### Water Research 127 (2017) 191-203



Contents lists available at ScienceDirect

### Water Research

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

### A novel Eulerian approach for modelling cyanobacteria movement: Thin layer formation and recurrent risk to drinking water intakes



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### ARTICLE INFO

Article history: Received 10 March 2017 Received in revised form 23 June 2017 Accepted 9 October 2017 Available online 10 October 2017

Keywords: Cyanobacteria Water Hydrodynamic Eulerian Phototaxis Wind

### ABSTRACT

Toxic cyanobacteria (CB) blooms are being reported in an increasing number of water bodies worldwide. As drinking water (DW) treatment can be disrupted by CB, in addition to long term management plans, short term operational decision-making tools are needed that enable an understanding of the temporal variability of CB movement in relation to drinking water intakes. In this paper, we propose a novel conservative model based on a Eulerian framework and compare results with data from CB blooms in Missisquoi Bay (Québec, Canada). The hydrodynamic model considered the effects of wind and light intensity, demonstrated that current understanding of cell buoyancy in relation to light intensity in fullscale systems is incomplete and some factors are yet to be fully characterized. Factors affecting CB buoyancy play a major role in the formation of a thin surface layer that could be of ecological importance with regards to cell concentrations and toxin production. Depending on velocities, wind contributes either to the accumulation or to the dispersion of CB. Lake recirculation effects have a tendency to create zones of low CB concentrations in a water body. Monitoring efforts and future research should focus on short-term variations of CB throughout the water column and the characterization of factors other than light intensity that affect cell buoyancy. These factors are critical for understanding the risk of breakthrough into treatment plants as well as the formation of surface scums and subsequent toxin production.

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### 1. Introduction

Cyanobacteria (CB) blooms affect many lakes and water reservoirs globally, with blooms expected to increase as a result of eutrophication and climate change (O'Neil et al., 2012). Toxins released by many CB species constitute a threat for aquatic communities, humans and animals (Codd et al., 1999). CB blooms induce water quality problems, including water treatment disruption (Zamyadi et al., 2012) and are associated with increased economic costs (Steffensen, 2008; Hamilton et al., 2014). Therefore, knowledge of the relationship of CB growth and accumulation with

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environmental factors is essential for defining long term management plans for preventing CB blooms or reducing the risk of exposure through drinking water (DW) (Rabouille et al., 2003). Computational modelling is a useful tool for water managers and DW treatment plant operators to better understand mechanisms controlling CB movement and implications for DW treatment (Visser et al., 1997).

Understanding ecological aspects of CB formation such as the development of a thin layer near the surface (surface scum) or bottom of a water-body during blooms, as well as the role of advection and recirculation, is needed for choosing an appropriate location for a DW intake and identifying periods of risk of CB breakthrough into treatment plants. Given that intense CB blooms appear to have increased in many water bodies, changing the location of an intake could be explored as an option to minimize the risk to DW. Better prediction of blooms would lead to improved

operational decision-making at DW treatment plants (Ndong et al., 2014; Wynne et al., 2013).

A thin phytoplankton layer at the water surface is observed in a wide variety of environments (Wang and Goodman, 2010). The thickness of this layer can vary from a few centimeters to a few meters and can cover a surface from  $m^2$  to  $km^2$  (Ryan et al., 2010). This thin layer may be composed of many different organisms and organic matter and their formation and maintenance are strongly dependent on organism behaviours (Ross and Sharples, 2008) and on physical and biological processes controlling the bloom formation. There is growing evidence that toxin production increases over short time scales as a result of increasing cell numbers typical of thin layer formation (Wood et al., 2011, 2012). Buoyancy and turbulence factors facilitate organisms' accumulation (Steinbuck et al., 2009). The initiation and development, maintenance, decline and vertical distribution of a thin layer is partly governed by physical processes (Velo-Suárez et al., 2010). Mechanisms involved in the formation of a thin layer of phytoplankton include in situ growth in the layer, turbulent mixing, internal wave action, and photo-adaptation (Franks, 1995). During upwelling events, the shear induced strain and buoyancy play an important role in phytoplankton thin layer formation and interact with local circulation patterns and episodic changes in a water body driven by wind and tidal forcing (in the case of marine environments) to govern the vertical distribution of phytoplankton (Velo-Suárez et al., 2010).

Environmental variables that are expected to control the thin layer formation of CB and the effects of recirculation are, respectively, light and wind stress. The role of wind on physical processes is important (Hu et al., 2009) and spatio-temporal distribution of phytoplankton is influenced by both wind and CB buoyancy (Webster, 1990). These two processes, biological (phototaxis) and physical (wind), have been discussed by others (Nguyen-Quang and Guichard, 2010; Wallace and Hamilton, 1999; Webster, 1990; Webster and Hutchinson, 1994). The distribution of CB in a water body can also be affected by physical processes that are closely related to meteorological events (Cuypers et al., 2011). The patchiness of CB blooms is biologically and physically controlled by hydrodynamic characteristics specific to each species, and by turbulent mixing and light intensity (Moreno-Ostos et al., 2006).

CB buoyancy regulation is affected by water temperature, light intensity, nutrient limitation, and colony size (Kromkamp et al., 1988; Kromkamp and Walsby, 1990; Visser et al., 1997; Wallace and Hamilton, 2000). Light intensity has been the most studied factor with regards to modelling CB buoyancy (Howard, 1997; Kromkamp et al., 1988; Wallace and Hamilton, 1999). Light intensity varies in time and space and is a major and essential resource for phytoplankton (Litchman and Klausmeier, 2001). CB are photosynthetic microorganisms that must remain near the surface water layer for sunlight (Reynolds et al., 1987).

Statistical methods and Lagrangian based approaches have been commonly used to model CB distribution in a water body or column. The statistical approaches for describing the various mechanisms that influence CB spatio-temporal distribution are limited (Recknagel et al., 1997; Smith et al., 1987; Teles et al., 2006). However, they enable the evaluation of the risk associated with CB at DW intakes through a combination of the various factors that influence their concentrations (Peretyatko et al., 2010). Deterministic approaches (Kromkamp and Walsby, 1990; Porat et al., 2001; Verhagen, 1994; Visser et al., 1997; Wallace et al., 2000; Webster, 1990; Webster and Hutchinson, 1994) have also attempted to understand the spatio-temporal distribution of CB. A Lagrangian deterministic approach, where the position of a CB colony is followed in the water column has been used at the laboratory scale (Kromkamp et al., 1988; Kromkamp and Mur, 1984; Kromkamp and Walsby, 1990; Visser et al., 1997). The results from these studies enable the development of mathematical models to describe variations in CB density. Kromkamp and Walsby (1990) found that the variation of density of CB cells in the dark is a function of the history of exposure to light. In contrast Visser et al. (1997) showed that the variation of density of CB cells in the dark is a function of the cells' previous density (without considering vacuoles). This last approach is easier to implement and more representative to cvanobacteria movement induce by carbohydrate change, but it requires a correction to take into account the presence of vacuoles in the cells of CB. Furthermore, the Kromkamp and Walsby (1990) model is used solely for the estimation of settling velocities whereas the Visser et al. (1997) model is an improved model by considered and incorporating the irradiance-response curve of density change and by proposed an equation describing the rate of density change in the dark as a linear function of the cell density.

Although, the Lagrangian approach is interesting for studying the movement of cells at a laboratory scale, a Eulerian approach enables us to explore the full-scale spatial distribution of cells at specific times, for example, at a drinking water intake. Although other more complex and complete ecological CB models exist such as CAEDYM (Hipsey et al., 2006), none has explicitly modeled the effects of buoyancy in relation to phototaxis. As such, the upwards movement has been considered a process related to resuspension as a function of critical shear stress rather than as a density change intrinsic to the cells.

Our overall goal was to explain the recurrent risks of CB blooms at DW treatment plant intakes and improve decision making with regards to CB monitoring, toxin production, selection of water intake positions, and DW treatment plant operation in order to minimize CB breakthrough into DW treatment plants. This paper presents a novel 2D computational model based on a Eulerian approach with a numerically conservative scheme to simulate the spatial variability of CB concentrations. The objectives of the research were to investigate: 1) phototactic behaviour effect on the spatio-temporal distribution of CB in a water body; 2) the combination of light and wind effects on the distribution of CB, and 3) the coupled biological and physical effects related to CB blooms such as thin layers near the water surface and at the bottom of the waterbody. To our knowledge, the computation framework developed is the first full-scale model of CB transport using a numerically conservative Eulerian framework to model cell movement as a result of buoyancy changes and hydrodynamic effects induced by wind.

### 2. Theoretical calculations

### 2.1. Assumptions

Our model was developed for the general case of a homogeneous suspended CB population (e.g. a dominant *Microcystis* sp.) in a water body considering light and wind effects. We assumed that all physical properties of the fluid were constant including the specific density of water. We also assumed that there was no change in plankton metabolism, meaning that mortality and growth of CB were not considered. One key assumption is that CB will move positively towards the light source through phototaxis.

### 2.2. System of governing equations

Although a 3D model will improve predictions of CB concentrations at precise locations in a water body, the 2D modelling approach described below (starting with the continuity and momentum equations) is a simplified step to evaluate the relative importance of light and wind effects and to describe cyanobacterial accumulation in relation to environmental forcing similar to the more simplified approach of Webster and Hutchinson (1994).

$$\nabla \cdot V = 0 \tag{1}$$

### 2.2.2. Momentum equation

$$\rho_{w}\left[\frac{\partial \vec{\boldsymbol{V}}}{\partial t} + \left(\vec{\boldsymbol{V}} \cdot \nabla\right) \vec{\boldsymbol{V}}\right] = -\vec{\nabla}P + \nabla^{2}\vec{\boldsymbol{V}} + \rho\vec{g}$$
(2)

Where  $\vec{v}$  is the velocity of fluid (m/s); *P* is the dynamic pressure (Pa);  $\rho$  is the suspension density (kg/m<sup>3</sup>);  $\rho_w$  is the water density (kg/m<sup>3</sup>);  $\vec{g}$  is the gravitational acceleration (m s<sup>-2</sup>) and t is the time (s).

Equation (2) may be expressed in the vorticity and stream function form according to Nguyen-Quang & Guichard (2010):

$$\rho_{w}\frac{\partial\xi}{\partial t} + \rho_{w}\nabla(V\xi) = \upsilon\nabla^{2}\xi + \nabla \times \overrightarrow{\rho g}$$
(3)

$$\xi = -\nabla^2 \phi \tag{4}$$

The equations (3) and (4) for vorticity  $\xi$  and stream function  $\varphi$  were used in our model principally to eliminate the instability caused by the pressure term in the Navier-Stokes equations during the simulation process. v is the kinematic viscosity (m<sup>2</sup>/s).

Vorticity is related to velocity and stream function by the following equation:

$$\xi = \frac{\partial \boldsymbol{w}}{\partial \boldsymbol{x}} - \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{z}} = \frac{\partial^2 \varphi}{\partial \boldsymbol{x}^2} - \frac{\partial^2 \varphi}{\partial \boldsymbol{z}^2}$$
(5)

If we introduce the horizontal and vertical diffusivity coefficients, respectively, equation (3) becomes:

$$\frac{\partial\xi}{\partial t} + u\frac{\partial\xi}{\partial x} + w\frac{\partial\xi}{\partial z} = \Gamma_x \frac{\partial^2\xi}{\partial x^2} + \Gamma_z \frac{\partial^2\xi}{\partial z^2}$$
(6)

Where x, z are respectively the horizontal and vertical Cartesian coordinates; *u*, *w* correspond respectively to the two components of water velocity (m/s) in the x and z directions while  $\Gamma_x$  and  $\Gamma_z$  are the horizontal and vertical diffusivity coefficients (m<sup>2</sup>/s), respectively.

Equation (6) does not incorporate fluid buoyancy effects and the specific density of water was assumed to be constant. This implies that CB have a negligible effect on the bulk fluid density.

### 2.2.3. Transport equation

The form of the transport equation for CB is described as follows. This equation includes the cells' mass conservation equation and a mobility term for CB motion.

$$\frac{\partial C}{\partial t} + \nabla (VC) + \nabla (FC) = D\nabla^2 C$$
(7)

Where C is the CB cell or phytoplankton concentration  $(cell/m^3)$ ; V is the fluid medium velocity (m/s) acting on the CB cells and F (m/s) is the motion term of CB cells. This motion term can be understood as the taxis term (Nguyen-Quang and Guichard, 2010) such that under the effects of light, it represents the phototaxis of CB cells

### (e.g. Ghorai et al., 2010; Litchman and Klausmeier, 2001).

We propose here that a simple way to introduce the phototactic behaviour of CB is by using F as the sinking velocity (m/s). This sinking velocity may be obtained from equation (13) below as proposed by Visser et al. (1997).

The transport equation combines the effects of cell vertical velocity, F, with the fluid velocity (V). In other words, the combined effects of biological and physical processes via light and wind factors are included in the system of governing equations (1) and (5) and the transport equation (7).

### 2.2.4. Boundary and initial conditions

The conditions at the free surface determine the hydrodynamic behaviour. Indeed, they are affected by the meteorological factors such as the wind (speed and direction) and atmospheric pressure.

At the water surface the boundary conditions are expressed as:

$$\begin{cases}
w = \varphi_{s} = 0 \\
\Gamma_{x} \frac{\partial u}{\partial z} = \frac{\tau_{x}^{s}}{\rho_{w}}
\end{cases}$$
(8)

Boundary conditions for surface vorticity  $(\xi_s)$  may be expressed by:

$$\boldsymbol{\xi}_{\mathbf{s}} = \frac{\tau_{\mathbf{x}}^{\mathbf{s}}}{\Gamma_{\mathbf{x}}\boldsymbol{\rho}_{\mathbf{w}}} \tag{9}$$

Where  $\tau_x^s$  is the surface wind stress at the water surface (N m<sup>-2</sup>).

The effect of wind stress may be described by the empirical equation of Cole and Buchak (1995).

$$\boldsymbol{\tau}_{\boldsymbol{x}}^{\boldsymbol{s}} = \boldsymbol{C}_{\boldsymbol{v}} \times \boldsymbol{\rho}_{\boldsymbol{a}} \times \boldsymbol{W}_{\boldsymbol{a}}^2 = \boldsymbol{C}_{\boldsymbol{v}} \times \boldsymbol{\rho}_{\boldsymbol{w}} \times \boldsymbol{u}_{\boldsymbol{s}}^2 \tag{10}$$

where  $C_v$  is the drag coefficient;  $\rho_a$  is the air density (kg m<sup>-3</sup>);  $W_a$  is the wind speed at 10 m above the water surface (m s<sup>-1</sup>) and  $u_s$  is the surface water velocity (m s<sup>-1</sup>).

The surface water velocity is given by:

$$\boldsymbol{\mu}_{\boldsymbol{s}} = \sqrt{\frac{\rho_{\boldsymbol{a}}}{\rho_{\boldsymbol{w}}}} \times \boldsymbol{W}_{\boldsymbol{a}} \approx 0.03 \times \boldsymbol{W}_{\boldsymbol{a}} \tag{11a}$$

Wind direction change is taken into account by introducing the term **cos** ( $\phi$ ) as suggested by Hsu (1972), so that equation (11a) is modified to:

$$\boldsymbol{u}_{\boldsymbol{s}} = \sqrt{\frac{\rho_{\boldsymbol{a}}}{\rho_{\boldsymbol{w}}}} \times \boldsymbol{W}_{\boldsymbol{a}} \approx 0.03 \times \boldsymbol{W}_{\boldsymbol{a}} \times \cos(\varphi)$$
(11b)

where  $\phi$  is the wind direction.

At a closed boundary, the vorticity is null ( $\xi = 0$ ) and

$$\begin{cases} \frac{\partial^2 \varphi}{\partial \mathbf{x}^2} = 0 & \text{at left and right boundaries} \\ \frac{\partial^2 \varphi}{\partial \mathbf{z}^2} = 0 & \text{at bottom} \end{cases}$$
(12)

With regards to CB cells, closed boundary conditions were used (CB at boundary = 0 cells/mL). The initial condition for the concentration of CB was 100 cells/mL. Cells were assumed to be homogeneously distributed throughout the water body. This initial concentration was comparable to measured concentrations at Missisquoi Bay and simulations produced ranges of concentrations that were realistic in bloom conditions (Zamyadi et al., 2013).

Numerical validation of the hydrodynamic component of the model was conducted by comparing an analytical solution to our numerical solution and is presented in Section 1 (Supporting Information).

### 2.3. Method for resolution: discretization scheme for diffusionadvection equation

One important feature of the Eulerian approach for CB modelling is that CB density is required during all simulation steps. Traditional numerical schemes proposed such as QUICK or SIMPLE (Leonard, 1979; Patankar, 1980) do not allow for convenient monitoring of the CB density variation during each iteration. That means the numerical algorithm is not sufficiently conservative using these traditional schemes. To avoid this situation for CB modelling using a Eulerian approach, a constant CB buoyancy has traditionally been assumed for all calculation steps (Webster, 1990; Webster and Hutchinson, 1994) but this does not correspond to the physical reality of cells. Furthermore, laboratory-scale models using a Lagrangian approach have shown that CB are able to move due to their own mechanism of buoyancy (dependent on light intensity) (Kromkamp and Mur, 1984). In order to follow the variation of CB cell density in the water column as a function of light intensity for each iteration, while respecting conservation properties, we propose a new numerical scheme to replace traditional schemes such as QUICK or SIMPLE. Our computational model was based on the system of equations and boundary conditions detailed in Supporting Information.

### 2.4. Phototaxis behaviour of cyanobacteria buoyancy

The approach to calculate the velocity of CB as a function of light proposed by Visser et al. (1997) was selected for this study. Finally, the sinking velocity,  $F(m s^{-1})$  as a function of CB buoyancy is given by Stokes' law:

$$F = \frac{2gr^2 \mathbf{A}(\rho_{col} - \rho_w)}{9\Phi\mu}$$
(13)

g is the gravitational acceleration (9.8 m s<sup>-2</sup>); r is the effective radius of the colony (m); A is the cell volume to colony volume ratio (1) (Visser et al., 1997);  $\rho_{col}$  is the real density of CB (kg m<sup>-3</sup>) that must be between the minimum and maximum densities of 920 kg m<sup>-3</sup> and 1065 kg m<sup>-3</sup>, respectively;  $\rho_w$  is the water density (1000 kg m<sup>-3</sup>);  $\Phi$  is the form resistance (1) that is described by Reynolds et al. (1987) and  $\mu$  is the dynamic viscosity of the water (10<sup>-3</sup> kg m<sup>-1</sup> s<sup>-1</sup>).

The effective radius of the colony used in the model is 500  $\mu$ m (Chien et al., 2013). Chien et al. (2013) found that 300  $\mu$ m is the minimum size required to achieve active diurnal migration for *Microcystis* and that the maximum they had observed in field was 500  $\mu$ m. *Microcystis* has frequently been reported as the dominant species found at Missisquoi Bay (Zamyadi et al., 2012).

Wallace and Hamilton (1999) used a lag term to relate the rate of change of density to changing light intensity. The system of equations describing the phototaxis behaviour of cyanobacteria is described in Section 3 (Supporting Information).

## 3. Site selection and application of the Eulerian model to CB blooms

The model was applied using both simulated and real data for wind speed and light intensity. For simulated data, a constant wind stress of  $0.75 N m^{-2}$  was assumed and light intensity was simulated using a sinusoidal function with the maximum value of photon irradiance at noon equal to 1800 µmol photons  $m^{-2}s^{-1}and$  the length of the photoperiod (D<sub>L</sub>) of 12 h. For real CB blooms,

Missisquoi Bay in Québec, Canada was selected as the test site for the model. Missisquoi Bay is a large bay (77.5 km<sup>2</sup> in area and latitude and longitude of 45°01′37.63″ North and -73°07′34.84″West respectively) of Lake Champlain, which straddles the Canada -United States border (Fig. 1). Missisquoi Bay is shallow with a mean depth of 2.8 m (Galvez and Levine, 2003), thus the wave base can be deep enough to cause mixing of bottom sediments in areas without rooted aquatic vegetation (Myer and Gruendling, 1979). In this study, we assumed a uniform depth of 3.5 m because the drinking water intake on Missisquoi Bay is located at a depth of approximately 3.5 m on a length of L = 5 km (Fig. 1). The effect of the Pike River input flow was neglected at it is located at a distance of 3.7 km from the intake.

The simplified geometric representation of Missisquoi Bay enabled a more detailed development of the mathematical framework and resolution of equations for the evaluation of two of the dominant factors (light and wind) influencing CB movement and transport. A grid size of 200 m length scale ( $\Delta x$ ) and 0.5 m ( $\Delta z$ ) was applied to Missisquoi Bay for model simulations.

It is also the principal source of DW for a population of approximately 4500 residents and has experienced serious disruption of DW treatment as a result of CB blooms (Zamyadi et al., 2012). The initial CB cell concentration was assumed to be 10 000 cells/mL, representative of conditions in Missisquoi Bay (McQuaid et al., 2011). The model was developed generically for dominant cyanobacteria species (e.g. *Microcystis* sp.) occurring in the Missisquoi Bay, to study the primary processes affecting CB movement and transport at the lake-scale and did not consider differences in movement and transport related to different species differing in cell biovolume.

In 2011, a HOBO weather station (Onset Computer Corporation, Bourne, MA, USA) was installed at a DW treatment plant on the eastern shore of Missisquoi Bay, to collect data related to variables that may influence CB blooms such as temperature, humidity, wind speed, wind direction, and photosynthetic active radiation (PAR). Additional monitoring data collected are described in Ndong et al. (2014).

### 4. Results

### 4.1. Effects of light and wind

**Simulation results:** Results obtained from our mathematical model for Missisquoi Bay shown the phototactic behaviour of CB as a function of light sources under the effects of wind are presented in Figs. 2–5.

Figs. 2–4 show the model's results using light intensity and wind speed. Fig. 2a shows the light distribution as a function of water depth according to Beer-Lambert's law with the attenuation coefficient assumed to be approximately  $1.25 \text{ m}^{-1}$ .

Fig. 2b demonstrates that various spatial and temporal position of CB distribution are, through the water column, strongly associated with the light distribution shown in Fig. 2a. The distributions of CB as a function of depth are cyclic according to the periodicity of the light and the phototactic behaviour of the CB population (i.e. moving positively towards the light stimuli). CB distributions are more exposed to the light sources at the water surface (at 0.5 m, Fig. 2b). As can be seen in Fig. 2a et 2b, the distributions of cells below 1.5 m are less exposed to the effects of light. These phototactic distributions (with light stimuli only in Fig. 2b) are clearly affected by wind forces introduced in the system as shown in Fig. 2c: the curves of CB cell distribution are still cyclic but change in form with the wind intensity. At the water surface, at 0.5 m and 1.5 m depth (Fig. 2c), the CB distribution curves are more deformed by the effects of wind while at the deeper positions (more than



Fig. 1. Missisquoi Bay with drinking water intake position (PE) in Lac Champlain.

3 m), CB cells distribution curves are less modified (Fig. 2c).

When the light intensity continues along its sinusoidal time path and decreases to zero, the CB concentration in turn reaches its maximum value (at the different depth into the water column) as shown in Fig. 2b and c. This effect was also observed in simulations with observed data from Missisquoi Bay as discussed later.

CB accumulate in a thin layer formed at the water's surface and are then redistributed in the water column as shown in Fig. 3. Their redistribution is the result of two processes: (1) horizontal advection from wind effects that results in an accumulation of CB at the right (east) side of the Bay as shown in Fig. 3 *at* t = 67 min; and, (2) changes in buoyancy when their density becomes slightly greater than water density. CB settle slowly when vertical advection and phototaxis gradients are opposite. Their downward motion accelerates when these gradients have the same direction.

The process will continue periodically as long as a discrepancy exists in time between two cyclic curves of light intensity and CB concentration. This discrepancy in time is well illustrated in Fig. 3a, b and c, which present a panorama of different scenarios of CB phototactic motions in a 2D water column at different periods of time under light and wind effects. In Fig. 3a, the light intensity is attenuated through the water column according to Beer-Lambert's law. After a certain accumulation time, CB reach a critical concentration and move towards the maximum light intensity (t = 67 minand t = 1000 min, Fig. 3b). If the wind effects are considered, the CB population is blown towards one side of the water column (t = 67 min). Due to the recirculation effects induced by wind, the accumulated CB will be blown again over a long period of time as a function of light intensity and the advective motion in the water column (Fig. 3c). Thus, as seen in Fig. 3c, the recirculation effect induced by wind will create zones with low CB concentrations.

#### 4.2. The formation of a thin layer of CB during a bloom

Fig. 4 shows the spatial and temporal accumulation of the CB population observed near the shoreline as a result of light intensity only (Fig. 4a), coupled light and wind effects (Fig. 4b) and light intensity into the water column (Fig. 4c). According to the results

presented in Fig. 4a, b and c thin layer of CB appears near the water's surface during low light intensity. Phototaxis and wind effects strongly influence the formation of the thin layer. Indeed, by considering the phototaxis effect only (Fig. 4a), we observe a formation of large thin layer of CB at the water surface and at the bottom of the water body during low light intensity. This accumulation trend can largely be prevented by wind effects as illustrated by the results obtained in Fig. 4b. The thin layer formation is a consequence of CB phototaxis behaviour in a largely quiescent, e.g. with weak turbulence. Wind has a tendency to disperse this layer through its transport vector and creates other various thin layers near the shoreline as shown in Fig. 3c.

Not all of the CB cells in the water column are affected by wind; the wind has strong effects on the distribution of CB in limited zones. The dimensions of these limited zones (in Fig. 4a and b) depend strongly on the light intensity (indicated depth>1.5 m, Fig. 4c) and wind effect highlight the influencing areas of wind effects and limitations to CB mass dispersion induced by winds of insufficient strength to disperse surface accumulations. Consequently, the CB cells' buoyancy appears to be the dominant factor at the bottom of the water column.

Fig. 4 shows that: i) because of light intensity and the phototactic motion of CB cells themselves, they can accumulate at the water surface, ii) the recirculation effects induced by the wind results in the advection and dispersion of CB; iii) even with a critical concentration to create a CB bloom, the bloom is periodic and changes position, and iv) far from the shoreline in the center of water column, there is always a low concentration of CB.

## 4.3. Application of the Eulerian model to Missisquoi Bay and comparison to field data

The simulations performed with observed wind and light intensity (photosynthetically active radiation) data collected at Missisquoi Bay (Fig. 5a), shows the presence of a thin layer of CB from the surface to the bottom of the water column (Fig. 5b and c). Using real meteorological data from Missisquoi Bay, it can be seen that light penetration in the water column showed little variation from



Fig. 2. a) Light intensity penetration in water column, b) Cyanobacteria concentration according to light intensity only and c) Cyanobacteria concentration according to the effects of both wind and light intensity.

its sinusoidal curve during all days that were used for simulation (Fig. 5a).

We considered two cases for the photoadaption time response: 1) when CB are exposed to light intensity greater than their compensation point (Ic: defined as the light intensity at which the carbon dioxide and oxygen used in photosynthesis and respiration are released in equal amounts) and, 2), when light intensity is less than Ic. For the first case, the time delay from laboratory data suggested by Wallace and Hamilton (2000) was used (4 min) when Iz, irradiance occurring in the water column at depth z, was higher than compensation irradiance (Ic). For the second case (when Iz < Ic) two different values for the time delay in the dark were tested: 1) a delay of 4 min (Fig. 5b), 2) and no delay (c). The time response associated with CB photoadaptation must be considered when modelling the CB distribution. Ignoring this delay leads to unrealistically rapid CB movement that don't permit to capture CB blooms events as shown in Fig. 5b.

To compare model results with field observations, a threshold of 10.1 RFU (in vivo phycocyanin fluorescence) was fixed to define a bloom event based on the study of Missisquoi Bay by McQuaid et al. (2011). This value corresponds to the alert level 2 with a cyanobacterial biovolume threshold of 10 mm<sup>3</sup>/L and maximum potential



Fig. 3. a) Light penetration in the water column, b) Cyanobacteria movement according to the light intensity effect only, c) Cyanobacteria movement according to the effects of wind and light intensity.

(theoretical) microcystin concentration of 130  $\mu$ g/L (McQuaid et al., 2011). For all the values of RFU above this limit value (10.1 RFU) on the sampling day (Fig. 5d), CB bloom occurrences were observed in the model within a 24-h period of the observations (when Iz > Ic: with a time delay of 4 mins and Iz < Ic: without time delay) as shown in Fig. 5b and c. The results shows that when using the time delay of 4 min for Iz > Ic (Fig. 5c), we can observe that the model can

capture the thin layer formed at the water surface according to the results in Fig. 5d. The RFU value above the alert level (Fig. 5d) coincide with the models results when CB concentration at surface layer is high (Fig. 5c). During the times CB blooms were observed (Fig. 5d at 10 August 2011, 17 August 2011 and 31 August 2011) with an accumulation at the surface as shown in Fig. 5c, low CB biovolumes were recorded at the drinking water intake. During the





**Fig. 4.** a) Spatio-temporal distribution of cyanobacteria according to the effect of light intensity alone, b) Spatio-temporal distribution of cyanobacteria according to the effects of both wind and light intensity, c) Light penetration in the water column. The zone above a depth of 1.5 m is strongly influenced by both light intensity and wind.

times when no CB bloom were observed at the surface (Fig. 5d at 3 August 2011 and 23 August 2011) CB biovolumes at the bottom of the water column appeared to be high or increasing. The CB biovolumes observed entering the drinking water treatment plant were inversely proportional to their presence at the surface of the water column (Fig. 5e, d).

The model performed well when considering no time delay when the CB were in dark conditions (Fig. 5c). Indeed, the periods with blooms (BL) with CB accumulation (10 August 2011, 17 August 2011 and 31 August 2011) as shown in Fig. 5d were well captured by the model simulated without any time delay (5c). The periods with no CB blooms (NBL) based on field data (Fig. 5d) correspond to no or low observed accumulations at the water surface (3 August 2011) and 23 August 2011). When the model considers a time delay of 4 min (the same used by Wallace and Hamilton, 2000) when CB are in the dark (Fig. 5b) it cannot capture the bloom periods (Fig. 5d). Thus, factors other than light are influencing the buoyancy of CB cells and their full-scale movement is not well represented by

current models integrating published time delays.

The wind speed effects (Fig. 5f) show that no or low CB accumulations are observed in the water column (Fig. 5c and d) when the wind speed is greater than 3 m/s.

### 4.4. Sensitivity analysis

A sensitivity analysis was conducted to determine the effects of the time delay response on changes of CB density when they are exposed to light intensity longer than the compensation light (Ic). This time delay when light intensity is longer than Ic has been estimated to 4 min based on previous studies by Wallace and Hamilton (2000). Below Ic, the time delay has not been investigated through experimentation and their influence has not been shown in any previous model of CB distribution.

Through our results shown in Fig. 6a, b and c, it appears that changes in the daily light intensity (Fig. 6a) affect CB accumulation at the surface and at the bottom of the water column (Fig. 6b and c). The global results show that the time delay response below Ic has a strong influence on CB accumulation at the surface and at the bottom of the water column. This influence is more apparent for CB accumulation at the surface of when the time delay is between 0 and 1 min (Fig. 6b and c) when the light intensity is less than Ic. Above this range (meaning that the time delay is > 1min) of values, the time delay response does not significantly affect CB movement into the water column.

The sensitivity analysis focused on the effect of the time delay required before the colonies of CB begin to move. The focus on the time delay factor was because of the greater uncertainties with regards to its value. There is a lack of field scale data concerning this parameter that can be important for understanding cyanobacterial movement throughout the water column. The wind data used in this model were recorded by a weather station installed at the Missisquoi Bay during 2011. Thus, wind data are real measurements rather than parameters that are potentially subject to calibration. Furthermore, the effects of the amplitude of wind speed were clearly demonstrated in the simulations with no CB blooms occurring when wind speeds exceeded 3 m/s as described above.

### 5. Discussion

# 5.1. Ecological and drinking water treatment implications of simulations of light and time delay effects

It is important to note that although phototaxis can lead the CB population to move towards the light, there is a lag time as the CB gather together to reach a critical mass and move to the light stimulus. Galante et al. (2012) also observed a lag time for phototactic movement and modeled (at a micro-scale) the phototactic movement of CB cells considering. Chemotaxis was not considered in our model at this time. At the laboratory scale, chemotaxis was shown to be of low importance for some species of freshwater cyanobacteria (Galante et al., 2012); however, to our knowledge its importance in natural systems has not been fully explored. The lag time can be seen in Fig. 2: when the light intensity reaches its maximum value, the CB population does not yet reach its maximum concentration, as time is needed to compensate for buoyancy.

Although growth was not simulated, the effects of light and wind are also important for the onset of CB blooms and are related to the phenomenon of phyto-convection by two processes: 1) resting cells present in sediment layers are re-suspended by the circulation effects by wind mixing and phototaxis convection, and 2) cell germination is regulated by light conditions, hence the CB population grows (Hellweger et al., 2008).

The model result was sensitive to the time delay parameter,



**Fig. 5.** a) Light intensity in the water column, b) Spatio-temporal distribution of cyanobacteria simulated using observed wind and photosynthetically active radiation (PAR) data from Missisquoi Bay in 2011 with time delay photoadaptation in the dark of 4 min, c) Same as (b) without time delay photoadaptation in the dark, d) observed data of cyanobacteria occurrence in RFU recorded above the drinking water intake (at PE – Fig. 1, e) Observed data of cyanobacteria biovolume recorded inside the water treatment plant, and f) wind speed recorded in August 2011 at Missisquoi Bay.

critical for correctly estimating blooms at the drinking water intake. To our knowledge no full-scale field investigations have been performed to study the specific influence of various factors such as temperature, light intensity and nutrient availability on the buoyancy of cells with regards to the time delay parameter. The buoyancy effects from phototaxis behaviour play the dominant role in the upward and downward motion of CB cells. The downward movement of CB is more influenced by the buoyancy force that pulls CB cells from the surface where they accumulate at the bottom of the water column, than by the effect of horizontal advection that transports them away from the shoreline. The risk associated with CB blooms would be cyclic (as observed in Fig. 2b and c) as the effects of buoyancy and recirculation are cyclic (Rabouille et al., 2005).

Cell buoyancy is of fundamental importance for understanding the formation of surface scums, toxin production and risks of cell breakthrough in drinking water treatment plants. As a result of their buoyancy, CB cells have been shown to accumulate in the settling tanks of a drinking water treatment plant leading to extreme concentrations of toxins (Zamyadi et al., 2012). The coupled physical and biological processes governing the thin layer formation of CB at the water surface and bottom were also discussed by Cheriton et al. (2009), who found that biological processes contribute to the formation of a thin layer of phytoplankton and that their aggregation is favoured by the physical environment. At the bottom of the water column, the thin layer formation is a consequence of the long exposure to light that enables CB to increase their carbohydrate content and density (Kromkamp and Walsby, 1990), leading CB cells to move downward and stay at bottom position until density decreases. However, the model revealed that the time delay for photoadaptation under dark conditions does not suitably capture CB accumulation during blooms.

Our results suggest that there are other factors that must be identified to improve the conceptual model of cell buoyancy in full-



Fig. 6. a) Light intensity (PAR), b) Sensitivity analysis of the time delay effects on cyanobacteria accumulation during the dark period at the surface of the water column, and c) Same as (b) but at the bottom of the water column.

scale systems, particularly as our field data showed no significant differences with regards to cell concentrations at the bottom of the water column (Fig. 5b and c) as a function of time delay. There is a need to study factors related to cyanobacteria accumulation at the bottom of the water column that are not related to light and hydrodynamic effects considered in the model (e.g during nutrients released from bottom sediments). The time delay was assumed to be constant throughout the water column depth. However, it is highly probable that the time delay response for phototaxis doesn't have a constant value in full-scale systems. There is a need for high frequency sampling and field experimentation to understand CB

behaviour throughout the water column to develop a mechanistic understanding of the time delay response when CB are exposed to light.

The recently published study by Steffen et al. (2017) examined the expression of some of the genes responsible for gas vesicle production that affect cell buoyancy. Their objective was to understand factors that led to the "do not drink advisory" in Toledo, Ohio, USA in 2014 as a result of a CB bloom in Lake Erie at its drinking water intake. Their data demonstrated that genes associated with gas vesicle production showed more downregulation in the year of Toledo, Ohio's drinking water advisory as compared to other years. The significance of these results are that lower gas vesicle production could be related to cells descending further into the water column and could have a greater effect on drinking water treatment plants that have their intakes deeper in the water bodies. Given that our simulation results support the idea that the time delay following light exposure is not necessarily the most important factor controlling the buoyancy of cells, more research in understanding the factors influencing the upregulation of gas vesicle production in cyanobacterial cells could enhance our understanding of the threats that cyanobacteria pose to drinking water treatment plant intakes.

# 5.2. Ecological and drinking water implications of simulations of light and wind-induced advection

Lake recirculation induced by wind has a large influence on the horizontal distribution of CB. CB can be advected by the recirculation due to the effects of the wind (Howard, 1997; Porat et al., 2001; Verhagen, 1994; Visser et al., 1997; Wallace et al., 2000; Webster and Hutchinson, 1994). Webster and Hutchinson (1994) showed that phytoplankton are entrained into water movement when wind speed is greater than 2–3 m/s as a critical threshold value. This was also observed in our results as shown in Fig. 3c where CB accumulation was not observed when the wind speed was greater than 2-3 m/s. Wind direction must also be considered because it affects CB accumulation and enhances blooms. Verhagen (1994) analysis of CB buoyancy velocities versus water velocity showed that in the region of downwelling water near the downwind shore, if the CB buoyant velocity was greater than the downward water velocity. CB will aggregate in the upper water layer near the downwind shore. They concluded that a wind-induced water circulation pattern is a key factor for the mechanism of CB aggregation in the upper water layer (forming thin layer). Through the results shown in Fig. 3c at times 725 min and 752 min, we can observe CB accumulating in the upper layer of the water column due to recirculation. However, this recirculation effect can also contribute to CB movement from the top to the bottom of the water's surface. Thus, the interaction of water velocity currents and CB buoyancy determine the path of CB in a mixed water column, as has been shown by others (Wallace et al., 2000; Wallace and Hamilton, 1999).

The siting of an intake is critical for DW treatment plants. To reduce the risk of the disruption of drinking water production associated with CB bloom occurrence, it is important to choose an appropriate position for a DW intake in a water body. From Fig. 3b and c, our results show that the movement of CB blooms can cause a significant risk for a DW intake located at the bottom of a shallow water column.

George (1993) and Falconer et al. (1999) demonstrated that within a few hours, wind induced effects could cause a significant accumulation of phytoplankton cells by a factor of 1000. Winds with speeds < 2-3 m/s produce the largest accumulations can increase the risk to DW intakes. Turbulent mixing in the bottom of the water column could supply nutrients (from deposited sediment) available to promote new CB production and entrain cells from the surface to the bottom of water column (Velo-Suárez et al., 2010). Therefore, for the design of the water intake system for water sources affected by CB, both light effects and wind stresses must be well integrated to evaluate the risk associated with CB blooms at the first step of design.

One of the outcomes of our current study is to identify the possible areas where CB concentration under the coupled effects of light and wind factors might be lower. These zones may depend on dominant species of CB and also the recirculation intensity and dimensions of the water body. The bottom of the water column is a vulnerable location for a DW intake in a shallow water body such as Missisquoi Bay. Our results suggest that an intake near the middle of the water column would be a better location. However, other factors must be considered, such as the effects of water depth above the intake on pumping, variations in water depth in relation to climate change and climate variability (Barbeau et al., 2008), and physical risks from other activities in the water body. Webster (1990) also found that gradients of plankton concentrations near the lake center were close to zero. High frequency sampling throughout the water column is required to confirm zones of low concentrations. Another consideration for DW treatment plants is that even if zones with low concentrations of CB are found, CB from low concentration sources can accumulate within conventional drinking treatment plants and reach high concentrations (Zamyadi et al., 2013). Thus, although risk of CB breakthrough into DW could be reduced by moving a DW intake, without appropriate treatment processes at the DW treatment plant, the risk of elevated CB would remain. Although the model developed here was intended for water bodies, it could also be adapted for Computational Fluid Dynamics models of drinking water treatment plants and the accumulation and removal of CB cells.

In a water body where there are CB bloom occurrences and wind speeds are weak, the buoyancy effect is dominant and CB cells may descend to DW intakes or form surface scums. Given the observed relationship between cell concentrations and the upregulation of microcystin synthesis (Wood et al., 2011), these hydrodynamic factors are important with regards to the toxic potential of blooms.

Results from this investigation serve as a basis for answering key ecological questions related to CB with regard to the heterogeneity of CB distribution in a well-mixed water system, the sinking and self-shading effects of CB, and buoyancy and sinking rates affecting the formation of thin layers at the surface and bottom of a water body. There is a need to explore factors such as the availability of nutrients that could also play a role in the distribution of CB in the water column.

Through the Eulerian approach proposed in this study, it is possible to explore the full-scale spatial distribution of CB cells at specific times in contrast to the Langragian approaches from other studies (Kromkamp et al., 1988; Kromkamp and Mur, 1984; Kromkamp and Walsby, 1990; Visser et al., 1997. This paper is the first examining the photoadaptation and movement of cells at a full scale. The comparison of model simulations with monitoring data revealed the need for full-scale, high temporal frequency data of factors influencing CB cell buoyancy.

### 6. Conclusions

Light intensity and wind are among the dominant factors in CB bloom formation. They favour CB accumulation at the shorelines and the formation of thin CB layers at the surface and bottom of the water column. The model demonstrated that: a) CB thin layer formation is governed by the buoyancy term via phototaxis behaviour and CB dissipation is favoured by strong winds, b) our understanding of cell buoyancy as a function of light is incomplete and other uncharacterized (such as the time lag related to density change) factors must be further investigated, c) the risk to DW intakes would be cyclic and depends on both light intensity and wind stresses, and d) as a result of the recirculation by advection, there will be zones of low CB concentration.

The model based on the novel Eulerian framework demonstrated a good conservation of mass (mass balance was strictly respected during all simulations) using our new scheme for solving the advection-diffusion equation. This mass conservation scheme will be useful when other processes such as growth and mortality are considered. The forcing of the model was accurate by considering the strict mass conservation. However, we expect that the model will be improved by considering additional processes, particularly those governing cell buoyancy and CB growth. The present model demonstrates that wind forcing functions coupled with a set of simple physical and biological process equations (CB cells transport equation and buoyancy change) explain field observations with regards to cell accumulation and dispersion. It also clearly lays out important research needs with regards to cell buoyancy and time delay for the development of a complete conceptual model of CB movement.

### **Funding sources**

This research was supported financially by the 1) Engineering Research Council of Canada (NSERC), 2) Canada Foundation for Innovation, 3) Fonds de Recherche du Québec - Nature et Technologies, Canada, 4) Canada Research Chairs. Thanks to Susie Wood (Cawthron Institute) for discussions on cyanobacteria cell buoyancy for the interpretation of results.

### Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.watres.2017.10.021.

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