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Coupling high-frequency measurements and predictive modelling for monitoring and an early warning system of cyanobacteria blooms

Brigitte Vinçon-Leite*¹, Francesco Piccioni¹, Yi Hong¹, Viet Tran Khac¹, Bruno J. Lemaire¹, Denis Furstenuau Plec¹, Chenlu Li¹, Philippe Dubois¹, Mohamed Saad¹, Gabriel Hmimina², Kamel Soudani², Catherine Quiblier³, Kévin Tambosco⁴, Gonzague Six⁵, Catherine Freissinet⁶, Brigitte Decencièrè⁷, Jean-François Humbert⁴

¹ LEESU, Ecole des Ponts ParisTech, AgroParisTech, UPEC, Université Paris Est, Marne La Vallée, France

² Ecologie Systématique Evolution, CNRS, AgroParisTech, Université Paris-Saclay, Orsay, France

³ Museum National d'Histoire Naturelle, UMR 7245 MNHN-CNRS, 75231 Paris, France

⁴ iEES Paris-INRA, Sorbonne Université, 75005 Paris, France

⁵ IFSTTAR, Université Paris Est, Marne La Vallée, France

⁶ ARTELIA, 6 Rue Lorraine, F-38130 Echirolles, France

⁷ ENS, CNRS, CEREEP Ecotron IDF, UMS 3194, St Pierre Les Nemours, France

* corresponding author's email: b.vincon-leite@enpc.fr

Abstract

In urban watersheds, anthropogenic activities have major impacts on the ecological quality of water bodies. The degradation of water quality can result in toxic cyanobacteria blooms, which in turn may cause serious health risks to people in contact with water, *e.g.* when doing water sports. Due to the complexity of natural processes in water bodies, physically-based and spatially distributed models are valuable tools for better understanding the interactions between variables driving cyanobacteria blooms, as well as for helping stakeholders determine management strategies. However, traditional *in situ* measurements are limited by temporal and spatial resolution to make such numerical models reliable. Continuous *in situ* measurements provided by automated high-frequency monitoring can significantly improve adaptive decision-making.

The main objectives of this work were to (i) set up a full-scale experimental site for high-frequency monitoring of cyanobacteria biomass in an urban lake; (ii) couple the high-frequency measurements and a physically-based three-dimensional hydro-ecological model for predicting cyanobacteria blooms; (iii) implement a transfer platform for real-time data management; and (iv) develop a web platform for communicating information to lake managers, other stakeholders and the public. These steps were conducted in the framework of the *OSS-cyano* project, funded by the French Research Agency (ANR). The study site is Lake Champs-sur-Marne (0.12 km² surface, 3.5 m maximum depth), located in Greater Paris. The field monitoring includes measurements of water temperature, dissolved oxygen, chlorophyll-a fluorescence and phycocyanin fluorescence at 10 min time steps, and regular vertical profiles of temperature and fluorescence of the main phytoplankton groups. The Delft3D hydrodynamic and ecological modules, *Flow* and *Bloom* respectively, were implemented. Using continuous measurements and short-term meteorological forecast, a predictive modelling of the cyanobacteria biomass evolution over four days was performed. Simulation results can then be communicated to the lake manager and the public through a web platform for health risk warning.

Keywords: urban lakes, forecasting, 3D modelling, web platform

Introduction

Urban lakes provide essential ecosystem services. They are important recreational areas and hotspots of biodiversity (*e.g.* Hill et al., 2015). Many urban lakes can also be considered as key elements in the drainage network as they retain storm water and prevent floods and also reduce associated pollutant loadings (*e.g.* Hassall and Anderson, 2015). Their role in the hydrological cycle and the fate of pollutants in urban watersheds must be better

understood (Birch and McCaskie, 1999). Most urban lakes react rapidly to external hydrological and meteorological forcings and are directly affected by climate change. Efficient monitoring systems are increasingly required for the management of lake ecosystems.

High nutrient loads from anthropogenic activities in the watershed can boost aquatic primary production. Due to global warming the risk of toxic

cyanobacteria blooms increases and so do public health problems (Lüring et al., 2017; O'Neil et al., 2012). For bathing areas, threshold levels of cyanobacteria biomass and toxin concentrations are provided by the European Union bathing water directive 2006-7 EC or the World Health Organization (WHO) guidelines which require that cyanobacteria biomass is monitored to avoid health risks. The EU directive in each member country is implemented by monitoring schemes based on cyanobacteria cell numbers. The regulation application is hampered by the delay between water sampling and the availability of the laboratory results which can take more than one week. This can lead to wrong decisions: swimming should have been banned some days earlier or conversely, the bathing prohibition decided on before getting the lab results was not necessary. In this context, the *Oss-Cyano* project (Development of optical sensors and drone system for the survey of cyanobacteria) was instigated with the aim to develop and validate a low cost, adaptive and efficient monitoring system of cyanobacteria blooms. In parallel with the development of a new aerial sensor (Hmimina et al., 2018), part of the project was dedicated to cyanobacteria bloom forecasting, through the coupling of high-frequency ground-truthing measurements to a physically-based three-dimensional hydro-ecological model. Six public research laboratories and one private company were involved in this project, funded by the French Research Agency (ANR).

During the last decade, specialized sensors that make it possible to measure *in situ* proxies of cyanobacteria biomass were developed. Nevertheless, operational measuring systems of the cyanobacteria specific pigment, phycocyanin, are not widely used and seldom *in situ* validated with reference methods. Warning stations using these sensors are even less common in freshwater bathing areas. In this paper we present (i) the design of a high-frequency monitoring of cyanobacteria biomass in a recreational urban lake; (ii) the field survey implemented for validating the real-time monitoring system and the predictive modelling; (iii) the dataset obtained and the results of the hydro-ecological model and (iv) the web platform for communicating information to lake managers, other stakeholders and the public.

Materials and Methods

Study site

Lake Champs-sur-Marne (48°51'50"N, 2°35'53"E) is located in the eastern Great Paris area, France. It is a sand-pit lake fed by the water table from the

nearby Marne River (Fig. 1). The lake is small (12 ha) and shallow (mean depth 2.4 m). It is a recreational area offering diverse outdoor activities (bathing, kayaking, sailing). Every summer, more than 5000 children from the neighbourhood visit the lake. Toxic cyanobacterial blooms, mainly *Aphanizomenon*, *Dolichospermum* and *Microcystis*, frequently occur.



Fig. 1 Location of the monitoring sites

High-frequency monitoring system

High frequency measurements (every 10 min) of physical-chemical variables (water temperature, conductivity, pH, O₂), chlorophyll-a fluorescence (Chla hereafter), as a proxy of total phytoplankton biomass, and phycocyanin fluorescence, as a proxy of cyanobacteria biomass, were performed at three different sites (P, A and B, Figure 1). At each site, the continuous monitoring was performed at three depths for sites A and B and two depths for site P using a set of different underwater sensors. At sites A and B two thermal sensors were installed at 0.5 and 2.5 m depths; at site P only at 0.5 m depth. At the three sites a multi-parameter sensor was located at 1.5 m depth for measuring water temperature, pH, conductivity, dissolved oxygen, Chla and additionally phycocyanin at site B. The detailed technical characteristics of the sensors are presented in Tran Khac et al. (2018). At site B the data were measured at 1.5 m with a multiparameter probe (nke Sambat) and transmitted by a GPRS system to an onshore server once a day.

Field sampling

Fortnightly (in summer and autumn) to monthly (in spring and winter) field profiles were measured for four years, from mid-2015 to 2018 (75 samplings). Four phytoplankton groups (green algae, diatoms, cryptophytes and cyanobacteria) were measured with a spectrofluorimetric probe (BBE

Fluoroprobe), temperature, conductivity, dissolved oxygen and pH with a multi-parameter probe (Seabird SBE19). Laboratory analysis of Chla and phycocyanin were done in 2017 and 2018 (20 campaigns).

The model

Within the three-dimensional modelling suite Delft3D (Deltares, 2019) *Flow* and *Bloom* modules were used to simulate the hydrodynamics and the chlorophyll concentration used as a proxy of the total phytoplankton biomass, possibly including cyanobacteria. The physical domain features 801 cells (10 m x 10 m), in 12 horizontal layers (0.35 m thick) on the vertical axis. The $k-\epsilon$ turbulence closure model was used. The ecological module included 4 classes of phytoplankton: green algae, diatoms, flagellates and cyanobacteria.

Results and Discussion

Design of the warning system

The monitoring and warning systems were respectively based on the on-line measurements of water temperature, Chla and phycocyanin fluorescence collected at 1.5 m depth at site B and on the predictive modelling of cyanobacteria biomass during the 3 following days (Fig.). The data were validated through an automated script chain and stored in an onshore database (Tran Khac et al., 2018). In parallel a three-day progressive weather forecast was also provided to the database. On the one hand, the data were displayed for a visual assessment and on the other hand, they supplied the model initial concentrations of Chla and cyanobacteria. The model provides a space and time prediction of water temperature, Chla and cyanobacteria concentrations, in particular in the region of interest, the bathing area near site P (Figure 1).

Validation of the real-time monitoring data

It was necessary to assess the reliability of the realtime data of Chla and phycocyanin at site B before using them in the warning system. For doing this, the continuous measurements at 1.5 m depth at site B were compared to the measurements of the same variables at the other sites A and P and at other depths, with different sensors and with lab analysis. The automatic correction and validation algorithms were based on the comparative analysis of these data.

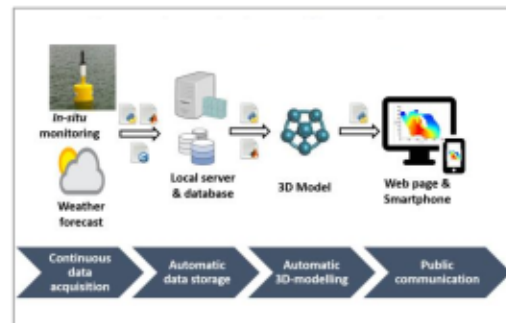


Fig. 2. Monitoring and warning system design

Modelling results

Hydrodynamics - The performance of the hydrodynamic model was first assessed. Beyond water temperature, the hydrodynamic model provides the biological module with the alternation of stratification and mixing of the water column, which drives the water motion and has a strong impact on cyanobacteria growth and transport. *Delft3D-Flow* was calibrated with a dataset collected in July 2015 and validated against the 2016 data. The hourly simulated and observed temperature at the measuring sites (0.5, 1.5 and 2.5 m depth) for the years 2016, 2017 and 2018 were compared. The agreement between modelling results and data, assessed through the Root Mean Square Error (RMSE) value (0.8°C) can be considered excellent and comparable to modelling results obtained in a neighbour shallow urban lake (Soullignac et al., 2017). The hydrodynamic model is able to satisfactorily simulate the changing hydrodynamics in Lake Champs and its impact on cyanobacteria biomass.

Cyanobacteria biomass - The biological module *Delft3D-Bloom* was then calibrated with a dataset collected for two weeks in July 2015. The results of a simulation performed over another 2 week period in 2018 (July 25th to August 8th) are presented on Figure 3. This period featured a sequence of thermal stratification of the water column (25th to 28th July), a mixing period from 29th to 31st July and a new stratification period from August 1st. The biological model was able to capture the timing and intensity of the observed Chla peak on July 29th (Figure 3). However, the simulated Chla concentration was overestimated, reaching a peak on July 31st. The following decreasing trend was then correctly represented. The cyanobacteria biomass also slightly increased until July 29th and then remained at this level. The model was able to simulate the cyanobacteria dynamics.

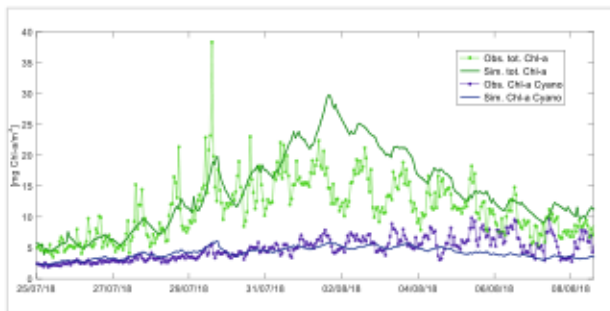


Fig. 3. Simulated and observed total and cyanobacteria chlorophyll (site B Jul-Aug 2018)

On-line warning system

The monitoring data and short-term predictive chain were embedded in a prototype of the warning system. An example of the short-term forecast (01-05/08/2018) is displayed in Fig. . The predictive results can be afterwards compared with the measured concentrations in order to check the validity of the forecast. In this case, the model forecast was close to the lower threshold of chlorophyll concentration in recreational waters considered as a moderate health risk level by the WHO (Chorus et al., 2000). This forecast, based on predicted chlorophyll concentration, would have drawn a moderate attention at the development of cyanobacteria. The lake managers would not need to collect samples for species identification and toxin analysis.

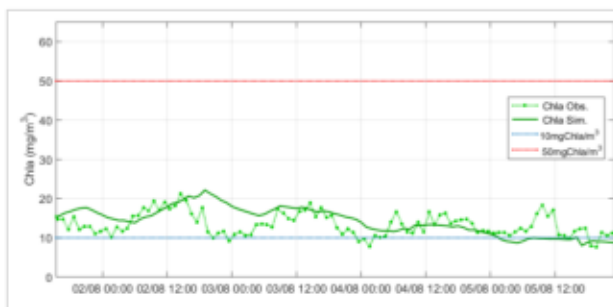


Fig. 4. Short-term forecast (4 days) of chlorophyll concentration. The blue and red lines indicate the threshold according to the WHO guidelines for low (10 µg/L) and moderate (50 µg/L) cyanobacteria health risk levels.

The website for displaying the monitoring data and the short-term forecast is under construction. The prototype webpage (<https://balneau-leesu-rec.enpc.fr/#!/dashboard>) of the forecast display is presented in Fig. .



Fig. 5. Website page of the short-term forecast

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