensing data to 3D hydrodynamic lake models: A case study using Delft3D-FLOW v4.03 and

OpenDA v2.4. Special Issue: Modelling lakes in the climate system (GMD/HESS inter-journal SI). Geoscientific Model Development Discussions, 10.5194/gmd-2019-47.. https://www.geoscientific-model-development.net/index.html.
Baracchini, T., Hummel, S., Verlaan, M., Cimatoribus, A., Wüest, A., Bouffard, D., 2019b. An Automated Calibration Framework and Open Source Tools for 3D Lake Hydrodynamic Models. Submitted to Environmental Modelling & Software.
Baschek, B., Schroeder, F., Brix, H., Riethmüller, R., Badewien, T.H., Breitbach, G., Brügge, B., Colijn, F., Doerffer, R., Eschenbach, C., Friedrich, J., Fischer, P., Garthe, S., Horstmann, J., Krasemann, H., Metfies, K., Merckelbach, L., Ohle, N., Petersen, W., Pröfrock, D., Röttgers, R., Schlüter, M., Schulz, J., Schulz-Stellenfleth, J., Stanev, E., Staneva, J., Winter, C., Wirtz, K., Wollschläger, J., Zielinski, O., Ziemer, F., 2017. The coastal observing system for northern and arctic seas (COSYNA). Ocean Sci. 13, 379–410. https://doi.org/10.5194/os-13-379-2017.
Bouffard, D., Kiefer, I., Wüest, A., Wunderle, S., Odermatt, D., 2018. Are surface temperature and chlorophyll in a large deep lake related? An analysis based on satellite observations in synergy with hydrodynamic modelling and in-situ data. Rem. Sens. Environ. 209, 510–523. https://doi.org/10.1016/j.rse.2018.02.056.
Bouffard, D., Lemmin, U., 2013. Kelvin waves in lake Geneva. J. Great Lake. Res. 39, 637–645. https://doi.org/10.1016/j.jglr.2013.09.005.
Brookes, J.D., Antenucci, J., Hipsey, M., Burch, M.D., Ashbolt, N.J., Ferguson, C., 2004. Fate and transport of pathogens in lakes and reservoirs. Environ. Int. 30, 741–759. https://doi.org/10.1016/j.envint.2003.11.006.
Bruce, L.C., Frassl, M.A., Arhonditsis, G.B., Gal, G., Hamilton, D.P., Hanson, P.C., et al., 2018. A multi-lake comparative analysis of the General Lake Model (GLM): stress-testing across a global observatory network. Environ. Model. Software 102, 274–291.
Carmichael, W.W., Boyer, G.L., 2016. Health impacts from cyanobacteria harmful algae blooms: implications for the North American Great Lakes. Harmful Algae 54, 194–212. https://doi.org/10.1016/j.hal.2016.02.002.
Chu, P.Y., Kelley, J.G.W., Mott, G.V., Zhang, A., Lang, G.A., 2011. Development, implementation, and skill assessment of the NOAA/NOS great lakes operational forecast system. Ocean Dynam. 61, 1305–1316. https://doi.org/10.1007/s10236-011-0424-5.
Coccia, G., Todini, E., 2011. Recent developments in predictive uncertainty assessment based on the model conditional processor approach. Hydrol. Earth Syst. Sci. 15, 3253–3274. https://doi.org/10.5194/hess-15-3253-2011.
Deltares, 2015. Delft3D-FLOW User Manual: Simulation of Multi-Dimensional Hydrodynamic Flows and Transport Phenomena, Delft Nederlands.
Dodds, W.K., Bouska, W.W., Eitzmann, J.L., Pilger, T.J., Pitts, K.L., Riley, A.J., Schloesser, J.T., Thornbrugh, D.J., 2009. Eutrophication of U.S. freshwaters: analysis of potential economic damages. Environ. Sci. Technol. 43, 12–19. https://doi.org/10.1021/es801217q.
Drusch, M., Scipal, K., de Rosnay, P., Balsamo, G., Andersson, E., Bougeault, P., Viterbo, P., 2009. Towards a Kalman Filter based soil moisture analysis system for the operational ECMWF integrated forecast system. Geophys. Res. Lett. 36, L10401. https://doi.org/10.1029/2009GL037716.
Gaudard, A., Råman Vinnå, L., Bärenbold, F., Schmid, M., Bouffard, D., 2019. Toward an open-access of high-frequency lake modelling and statistics data for scientists and practitioners. The case of Swiss Lakes using Simstrat v2.1. Geosci. Model Dev. (GMD) 12 (9), 3955–3974.
Gaudard, A., Schwefel, R., Vinnå, L.R., Schmid, M., Wüest, A., Bouffard, D., 2017. Optimizing the parameterization of deep mixing and internal seiches in one-dimensional hydrodynamic models: a case study with Simstrat v1.3. Geosci. Model Dev. (GMD) 10, 3411–3423. https://doi.org/10.5194/gmd-10-3411-2017.
Hering, D., Carvalho, L., Argillier, C., Beklioglu, M., Borja, A., Cardoso, A.C., Duel, H., Ferreira, T., Globevnik, L., Hanganu, J., Hellsten, S., Jeppesen, E., Kodeš, V., Solheim, A.L., Nõges, T., Ormerod, S., Panagopoulos, Y., Schmutz, S., Venohr, M., Birk, S., 2015. Managing aquatic ecosystems and water resources under multiple stress — an introduction to the MARS project. Sci. Total Environ. 503–504, 10–21. https://doi.org/10.1016/j.scitotenv.2014.06.106.
Kiefer, I., Odermatt, D., Anneville, O., Wüest, A., Bouffard, D., 2015. Application of remote sensing for the optimization of in-situ sampling for monitoring of phytoplankton abundance in a large lake. Sci. Total Environ. 527–528, 493–506. https://doi.org/10.1016/j.scitotenv.2015.05.011.
Kimura, N., Wu, C.H., 2018. Using a nowcasting system to better understand lake water dynamics. Lakes Reservoirs Res. Manag. 23, 367–380. https://doi.org/10.1111/lre.12239.
Kirillin, G., Hochschild, J., Mironov, D., Terzhevik, A., Golosov, S., Nützmann, G., 2011. FLake-Global: online lake model with worldwide coverage. Environ. Model. Software 26, 683–684. https://doi.org/10.1016/j.envsoft.2010.12.004.
Kourafalou, V.H., De Mey, P., Staneva, J., Ayoub, N., Barth, A., Chao, Y., Cirano, M., Fiechter, J., Herzfeld, M., Kurapov, A., Moore, A.M., Oddo, P., Pullen, J., van der Westhuysen, A., Weisberg, R.H., 2015. Coastal Ocean Forecasting: science foundation and user benefits. J. Oper. Oceanogr. 8, 147–167. https://doi.org/10.1080/1755876X.2015.1022348.
Lieberherr, G., Riffler, M., Wunderle, S., 2017. Performance assessment of tailored split-window coefficients for the retrieval of lake surface water temperature from AVHRR satellite data. Rem. Sens. 9, 1334. https://doi.org/10.3390/rs9121334.
Lieberherr, G., Wunderle, S., 2018. Lake surface water temperature derived from 35 years of AVHRR sensor data for European lakes. Rem. Sens. 10, 990. https://doi.org/10.3390/rs10070990.
Marques, C.A.F., Ferreira, J.A., Rocha, A., Castanheira, J.M., Melo-Gonçalves, P., Vaz, N., Dias, J.M., 2006. Singular spectrum analysis and forecasting of hydrological time series. Phys. Chem. Earth, Parts A/B/C 31, 1172–1179. https://doi.org/10.1016/j.pce.2006.02.061.
MeteoSwiss, 2019a. COSMO-1 – high-resolution forecasts for the Alpine region. accessed 2.21.2019. https://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/warning-and-forecasting-systems/cosmo-forecasting-system/cosmo-1-high-resolution-forecasts-for-the-alpine-region.html.
MeteoSwiss, 2019b. COSMO-E – probabilistic forecasts for the Alpine region. accessed 2.21.2019. https://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/warning-and-forecasting-systems/cosmo-forecasting-system/cosmo-e-probabilistic-forecasts-for-the-alpine-region.html.
Nouchi, V., Kutser, T., Wüest, A., Müller, B., Odermatt, D., Baracchini, T., Bouffard, D., 2019. Resolving biogeochemical processes in lakes using remote sensing. Aquat. Sci. 81, 27. https://doi.org/10.1007/s00027-019-0626-3.
Paerl, H.W., Hall, N.S., Calandrino, E.S., 2011. Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. Sci. Total Environ. 409, 1739–1745. https://doi.org/10.1016/j.scitotenv.2011.02.001.
Pappenberger, F., Bartholmes, J., Thielen, J., Cloke, H.L., Buizza, R., de Roo, A., 2008. New dimensions in early flood warning across the globe using grand-ensemble weather predictions. Geophys. Res. Lett. 35, L10404. https://doi.org/10.1029/2008GL033837.
Pappenberger, F., Beven, K., Frodsham, K., Romanowicz, R., Matgen, P., 2007. Grasping the unavoidable subjectivity in calibration of flood inundation models: a vulnerability weighted approach. J. Hydrol. 333, 275–287. https://doi.org/10.1016/j.jhydrol.2006.08.017.
Schwab, D.J., Bedford, K.W., 1994. Initial implementation of the great lakes forecasting system: a real-time system for predicting lake circulation and thermal structure. Water Qual. Res. J. 29 (2–3), 203–220.
Schwefel, R., Gaudard, A., Wüest, A., Bouffard, D., 2016. Effects of climate change on deepwater oxygen and winter mixing in a deep lake (Lake Geneva): comparing observational findings and modeling. Water Resour. Res. 52, 8811–8826. https://doi.org/10.1002/2016WR019194.
Soomets, T., Kutser, T., Wüest, A., Bouffard, D., 2019. Spatial and temporal changes of primary production in a deep peri-alpine lake. Inland Waters 9 (1), 49–60. https://doi.org/10.1080/20442041.2018.1530529.
Soulignac, F., Danis, P.A., Bouffard, D., Chanudet, V., Dambrine, E., Guénand, Y., et al., 2018. Using 3D modeling and remote sensing capabilities for a better understanding of spatio-temporal heterogeneities of phytoplankton abundance in large lakes. J. Great Lake. Res. 44 (4), 756–764.
Soulignac, F., Anneville, O., Bouffard, D., Chanudet, V., Dambrine, E., Guénand, Y., et al., 2019. Contribution of 3D coupled hydrodynamic-ecological modeling to assess the representativeness of a sampling protocol for lake water quality assessment. Knowl. Manag. Aquat. Ecosyst. 420, 42.
Thielen, J., Bartholmes, J., Ramos, M.-H., de Roo, A., 2009. The European flood alert system – Part 1: concept and development. Hydrol. Earth Syst. Sci. 13, 125–140. https://doi.org/10.5194/hess-13-125-2009.
Toffolon, M., Piccolroaz, S., 2015. A hybrid model for river water temperature as a function of air temperature and discharge. Environ. Res. Lett. 10, 114011. https://doi.org/10.1088/1748-9326/10/11/114011.
van Velzen, N., Verlaan, M., 2007. COSTA a problem solving environment for data assimilation applied for hydrodynamical modelling. Meteorol. Z. 16, 777–793. https://doi.org/10.1127/0941-2948/2007/0241.
Vörösmarty, C.J., Hoekstra, A.Y., Bunn, S.E., Conway, D., Gupta, J., 2015. Fresh water goes global. Science 349, 478–479. https://doi.org/10.1126/science.aac6009.
Weerts, A.H., Winsemius, H.C., Verkade, J.S., 2011. Estimation of predictive hydrological uncertainty using quantile regression: examples from the national flood forecasting system (England and Wales). Hydrol. Earth Syst. Sci. 15, 255–265. https://doi.org/10.5194/hess-15-255-2011.
Wynne, T.T., Stumpf, R.P., Tomlinson, M.C., Fahnenstiel, G.L., Dyble, J., Schwab, D.J., Joshi, S.J., 2013. Evolution of a cyanobacterial bloom forecast system in western Lake Erie: development and initial evaluation. J. Great Lake. Res. 39, 90–99.
Woolway, R.I., Merchant, C.J., 2019. Worldwide alteration of lake mixing regimes in response to climate change. Nat. Geosci. 12 (4), 271–276. https://doi.org/10.1038/s41561-019-0322-x, 2019.