UNIVERSITÉ DE MONTRÉAL

ÉVALUATION DES FACTEURS ASSOCIÉS À L'OCCURRENCE DES CYANOBACTÉRIES À LA PRISE D'EAU ET MODÉLISATION DE LEUR DISTRIBUTION SPATIO-TEMPORELLE

MOUHAMED NDONG
DÉPARTEMENT DES GÉNIES CIVIL, GÉOLOGIQUE ET DES MINES
ÉCOLE POLYTECHNIQUE DE MONTRÉAL

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présentée par: NDONG Mouhamed
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a été dûment acceptée par le jury d'examen constitué de :

M. COURCELLES Benoît, Doctorat, président
Mme DORNER Sarah, Ph. D., membre et directrice de recherche
M. BIRD David, Ph. D., membre et codirecteur de recherche
M. NGUYEN-QUANG Tri, Ph. D., membre et codirecteur de recherche
M. NADEAU Daniel, Ph. D., membre
M. MANLEY Tom, Ph. D., membre externe

DÉDICACE

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RÉSUMÉ

La gestion des ressources en eau est un défi majeur compte tenu des menaces sur la qualité de l'eau. En effet, les cyanobactéries (CB) communément appelées algues bleu-vert prolifèrent fortement dans beaucoup de plans d'eau utilisés pour l'alimentation en eau potable. La gravité de ce phénomène, appelé «fleur d'eau», réside dans le fait que certaines espèces de cyanobactéries produisent des toxines qui peuvent traverser toutes les barrières du traitement conventionnel de l'eau (filtration, coagulation-floculation, sédimentation, désinfection). Plusieurs équipes de recherche à travers le monde travaillent sur cette question des «fleurs d'eau» afin de mieux comprendre ce phénomène en apportant des éléments explicatifs sur les principales causes. Cependant, la non-linéarité des facteurs impliqués (vent, température de l'eau, lumière, nutriments) ne facilite pas l'analyse des données recueillies afin de pouvoir :1) évaluer le risque d'occurrence associé à ces facteurs à une prise d'eau et 2) comprendre le rôle et l'interaction des différents mécanismes impliqués tels que l'advection et la flottabilité des cyanobactéries. L'advection dans un lac est souvent due au mouvement de l'eau induit par les effets des contraintes de vent à la surface du plan d'eau. La flottabilité des cyanobactéries est le résultat de leur changement de densité suite aux vésicules de gaz dont elles disposent et à la variation de leur contenu en glucides. C'est ainsi que cette étude a été entreprise à la suite des deux constatations relevées ci-dessus. L'objectif général est de développer des approches permettant : 1) d'évaluer quantitativement le risque d'occurrence des cyanobactéries à la prise d'eau et 2) de comprendre le rôle de l'hydrodynamique du plan d'eau, du mécanisme de régulation de la flottabilité des cyanobactéries à travers leur variation de densité et de la stratification thermique sur la distribution spatio-temporelle des cyanobactéries. Les objectifs spécifiques de cette thèse sont:

- de quantifier, avec une nouvelle approche, le risque associé à l'occurrence des cyanobactéries compte tenu de la position de la prise d'eau,
- de développer un modèle déterministe avec une approche eulérienne intégrant la flottabilité des cyanobactéries afin de mieux comprendre leur distribution spatio-temporelle,
- d'étudier le comportement des cyanobactéries compte tenu d'une éventuelle stratification thermique.

L'objectif premier a permis de développer un nouvel indice pour évaluer le risque d'occurrence des cyanobactéries à la prise d'eau. Cet indice, prenant en compte la température de l'eau, la

vitesse et la direction du vent, permet de constater qu'une probabilité d'occurrence de 68 % peut être attribuée à ces facteurs selon la position de la prise d'eau à la Baie Missisquoi (latitude : 45°01'37.63'' Nord et longitude : 73°07'34.84'' Ouest) qui est un plan d'eau situé au Québec (Canada) et qui est très souvent affecté par les « fleurs d'eau » durant l'été. Cependant, une éventuelle amélioration devrait pouvoir se faire dans la mesure où le rapport des nutriments d'azote inorganique dissous (DIN)/phosphore total (TP), qui n'a pas été pris en compte, constitue également un indicateur d'occurrence des cyanobactéries.

Le deuxième objectif, à savoir le développement d'un modèle mathématique avec une approche eulérienne, intégrant la flottabilité des cyanobactéries, a permis de mettre en évidence le rôle de l'advection et de la flottabilité des CB. Le risque d'occurrence à la prise d'eau serait fortement influencé par les propriétés éco-physiologiques des cyanobactéries de pouvoir se déplacer grâce à leur propre mécanisme de flottaison dans des conditions de stabilité de la colonne d'eau lorsque les vitesses de vent sont faibles (<3 m/s). Également, le risque que les cyanobactéries affectent la prise d'eau serait plus important dans des conditions d'une colonne d'eau calme (vitesse de vent inférieure à 3 m/s) favorisant une prédominance de la flottabilité des cyanobactéries grâce à leur propre mécanisme de variation de leur densité.

Le troisième objectif, à savoir l'étude de la stratification thermique, a permis de constater que cette dernière n'est pas si forte dans les lacs peu profonds comme la Baie Missisquoi (profondeur moyenne et maximale respective de 2,8 et 4 m). De ce fait, la stabilité de la colonne d'eau apparait comme étant la condition dominante qui favoriserait l'occurrence des CB dans le cas de Baie Missisquoi. Cette absence de stratification thermique significative pourrait également faciliter la dominance des CB dans toute la colonne d'eau. En effet, les processus dépendants de la température, en général comme le taux de croissance, pourraient être uniformes dans la colonne d'eau favorisant une éventuelle dominance des cyanobactéries quand la température optimale de croissance d'une espèce des cyanobactéries présentes est atteinte.

À l'issu de ces objectifs fixés dans cette thèse, les résultats suivants ont été obtenus :

1) une nouvelle approche a été développée pour évaluer le risque d'occurrence associé aux facteurs tels que la température de l'eau, la vitesse et la direction du vent,

2) un modèle mathématique, avec une approche eulérienne, a été développé permettant de mieux comprendre la distribution spatio-temporelle des cyanobactéries et de constater à travers une

étude de la stratification thermique dans les lacs peu profonds et eutrophes comme la Baie Missisquoi, que cette dernière n’est pas si forte et pourrait favoriser une dominance des cyanobactéries lorsque la colonne d’eau est stable et que les températures optimales de croissance sont atteintes.

ABSTRACT

Cyanobacteria or blue green algae are a concern for water resources management as a result of their occurrence in many drinking water sources. Many cyanobacterial (CB) species produce toxins that can break through the conventional water treatment processes unmodified. Many studies have been conducted to understand the main causes leading to the phenomenon of CB blooms. However, the non-linearity of the controlling factors (wind, water temperature, light, nutrients) combined with the importance of the geographic position of the drinking water intake do not facilitate the analysis of data. Among the challenges are1) to estimate the risk that CB occurs at drinking water intake and 2) to understand the interactions between the physics and biology among transport mechanisms such as advection and CB buoyancy. Advection in a lake is often the transport induced by water movement under wind stress effects. CB buoyancy is the result of their change of density, due to variation in the content of aerotopes (gas vesicles) and denser-than-water carbohydrate storage products. The main objective was to develop new approaches in order to: 1) evaluate CB occurrence risk at a drinking water intake and 2) understand the effects of hydrodynamics, CB buoyancy and thermal stratification on CB distribution. As such, the specific objectives of this thesis were:

- to quantify, through a new approach, the risk associated with cyanobacteria occurrence considering the geographic position of drinking water intake
- to develop a deterministic model with an eulerian approach taking into account cyanobacteria buoyancy in order to better understand their spatial and temporal distribution
- to study the behavior of cyanobacteria considering a possible thermal stratification into the water column

The first objective permitted the development of a new index to evaluate the risk associated with cyanobacteria occurrence at a drinking water intake. This index takes into account the water temperature and wind speed and direction; it showed that these factors explain together about 68% of the chance that cyanobacteria will occur at the drinking water intake in the case of a eutrophic water body like Missisquoi Bay, considering the geographic position of the drinking water intake. We suggest that it will be possible to improve this index by integrating water chemistry and fertility via the ratio of dissolved inorganic nitrogen (DIN)/total phosphorus (TP). We show that this ratio can be used as an indicator of CB risk, confirming earlier speculation.

The second objective, based on the development of a mathematical model using an eulerian approach and taking into account cyanobacterial buoyancy, was to highlight the role of advection due to wind stress and CB phototaxis in the induction of cyanobacteria density change. Through this objective, it is shown that the facilitation of vertical movement due to modification of cell buoyancy in a calm body of water (wind speed <3 m/s) is the main factor exposing the drinking water intake to cyanobacterial toxins.

The third study focused on thermal stratification. From the preceding results, it is clear that water column stability is critical to bloom dynamics. Here we show that temperature stratification that stabilizes the lake is not strong in shallow, eutrophic water bodies like Missisquoi Bay. Water column stability appears as a main condition favouring CB dominance in Missisquoi Bay. Weak stratification permits CB dominance of the entire water column. Indeed, the rate of growth, which is dependent on water temperature, could be uniform in the mixed water column and thereby facilitate a possible dominance of cyanobacteria when the optimal growth temperature of the cyanobacteria is reached in midsummer, when other forms of phytoplankton are beyond their temperature optima.

Based on the objectives defined the following findings are presented in this thesis. First, a new statistical approach is developed in order to estimate cyanobacteria risk at drinking water intake based on water temperature, wind speed and direction in a eutrophic water body like Missisquoi Bay. Second, a deterministic mathematical model based on an eulerian approach has been developed in order to understand cyanobacteria distribution in a water body. This model allowed us to show that weak thermal stratification in a shallow lake, such as Missisquoi Bay in particular, could favour cyanobacteria dominance in the water column when the elevated optimal growth temperatures are reached.

TABLE DES MATIÈRES

LISTE DES TABLEAUX

LISTE DES FIGURES

LISTE DES SIGLES ET ABBRÉVIATIONS

ACDI	Agence Canadienne pour le Développement International
CB	Cyanobacteria
CBV	Cyanobacterial biovolume
CFI	Canadian Fondation for Innovation
CIDA	Canadian International Development Agency
CMA	Concentration Maximale Acceptable
CRC	Canadian Research Chair
CRSNG	Conseil de Recherches en Sciences Naturelles et en Génie du Canada
DW	Drinking Water
INSPQ	Institut National Santé Publique du Québec
TP	Total Phosphorus
TN	Total Nitrogen
DIN	Dissolved Inorganic Nitrogen
MDDELCC	Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques
NSERC	Natural Sciences and Engineering Research Council of Canada
NOAA	National Oceanic and Atmospheric Administration
PAR	Photosynthetically Active Radiation
RFU	Relative Fluorescence Ratios
USEPA	United States Environmental Protection Agency
WHO	World Health Organisation

INTRODUCTION

Mise en contexte

L’apparition soudaine de fortes densités de cyanobactéries est un constat fait depuis des décennies. Cependant, depuis quelques années, leur fréquence d’occurrence a fortement augmenté au Québec et un peu partout dans le monde. Communément appelées « fleurs d’eau », ces importantes proliférations de cyanobactéries touchent de plus en plus les sources d’approvisionnement en eau potable. Les cyanobactéries sont plus redoutées à cause des toxines qu’elles produisent (selon les espèces) et qui peuvent avoir des conséquences sanitaires néfastes (Lévesque et al., 2014).

L’occurrence des cyanobactéries a fait l’objet de plusieurs études, menées dans des plans d’eau différents par leurs niveaux d’eutrophisation (teneur en phosphore) et situées un peu partout dans le monde, afin d’apporter des éléments explicatifs permettant d’orienter la prise de décision pour bien préserver les ressources en eau qui sont exposées. Ces études mettent en cause les conditions eutrophes (concentration en phosphore élevée) et les facteurs environnementaux tels que les conditions climatiques (température, intensité lumineuse, précipitations) et relatent aussi les changements constatés sur la qualité de l’eau (Costa et al., 2006; Fastner et al., 2007; Imamura, 1981; Jayatissa et al., 2006; Kotak & Kenefick, 1993; Lahti et al., 1997; Wang et al., 2002; Wu et al., 2008). Cependant, les résultats jusqu’ici publiés, en plus d’un désaccord sur les véritables conditions qui favorisent les fleurs d’eaux, explorent peu les comportements hydrodynamiques des plans d’eau touchés afin de mieux comprendre l’occurrence des cyanobactéries en un endroit précis d’un plan d’eau. Les informations fournies à travers ces études ne permettent pas aux gestionnaires des plans d’eau d’évaluer le risque associé à l’occurrence des cyanobactéries au niveau des prises d’eau compte tenu de leur position et des conditions climatiques.

Quant à la distribution spatio-temporelle des cyanobactéries, les efforts de modélisation ont été plus axés sur une approche lagrangienne due faite de la difficulté qu’il y a de prendre en compte le comportement hydrodynamique du plan d’eau en plus de la capacité dont disposent les cyanobactéries de pouvoir réguler leur position par leur propre mécanisme de flottabilité. L’approche lagrangienne, même si elle est intéressante, permet de suivre qu’un nombre très réduit de cellules de cyanobactéries, de ce fait une vue d’ensemble sur le plan d’eau touché ne pouvait pas être obtenue.

À la suite de ces constats, les principaux axes de recherches suivants ont été retenus durant ces travaux de recherche :

1) évaluer le risque associé à l'occurrence de cyanobactéries selon la position de la prise d'eau et compte tenu de certains facteurs météorologiques. Il s'agit de développer une nouvelle approche permettant de quantifier pour une première fois la contribution des facteurs météorologiques comme le vent (vitesse, direction) et la température de l'écosystème;
2) de modéliser le mouvement des cyanobactéries en tenant en compte l'hydrodynamique du milieu (advection des cyanobactéries) et la capacité de déplacement des CB, appelée flottabilité, qui est une des propriétés éco-physiologique qui fait d'elles des espèces phytoplanctoniques particulières. Dans cette démarche, nous avons implémenté une approche de type eulérienne tout en essayant d'assurer une très bonne conservation de masse quelque soit la durée de la période simulée;
3) d'investiguer sur la stratification thermique à la Baie Missisquoi et son éventuelle influence sur la distribution des cyanobactéries.

- **Organisation générale de la dissertation**

Cette thèse s'articule autour de 8 parties incluant les chapitres d'articles publiés ou soumis aux revues scientifiques *Water Research* et *Environmental Science and Technology*. Il s'agit:

<u>1$^{\text{ère}}$ Partie</u>: L'introduction dans laquelle une mise en contexte est faite afin de situer le besoin de recherche. Elle est suivie d'une présentation de la structure de la dissertation.

<u>2$^{\text{ème}}$ Partie</u>: Il s'agit du Chapitre 1 qui présente la revue de la littérature dans laquelle nous rappelons l'état de la situation à travers le monde et particulièrement au Québec, les caractéristiques éco-physiologiques des cyanobactéries, les avancées de la recherche afin d'apporter des éléments explicatifs permettant de mieux comprendre l'occurrence des cyanobactéries, les mesures recommandées afin de pouvoir alerter les gestionnaires des plans d'eau, les approches mathématiques jusqu'ici développées afin de modéliser le mouvement des cyanobactéries et enfin le site d'étude qui est la Baie Missisquoi (Québec, Canada).

3ème Partie: C'est le Chapitre 2 dans lequel les objectifs visés à travers ces travaux de recherche sont présentés afin de délimiter le sujet dans la mesure où il s'agit d'un domaine de recherche qui implique des aspects biologiques, biochimiques, hydrologiques et hydrodynamiques. Ils sont suivis des hypothèses de travail et enfin de la cohérence des articles issus de cette recherche

4ème, 5èmeet 6ème Partie: Ces trois parties représentent les Chapitres 3, 4 et 5 d'articles publié et soumis dans les revues scientifiques *Water Research* et *Environmental Science and Technology*. Elles présentent les différents résultats obtenus durant ces travaux de recherche. Il s'agit principalement:1) de la méthode d'évaluation du risque d'occurrence de cyanobactéries associées aux facteurs tels que le vent (vitesse et direction) et la température de l'eau (Chapitre 3 : article 1 publié à *Water Research*), 2) de la modélisation de la distribution spatio-temporelle des cyanobactéries suivant une approche eulérienne qui couple l'aspect hydrodynamique et la flottabilité des cyanobactéries sous l'effet de la lumière (Chapitre 4 : article 2 soumis à *Environmental Science and Technology*), 3) enfin, de l'effet de la stabilité de la colonne d'eau et d'une éventuelle stratification thermique sur la distribution spatio-temporelle des cyanobactéries (Chapitre 5 : article 3 soumis à *Water Research*).

7ème Partie: Il s'agit du Chapitre 4 qui présente la discussion générale. Dans cette partie, une évaluation des résultats trouvés par rapports aux objectifs fixés et aux hypothèses de travail est faite. D'éventuelles pistes de recherche sont aussi dégagées tenant compte des aspects non pris en compte et qui pourraient nettement améliorer les résultats trouvés. Nous y abordons aussi le rôle des processus physiques et biologiques sur la distribution spatio-temporelle des cyanobactéries (en particulier l'advection et la flottabilité), ainsi que l'emplacement des prises d'eau compte tenu des dispositions sur le projet de règlement sur la protection des sources d'eau. Et enfin, nous mettons en exergue les apports de ces travaux par rapport à la problématique des cyanobactéries dans les plans d'eau.

8ème Partie: Cette dernière partie aborde la conclusion ainsi que les recommandations faites à la suite de ces travaux.

CHAPITRE 1 : REVUE CRITIQUE DE LA LITTÉRATURE

1.1 État de la situation à travers le monde et particulièrement au Québec

- À travers le monde

Plusieurs cas d'occurrence de cyanobactéries et leurs effets sur la santé humaine ont été constatés à travers le monde. Au vu de quelques-uns présentés dans le **Tableau 1.1**, des décès ont été rapportés, ce qui démontre les effets néfastes qui peuvent découler d'une forte prolifération de cyanobactéries dans les plans d'eau.

Tableau 1.1: Les effets néfastes enregistrés à travers le monde à la suite d'occurrence de cyanobactéries

Événements/Conséquences	Année	Lieu	Référence
Plusieurs cas de gastro-entérites rapportés	1931	Ohio River (USA)	(Kuiper-Goodman et al., 1999)
Cas récurrents de gastro-entérites rapportés chez les enfants chaque année à la suite de bloom de cyanobactéries (*Microcystis sp*)	……	Harare (Zimbabwe)	(Zilberg, 1966) rapporté par (Kuiper-Goodman et al., 1999)
13 personnes tombent malades après avoir fréquenté un lac affecté par les cyanobactéries	1959	Saskatchewan (Canada)	(Dillenberg & Dehnel, 1960)
Plusieurs cas d'hépato-entérites rapportés (140 enfants et 10 adultes ont dû recourir à un traitement médical avancé-thérapie intraveineuse)	1979	Queensland (Australie)	(Byth, 1980) Rapporté par (Kuiper-Goodman et al., 1999)
88 cas de décès, en majorité des enfants, en plus de 2000 cas de gastro-entérites rapportés à la suite d'un événement de bloom de cyanobactéries survenu après la construction d'un barrage	1988	(Bahia) Brésil	(Teixeira et al., 1993)
20 nouvelles recrues de l'armée souffrent d'intoxication (dont 2 cas très sévères)	1989	Royaume-Uni	(Turner et al., 1990)
Plusieurs cas d'empoisonnement d'animaux dans plusieurs pays	......	Argentine, Australie Canada, Finlande Royaume-Uni, USA, Écosse	Selon la revue de synthèse présenté par (Kuiper-Goodman et al., 1999)
Avis de non-consommation de l'eau durant une longue période suite à l'enregistrement de concentration en toxines très élevées (population affectée: environ 4500 habitants)	du 13 Juillet au 30 Août 2011	Municipalité de Bedford (Missisquoi Bay - Québec-Canada)	(Agence de la santé et des services sociaux de la Montérégie-Québec, 2011)
Avis de no- consommation de l'eau durant plusieurs jours suite à l'enregistrement de concentration en toxines très élevées (population affectée: environ un demi-million d'habitants)	2014	Toledo (Ohio-États-Unis d'Amérique)	From web journal (Vox Media Inc, 2014)

Notons que cette liste non-exhaustive (**Tableau 1.1**) est loin de refléter l'ampleur du problème au niveau mondial. Cependant, elle met en exergue certains cas (des plus anciens au plus récents) qui ont été documentés.

- **Au Québec**

L'occurrence des CB au Québec a connu une très large médiatisation entre 2007 et 2008. Plusieurs cas de plans d'eau affectés par les CB ont été rapportés par le Ministère du Développement durable de l'Environnement et de la Lutte contre les changements climatiques (MDDELCC) (**Figure 1.1**). Des concentrations très élevées en toxines ont été enregistrées entrainant des avis de non-consommation comme dans le cas de la Baie Missisquoi en 2011 (**Tableau1.1**). Rappelons que ces avis sont émis lorsque les concentrations en toxine dépassent la concentration maximale acceptable (CMA) qui est de 1.5µg/L pour la microcystine-LR selon les recommandations faites par Santé Canada et préconisées aussi l'INSPQ (Institut National Santé publique du Québec (INSPQ), 2005). L'organisation mondiale de la santé (WHO) recommande une CMA de 1µg/L pour la microcystine-LR (WHO, 1998). Au vu des résultats présentés dans la **Figure 1.1**, nous pouvons constater que le pourcentage de plans d'eau affectés est assez important (entre 50% et 70%) mais il est également à noter qu'il y a une baisse du suivi fait par le MDDELCC (nombre de sites visités). Malgré cette tendance à la baisse des sites visités **(Figure 1.1)**, nous pouvons noter que les ressources en eau sont toujours menacées par les fortes proliférations de cyanobactéries. En effet, à cause des cyanobactéries, environ un demi-million de personnes ont reçu un avis de non consommation de l'eau pendant des jours dans la municipalité de Toledo en Ohio aux USA (récemment, en Août 2014), en plus de celui qui est survenu au Québec (Canada) en 2011 dans la municipalité de Bedford (**Tableau 1.1**).

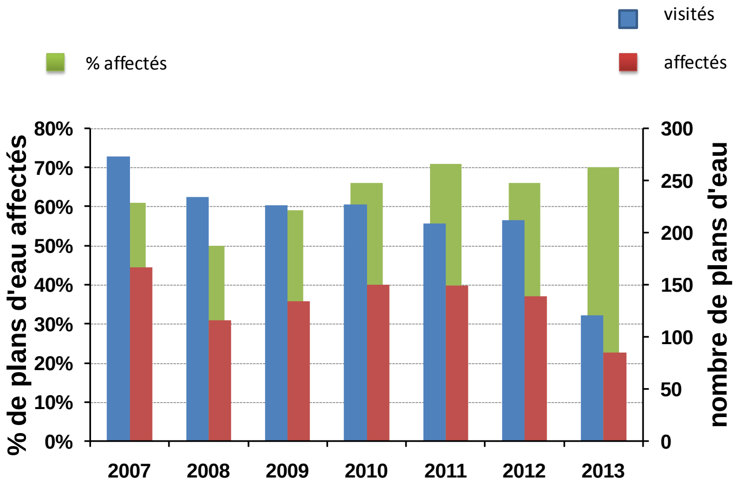

Figure 1.1: Évolution de la situation sur l'occurrence des cyanobactéries dans les plans d'eau au Québec (Canada) (Ministère du Développement durable de l'Environnement et de la Lutte contre les Changements Climatiques, 2013)

1.2 Nature, diversité et mode d’adaptation des cyanobactéries

D’après les travaux de Hoek et al. (1996), les cyanobactéries comptent 2000 espèces réparties en 150 genres. Selon certains auteurs, 40% des espèces sont supposées toxigéniques (Jayatissa et al., 2006). Les toxines sécrétées par certaines espèces sont classées en quatre grandes catégories : les neurotoxines, les hépatotoxines, les cytotoxines et les toxines irritants comme les lipopolysaccharides (Pearson et al., 2008). Comme décrite par Rizvi and Rizvi (1992), l’interaction des cyanobactéries avec les autres organismes présents dans leur milieu est plus marquée par la production de toxines. Les cyanobactéries peuvent être classées en cinq ordres que sont: les chroococcales, les pleurocapsales, les oscillatoriales, les nostocales et les stigonématales (les deux derniers sont hétérocystes). La forme, la mobilité et la tolérance à la température (psychrophiles, mésophile, thermophile) sont également des critères de différenciation (Merceron, 2004).

Leur principal mode de métabolisme énergétique est la photosynthèse (Mur et al., 1999). Beaucoup d’études révèlent que les cyanobactéries sont observées durant les périodes pendant lesquelles la température de l’eau excède 25°C (Coles & Jones, 2000; Rapala, 1998; Robarts & Zohary, 1987). Cependant, d’après Lavoie et al. (2007) des « fleurs d’eau » ont été même observées sous un couvert de glace, ce qui laisse croire que les cyanobactéries ont une excellente capacité d’adaptation et qu’elles sont capables de proliférer quel que soit le milieu dans lequel elles vivent.

Afin de pouvoir s’adapter à une carence d’un ou de plusieurs nutriments, les cyanobactéries adoptent certains comportements que sont : l’augmentation de l’efficacité d’assimilation des nutriments, la mobilisation des réserves internes en nutriments, ou la limitation des activités non nécessaires à la survie. Les réactions généralement enregistrées lors d’une carence en nutriments sont : l’arrêt de la division cellulaire ou des altérations importantes de la structure cellulaire et du métabolisme. En cas de limitation en nitrates ou ammoniac, considérés comme les sources préférées d’azote, les cyanobactéries consacrent environ 10 % de leurs cellules synthétisées aux nitrogénases (Mur et al., 1999). Une autre possibilité pour faire face à ce déficit d’azote est de fixer ce dernier à partir de l’atmosphère (Merceron, 2004). En effet, la capacité à fixer ou non l’azote atmosphérique est une caractéristique de diversité biologique qui est propre aux hétérocystes (Wolk, 1996). Dans les travaux de Cohen et al. (1986), il est reconnu que les cyanobactéries peuvent supporter de faibles concentrations en oxygène. Elles peuvent utiliser le bicarbonate comme source de carbone en plus du CO_2 (Lavoie et al., 2007; Shapiro, 1997). Ce qui entraine une augmentation du pH à la suite des réactions d'équilibre carbonique.

Le caractère photoautotrophe strict des cyanobactéries leur impose une adaptation chromatique selon la qualité et l'intensité de la lumière comme étudié par Van Liere and Walsby (1982). Exposées à un éclairement solaire excessif, les cyanobactéries, grâce à leurs vésicules à gaz, peuvent réguler leur flottabilité pour se mettre à un certain niveau de la colonne d'eau (Belov & Giles, 1997; Howard, 1997; Kromkamp & Mur, 1984; Kromkamp & Walsby, 1990; Reynolds & Irish, 1997; Wallace & Hamilton, 2000). Cette régulation est conditionnée par la recherche de nutriments, d'éclairement adéquat, ou de proximité avec l'air. Leur habileté à se maintenir en suspension est un important facteur qui contribue à la prédominance des cyanobactéries dans les lacs (Thomas & Walsby, 1985). Cette propriété leur permet aussi de disposer des nutriments et de la lumière (Carey et al., 2012) mais aussi de ne pas être trop exposées à la lumière pouvant entrainer la photoinhibition (Sherman & Webster, 1994; Zhang et al., 2008). Cependant, certaines espèces comme Nudularia peuvent survivre à la surface de la colonne d'eau même si elles sont exposées à de fortes irradiances (Kanoshina et al., 2003). Ce phénomène d'inhibition du métabolisme de photosynthèse, pouvant être considéré comme un mécanisme de protection à long terme, permet aux cellules de réduire les dommages (Oquist et al., 1992). Visser et al. (1997) et Walsby (1997) suggèrent que l'espèce *Microsystis* possède cette habileté d'éviter la photoinhibition en se déplaçant au fond de la colonne d'eau. La photo-acclimatation est un autre moyen d'adaptation qui jouerait un rôle majeur dans l'optimisation du taux de photosynthèse (Schagerl & Mueller, 2006).

La présence de certaines substances peut également influencer l'abondance de la communauté cyanobactérienne. En effet, Pannard et al. (2008) de même que Lurling and Roessink (2006) montrent respectivement que l'atrazine et le metribuzin, qui sont des herbicides très largement utilisés dans le monde, influencent l'abondance et la communauté phytoplanctonique à l'avantage des cyanobactéries dans la mesure où elles sont moins sensibles à l'effet de ces herbicides contrairement aux algues vertes. Le dernier recours des cyanobactéries dans un milieu totalement défavorable est la possibilité d'entrer en dormance (Merceron, 2004).

1.3 Occurrence des fleurs d’eaux : hypothèses explicatives jusqu’ici avancées

1.3.1 Nutriments

La disponibilité et la concentration de certains éléments des cellules algales sont déterminantes pour l'occurrence des cyanobactéries. Il s’agit en particulier du carbone, de l’hydrogène, de l’oxygène, du phosphore, de l’azote et du sulfure. Dans un environnement aqueux naturel, l’oxygène et l’hydrogène sont fournis en quantités illimitées et le sulfure est fréquemment en excès (Downs et al., 2008; Mur et al., 1999). En ce qui concerne le carbone, c’est un important élément qui est rarement considéré comme limitant contrairement à l’azote et au phosphore (Wang et al., 2002). D’après Wongsai and Luo (2007), les « fleurs d’eau » surviennent en général dans les conditions suivantes : pH et températures élevées (supérieure à 20 °C), faible intensité lumineuse, concentration en nutriments (particulièrement le phosphore)élevée et réduction de la turbulence de l’eau. Il faut cependant noter que les variations de pH et de turbidité seraient des conséquences d’une forte densité de cyanobactéries présentes dans la colonne d’eau.

Le rapport TN/TP (azote total / phosphore total) a fait l’objet de plusieurs études pour expliquer l’occurrence des fleurs d’eaux. En effet, selon Chellappa et al. (2008), une abondance des cyanobactéries ne s’accorde pas avec un rapport (TN/TP) en deçà de 10 considéré comme étant faible. Les résultats des études de Schreurs (1992) rapportés par Mur et al. (1999), donnaient une plage de 16-23 molécules de N pour 1 molécule de P comme étant le plus favorable pour l’optimum de croissance des cyanobactéries. Auparavant, certaines études avaient conclu que la biomasse des cyanobactéries totales augmente si ce rapport (TN/TP) est supérieur à 29 (Smith, 1986), alors que ce serait la biomasse des cyanobactéries fixatrices d’azote qui augmenterait s’il décroit de 15 à 5 (Schindler, 1977). Ainsi, il apparait qu’il n’y a pas de consensus sur l’usage du rapport TN/TP comme indicateur de l’occurrence des cyanobactéries dans un plan d’eau. Ceci est confirmé par les travaux de Jayatissa et al. (2006) réalisés au niveau des eaux douces du Sri Lanka où ces auteurs trouvent un rapport (TN/TP) inférieur à 15, conduisant dans certains cas à des proliférations abondantes de cyanobactéries alors que dans d’autres cas, il n’y en avait pas. Ainsi, ils concluent que ce rapport gênerait faiblement la croissance des cyanobactéries si les autres facteurs sont réunis.

Dans leurs récents travaux, Zhang et al. (2012) montrent que les événements de blooms de CB n’étaient pas liés au rapport (TN/TP). Cette absence de consensus pourrait être une résultante de la capacité de stockage dont disposent les CB. En effet, il faut noter que les cyanobactéries peuvent stocker l’excès d’azote et qu’une croissance significative s’observe lorsque la concentration totale en azote est au-dessus de 0,3 mg/L (Wang et al., 2002). Ceci s’accorde avec les travaux précédents de Mur et al. (1999) selon lesquels cette possibilité de stockage dont disposent les cyanobactéries est déterminante dans la mesure où elle leur confère un avantage compétitif à long terme.

Cependant, les récents travaux faits sur les rapports de nutriments montrent qu’un faible rapport DIN/TP (azote inorganique dissous/phosphore total) serait un bon indicateur de l’occurrence des cyanobactéries dans un plan d’eau (Bergström, 2010; Ptacnik et al., 2010).

Le fer biodisponible est également considéré comme un paramètre qui a une influence sur la biomasse des cyanobactéries qui tend à augmenter quand ce dernier diminue (Hyenstrand et al., 2000). Selon Sevilla et al. (2008), la disponibilité du fer affecte la croissance cellulaire. Pour la silice, les études faites sur les écosystèmes riches en nutriments montrent que les diatomées tendent à augmenter leur compétitivité et elles sont largement avantagées par la présence de cet élément (Schelske & Stoermer, 1971).

1.3.2 Intensité lumineuse

La lumière fournit l’énergie photosynthétique d’où son importance dans la croissance algale (Liu et al., 2013). Zhang et al. (2012) considèrent que les conditions lumineuses sont déterminantes à l’initiation et à la durée des blooms de CB et favorisent ainsi la dominance des CB quand la disponibilité de la lumière est plus longue. Une exposition intermittente à de hautes intensités lumineuses conduit à des taux de croissance cyanobactérienne atteignant presque le maximum (Loogman, 1982).

Les CB disposent de pigments qui leur confèrent un avantage compétitif devant les autres communautés algales (Osborne & Raven, 1986). Les principaux pigments jusqu’ici connus des cyanobactéries sont la chlorophylle-a et les phycobiliprotéines (allophycocyanine, phycocyanine, phycoérythrine). Ces derniers leur permettent d’exploiter toute longueur d’onde disponible. Beaucoup de cyanobactéries sont sensibles à une exposition prolongée à de fortes intensités lumineuses bien que celles observées en surface lors des floraisons semblent supporter ces hautes intensités lumineuses. Cependant, elles peuvent aussi résister à la photoinhibition comparé aux autres groupes d’algues (Visser et al., 1997; Walsby, 1997; Zhang et al., 2008). Une turbidité élevée peut être à l’origine d’une baisse de compétitivité des autres espèces au détriment des cyanobactéries qui arrivent à bien croître dans des conditions de forte turbidité et faible intensité lumineuse (Mur et al., 1999). Cependant, selon Huisman et al. (1999), une simple compétitivité à la lumière ne peut pas expliquer la dominance des cyanobactéries. En effet, selon ces auteurs, les caractères éco-physiologiques, en particulier la flottabilité des cyanobactéries leur permettent d’augmenter leur biomasse rapidement en facilitant l’accès aux éléments nécessaires à leur croissance (nutriments, lumière). Cependant, il faut rappeler que cette flottabilité est également fonction de l’intensité lumineuse selon plusieurs études (Belov & Giles, 1997; Kromkamp & Walsby, 1990; Reynolds et al., 1987; Wallace & Hamilton, 1999; Walsby et al., 1989). Selon Brooks et al. (1999), cette flottabilité leur confère un avantage très significatif si les nutriments sont rares à la surface du plan d’eau (migration vers les CB pour disposer d’assez de nutriments) ou en excès dans l’ensemble du plan d’eau (les CB vont migrer vers la surface pour bénéficier du maximum de lumière afin de disposer d’assez d’énergie pour leur croissance).

1.3.3 Température

La température est considérée comme un paramètre très important dans la mesure où les occurrences de blooms sont enregistrées durant les périodes correspondant aux températures optimales de croissance des espèces de cyanobactéries présentes. L’augmentation de la fréquence d’occurrence des cyanobactéries serait liée aux phénomènes de changements climatiques et plus particulièrement à l’augmentation des températures (Hudnell & Paul, 2008; Reichwaldt & Ghadouani, 2012). Carey et al. (2012) et Zhang et al. (2012) indexent le réchauffement des eaux de surface dans le cas où les éléments nutritifs ne sont pas limitants dans la colonne d’eau. La biomasse des cyanobactéries augmente avec la température (Kosten et al., 2011; Reynolds, 1984). Havens et al. (2003) soutiennent qu’une croissance algale rapide est observée pendant les moments chauds en été. Pour les cyanobactéries, les taux de croissance optimaux sont enregistrés durant les périodes de température de l’eau élevée, généralement quand elles excèdent 25°C (Coles & Jones, 2000; Robarts & Zohary, 1987). Ceci confirme les travaux de Wang et al. (2002) qui montrent que beaucoup d’espèces de CB atteignent un maximum de croissance lorsque la température de l’eau est au-delà de 25°C. Selon Hamilton et al. (2005), les blooms de cyanobactéries sont observés lorsque les températures au fond de la colonne d’eau sont autour de 22°C. La température semble avoir un effet sur la dominance d’une souche donnée. En effet, d’après Fastner et al. (2007), les espèces *Aphanizomenon* et *Anabeana* sont souvent dominantes dans les régions tempérées et prolifèrent fortement quand les conditions de croissance sont favorables. Dans les zones tropicales, c'est plutôt l'espèce *Cylindrospermopsis raciborskii* qui est la plus observée dans les « fleurs d'eau » (Berger et al., 2006). Ces auteurs trouvent que *Microcystis* est une des espèces qui s'adapte le mieux à une augmentation de la température combinée à un déficit en nutriments.

Il faut noter que la température de l'eau affecte sa viscosité dans la mesure où elle tend à diminuer lorsque la température de l'eau augmente. De ce fait, en analysant la loi de Stokes utilisée dans les modèles de mouvement des cyanobactéries (Carey et al., 2012; Howard, 1997; Kromkamp & Walsby, 1990; Visser et al., 1997), il apparait que leur vitesse de mouvement serait inversement proportionnelle à la viscosité (Reynolds, 2006). De ce fait, la formation de blooms ainsi que le mouvement seraient facilités pendant les périodes de températures élevées dans la colonne d'eau. Cependant, les faibles températures ($T<20^{o}C$) pourraient faire perdre aux cyanobactéries leur flottabilité après à une accumulation de carbohydrate causée par une sensibilité aux variations de température sur les mécanismes de respiration et de photosynthèse. La production et la consommation du carbohydrate sont des processus très sensibles à la température (Thomas & Walsby, 1986). Ces auteurs montrent que cette flottabilité perdue pourrait être retrouvée dès que des températures adéquates sont atteintes.

D'autres chercheurs tels Hense (2006), mettent l'accent sur le cycle de vie des cyanobactéries pour tenter d'expliquer les « fleurs d'eau ». Cependant, il n'en était qu'à l'étape de développement du modèle. D'après ses premiers essais, il semblerait que la probabilité d'observer une « fleur d'eau » soit plus grande quand la température est élevée.

1.3.4 Facteurs hydrologiques et hydrodynamiques

- **Précipitation**

Jusqu'ici il existe peu d'études qui mettent en évidence les effets des précipitations sur les « fleurs d'eau »(Paerl & Paul, 2012b; Reichwaldt & Ghadouani, 2012). En effet, suite au lessivage des sols durant les précipitations, des éléments nutritifs (azote, phosphore) de même que des micronutriments sont drainés vers les plans d'eau(King et al., 2007). Une accumulation à long terme de ces nutriments en présence d'autres conditions favorables (température, lumière, vent) favorise les proliférations abondantes de cyanobactéries (Mimeault, 2002). Ces travaux sont renforcés par ceux de Jones et al. (2005) selon lesquels le maintien de la dominance des cyanobactéries serait lié aux effets des changements climatiques qui, à la suite de fortes précipitations, augmenteraient les charges en éléments nutritifs dans les lacs.

- Stabilité de la colonne d’eau

La stabilité de la colonne d’eau induite par l’intensité des vitesses de vent combiné à la disponibilité de la lumière dans la colonne d’eau affectent fortement la distribution spatiale des cyanobactéries telles que *Microcystis aeruginosa* (Wang et al., 2011) et favorisent leur dominance (Carey et al., 2012; Paerl & Huisman, 2008; Taranu et al., 2012). Une alternance entre périodes de turbulence et de stabilité dans la colonne d’eau est nécessaire pour les cyanobactéries afin de pouvoir proliférer.

Quelques années auparavant Reynolds et al. (1983) montraient que la turbulence pouvait réduire le risque d’occurrence des cyanobactéries. Les occurrences de cyanobactéries sont inversement affectées par les vitesses de vents (Bormans et al., 2004). Pour confirmer cela, Cao et al. (2006) ont observé la formation d’écumes pendant les périodes durant lesquelles de faibles vitesses de vent. Une dispersion des cyanobactéries accumulées à la surface est observée quand il y a des vents de plus de 6 à 8 m/s (Kanoshina et al., 2003),ce qui montre l’importance de la stabilité de la colonne d’eau. Des auteurs comme Cao et al. (2006) et Webster and Hutchinson (1994) donnent les seuils respectifs de vitesses inférieures à 3.1 m/s ou entre 2 m/s et 3 m/s comme indicateur d’une colonne d’eau stable. Il existe quelques tentatives de modélisation de la turbulence sur la distribution des cyanobactéries faites par certains auteurs tels que Chen et al. (2009). En effet, selon ces auteurs (Chen et al., 2009), la turbulence aurait peu d’effet sur l’advection verticale. Cependant, notons que Chen et al.(2009) utilisent une approche lagrangienne pour modéliser la distribution des cyanobactéries en ignorant beaucoup d’interactions telles que l’effet de la densité de la suspension.

En effet, selon les études faites par Bouchard (2004), de courtes périodes d’anoxie, lorsque la colonne d’eau est stable, près du fond, sont nécessaires pour permettre la libération du phosphore des sédiments. Après libération, une période de turbulence permettrait de distribuer ce nutriment et les autres (fer, azote…) dans la colonne d’eau. Les cyanobactéries, grâce à leur capacité à se déplacer, vont naviguer dans la colonne d’eau pour ensuite s’imposer en ayant une importante part des nutriments à leur disposition. Il existe quelques rares espèces (munies de flagelles) qui entrent en compétition, par contre les cyanobactéries sont plus efficaces que ces dernières (Lavoie et al., 2007).

Selon les différentes saisons et les régimes de turbulence associés, un ou des groupes phytoplanctoniques peuvent être dominants du fait d'une éventuelle modification de la stratégie de consommation des nutriments (Litchman et al., 2004). Ces auteurs s'appuient sur les travaux de Reynolds (1984) qui montrent respectivement que les diatomées sont dominantes durant les périodes pendant lesquelles la colonne d'eau est mélangée (suite à l'effet turbulence). Selon Carey et al. (2012), en plus du réchauffement de la colonne d'eau, d'autres facteurs tels que morphologie du lac combinés à la stabilité de celle-ci sont indexées comme étant les principaux facteurs favorisant l'occurrence des cyanobactéries. Belov et al. (1999), dans ces études de modélisation qui n'ont pas été confrontées à des mesures environnementales, trouvent qu'une faible turbulence est favorable aux cyanobactéries du fait de leur aptitude à se déplacer le long de la colonne d'eau et que cet aspect combiné à la photosynthèse sous des conditions de faible intensité lumineuse sont les facteurs qui expliquent la dominance des cyanobactéries dans certains plans d'eau durant des périodes données.

Dans leurs travaux réalisés au Lac de Guiers (Sénégal), Berger et al.(2006) constatent que la prolifération d'espèces cyanobactériennes est survenue à la suite de la construction d'un barrage entrainant des effets considérables au niveau de l'écoulement de l'eau. Cependant, toutes ces observations ne permettent pas d'élucider le rôle du mécanisme de flottabilité des cyanobactéries suite à la variation de leur propre densité.

1.4 Toxicité (teneurs en toxines) lors d'une fleur d'eau

Par rapport à la toxicité des « fleurs d'eau », plusieurs hypothèses ont été avancées. En effet, d'aucuns considèrent que les cellules de CB produisent des toxines et que ces dernières sont relarguées après leur mort naturelle ou par algicide alors que pour d'autres chercheurs, elles peuvent libérer leurs toxines de leur vivant (Merceron, 2004). Selon Schmidt et al. (2009), le relargage de toxine est intimement lié au cycle de vie des cyanobactéries (toxines relarguées lors de la sénescence, la mort ou la lyse cellulaire). Dans leurs études au niveau de 8 lacs (eutrophes et hypertrophes) en zones subtropicales dans lesquelles l'occurrence des cyanobactéries est bien connue, Wu et al. (2008) observent que les toxines extracellulaires sont fortement reliées avec les facteurs chimiques et biologiques tels que le phosphore total, le carbone organique total, la Chlorophylle a et la biomasse de *Microcystis.*

El Herry et al. (2008) rapportent qu'une faible teneur en toxines à la suite d'une « fleur d'eau » pourrait s'expliquer par l'absence d'écumes. Contrairement à Janse et al. (2004) qui, dans leurs travaux, montrent qu'il existe une corrélation négative entre la teneur en microcystine par cellule et l'abondance du genre *Microcystis*, soutiennent que lors d'une prolifération de cyanobactéries, les colonies toxiques sont relativement dominantes, mais perdent le contrôle au fur et à mesure que la « fleur d'eau » progresse. Selon Kardinaal et al. (2007), la compétition à la lumière joue un rôle important dans la succession selon les saisons entre les souches toxiques et non toxiques de *Microcystis*. Ainsi, suite à ces expériences de compétition, ils conclurent que la souche non toxique de *Microcystis* est plus compétitive à la lumière que celle qui est toxique. En se basant sur les travaux de Nishizawa et al. (2000) et ceux de Tillett et al. (2000), selon lesquels la synthèse de toxine se fait grâce à de multiples enzymes très complexes et que cela requiert beaucoup d'énergie, Vezie et al. (2002) soutiennent que les souches non toxiques sont favorisées en milieu déficitaire en lumière et en nutriments. Ceci est aussi appuyé par les résultats de Lehtimäki et al. (1994) qui avaient constaté qu'une souche non toxique de *Nodularia* croit plus rapidement que la même souche toxique dans des conditions de faibles concentrations en phosphore. Ainsi, l'augmentation des charges nutritives conduisant à une forte eutrophisation favorise la croissance de souches toxiques au détriment de celles qui sont non toxiques (Chellappa et al., 2008).

D'autre part,Wongsai and Luo (2007)révèlent que la formation de souches toxiques ou non est dépendante de l'azote plutôt que du phosphore et que les « fleurs d'eau »toxiques surviendraient pour des rapports azote total sur phosphore total élevés en plus d'une teneur élevée en azote sous forme d'ammoniac. Ces propos, confirmés par des études spécifiques relatées à travers cette revue, permettent de voir que les cyanobactéries sont souvent mises dans des conditions idéales pour une éventuelle prolifération au détriment des autres espèces phytoplanctoniques. Le relargage de toxines en milieu aquatique naturel est considéré par Jang et al. (2008) comme un moyen de défense contre le zooplancton et que les substances produites par le zooplancton (dont la composition n'est pas connue) constituent l'élément déclencheur qui stimule le relargage.

Sur cet aspect de production de toxine selon les espèces présentes, il existe diverses explications aussi complexes les unes que les autres. Ainsi, il apparait une difficulté majeure afin de pouvoir évaluer le risque lié à la toxicité d'une « fleur d'eau » pour les plans d'eau qui sont utilisés comme sources d'approvisionnement en eau potable. La complexité de cet aspect, qui demeure la plus grande préoccupation lors des fleurs d'eaux, ne facilite pas sa prise ne compte dans les modèles existants.

1.5 Système d'alerte

La plupart des études initiées dans l'optique de pouvoir prévenir les risques causés par les cyanobactéries se sont basées sur les travaux de Bartram and Chorus (1999). Diverses propositions ont été faites dans ce sens afin de standardiser les paramètres les plus pertinents qui sont susceptibles de servir d'indicateurs pour le niveau de toxicité (concentration en toxine) lors de la prolifération de cyanobactéries. Les systèmes d'alerte jusqu'ici proposés essaient de relier la toxicité aux paramètres tels que le biovolume, la densité cellulaire et la biomasse. Le principal outil largement utilisé est la mesure in vivo des pigments fluorescents photosynthétiques. Cependant, d'après Gregor et al. (2007), ces pigments ne sont pas toujours directement reliés au biovolume, à la densité cellulaire et dans certains cas, cette mesure de fluorescence in vivo ne reflète pas la concentration de ces pigments. Argumentant ce fait, ils se basent sur travaux de Kiefer (1973), SooHoo et al. (1986) et Vincent et al. (1984) selon lesquels les pigments fluorescents photosynthétiques dépendent en partie de l'état physiologique des cellules et de leurs photosystèmes qui seraient affectés par d'autres facteurs tels que leur cycle de vie, la disponibilité des nutriments et l'accessibilité à la lumière.

Parmi les paramètres recommandés par l'Organisation mondiale de la santé (OMS) figure la concentration en chlorophylle a. Selon les études faites par Watzin et al. (2006) sur le lac Champlain entre 2002 et 2004, la chlorophylle a n'est pas un bon indicateur du niveau de toxicité et du potentiel de production de toxines par les cyanobactéries. Dans ces travaux, qui ont permis d'analyser 1011 échantillons recueillis au niveau de la Baie Missisquoi, de la Baie de Burlington, de St Albans et celle de Maquam ainsi que dans d'autres endroits du lac, il a été confirmé que les teneurs en microcystine ne sont pas corrélées avec la densité cellulaire phytoplanctonique. D'après Watzin et al. (2006), ceci a été déjà énoncé par Cronberg et al. (1999) et appuyé par les explications de Rinta-Kanto et al. (2005b) de même que Wilson et al. (2005), qui indexent la présence de souches toxiques et non toxiques comme la raison pour laquelle la densité cellulaire n'est pas généralement un bon prédicateur de la concentration en toxines. Il est apparu dans ces études faites par Wazin et al. (2006) que la teneur en toxine n'est proche de 1µg/L, correspondant au niveau d'alerte 1 de l'OMS, que si la densité cellulaire des souches toxiques dépasse les 4000 cellules/mL. C'est ainsi que le niveau d'alerte a été relevé de 2000 cellules/mL à 4000 cellules par mL en 2003 et 2004 concernant le seuil d'alerte « Vigilance » au niveau de Vermont (USA) (niveau Vigilance : Avis officiel d'une possible formation de bloom de cyanobactéries).

Les travaux de Watzin et al. (2006) doivent être nuancés si l'on se fie aux résultats obtenus par Izydorczyk et al. (2009) qui ont pu mettre en évidence une importante corrélation entre la chlorophylle a cyanobactérienne mesurée in vivo et les teneurs en toxines (microcystine). Rappelons que jusqu'ici, il n'a été relevé nulle part dans la littérature cette possibilité de mesurer les densités cellulaires des souches toxiques et non toxiques en utilisant des sondes fluorescentes. Seuls les comptes taxonomiques permettent d'accéder à cette information.

Selon Schmidt et al. (2009), les teneurs en toxine dissoute sont positivement corrélées avec la densité des vieilles cellules. Les derniers développements obtenus dans ce sens montrent une bonne corrélation entre biovolume et teneur en toxine pour les études menées en 2008 dans la Baie Missisquoi et dans un réservoir d'eau du Yamaska (au Québec) (McQuaid et al., 2011). Ces résultats de McQuaid et al.(2011) pourraient s'expliquer par un potentiel toxique qui serait en lien avec biovolume selon les espèces présentes.

Malgré les résultats trouvés, Watzin et al. (2006) reconnaissent la difficulté qui réside dans la recherche d'outils pour pouvoir alerter à temps d'une éventuelle prolifération abondante de cyanobactéries, même si un bon programme de suivi est mis en place dans un espace aquatique donné. Cette dernière serait fortement liée aux changements spatio-temporels des conditions météorologiques qui influencent le changement brusque de la densité cellulaire des cyanobactéries. Ainsi, il apparait une autre difficulté qui ne saurait être contournée qu'en incluant les facteurs météorologiques dans les systèmes d'alerte afin de tenir compte de cet aspect. Ceci a été également soulevé dans les travaux de Izydorczyk et al. (2005) qui ont eu à constater un changement rapide de la fluorescence quand les vents étaient dirigés vers la prise d'eau.

Dans le suivi de la prolifération des cyanobactéries, la variabilité spatio-temporelles est une des difficultés majeures rencontrées comme annoncé par Brient et al. (2008). Ainsi, dans le cas d'une zone qui devrait recevoir une prise d’eau, l’installation de cette dernière pourrait être faite tenant compte de la distribution spatio-temporelle des cyanobactéries, en cas de « fleur d’eau », influencée par le comportement hydrodynamique (dépendant des conditions météorologiques).

La variabilité qui peut exister au sein d’une espèce rend complexe la mise en place d’un éventuel système d’alerte par rapport aux teneurs en toxines. En effet, tel est le cas avec l’espèce *Cylindrospermopsis raciborskii* retrouvé dans les études de Berger et al. (2006) faites au Sénégal. Ce dernier n’exprime pas sa toxicité alors que, selon les études de Falconer (2001) rapportées par Lavoie et al. (2007), elle a été la principale espèce qui avait causé des cas d’intoxication en Australie. Cette variabilité pourrait expliquer les diverses corrélations trouvées de part et d'autre et répertoriées dans le **Tableau 1.2** qui donne les résultats d’études qui ont été faites afin de corréler la production de toxines et la biomasse ou densité cellulaire à certains paramètres.

Ainsi, une approche probabiliste pourrait servir dans l’évaluation du niveau de risque pour les prises d’eau.

Tableau 1.2: Études réalisées pour corréler divers facteurs liés aux cyanobactéries

Méthodologie	Site d'étude	Corrélation	Coefficient de détermination (r^2)	Auteurs
Pas de mesure in vivo. Toutes les méthodes utilisées sont analytiques	Lac Lianhuahu (Chine)	Toxine intra (Micorcystin (MC)) vs Chl a	0,11	(Zheng et al., 2004)
		Toxine intra (MC) vs biomasse Cyanobacteria	-0,18	
		Toxine intra (MC) vs biomasse A. flos aqua	-0,32	
		Toxine intra (MC) vs biomasse M. aeruginosa	0,16	
		Toxine intra (MC) vs Azote totale	0,02	
		Toxine intra (MC) vs Phosphore total	-0,74	
		Toxine intra (MC) vs nitrate	0,08	
		Toxine intra (MC) vs nitrite	-0,09	
		Toxine intra (MC) vs ammoniac	0,83	
		Toxine intra (MC) vs Phosphore total dissout	0,36	
		Toxine intra (MC) vs ortho-phosphate	-0,26	
		Toxine intra (MC) vs rapport azote sur phosphore	-0,76	
		Toxine intra (MC) vs Température	0,07	
		Toxine intra (MC) vs Conductivité	-0,13	
		Toxine intra (MC) vs pH	0,09	
		Toxine intra (MC) vs Oxygéne dissout	-0,17	
		Toxine extra (MC) vsChl a	-0,32	
		Toxine extra (MC) vsbiomasseCyano	0,32	
		Toxine extra (MC) vsbiomasse A. flos aqua	0,28	
		Toxine extra (MC) vsbiomasse M. aeruginosa	0,08	
		Toxine extra (MC) vs Azote totale	0,30	
		Toxine extra (MC) vsPhosphore total	0,38	
		Toxine extra (MC) vs nitrate	-0,41	
		Toxine extra (MC) vs nitrite	0,16	
		Toxine extra (MC) vs ammoniac	-0,29	
		Toxine extra (MC) vsPhosphore total dissout	0,61	
		Toxine extra (MC) vsortho-phosphate	-0,02	
		Toxine extra (MC) vs rapport azote surphosphore	-0,43	
		Toxine extra (MC) vs Température	0,50	
		Toxine extra (MC) vs Conductivité	-0,31	
		Toxine extra (MC) vs pH	0,61	
		Toxine intra (MC) vs Toxine extra (MC)	-0,01	
		Toxine extra (MC) vs Oxygéne dissous	0,58	
Mesure de la phycocyanine in vivo avec la sonde fluorométriques Turner, with phycocyanin optical kit Longueur d'onde d'excitation : 630 nm Longueur d'onde d'émission : 660 nm Limite minimale de détection : 1000 cellules/Ml	Réservoir d'eau de Sulejow (Pologne)	Fluorescence de la PC vs biomasse Cyan (si biomasse Cyan < 15mg/L)	r=0,65 (n=32, p<0,05)	(Izydorczyk et al., 2005)
		Fluorescence de la PC vs toxine totale (MC) (si toxine totale (MC) < 3 µg/L)	r=0,51 (n=32, p<0,05)	
		Biomasse Cyan vs toxine totale (MC)	r= 0,74 (n=31, p<0,05)	

Tableau 1.2: Études réalisées pour corréler divers facteurs liés aux cyanobactéries (Suite)

Méthodologie	Site d'étude	Corrélation	Coefficient de détermination (r^2)	Auteurs
Mesure de la fluorescence de la phycocyanine un spectromètre Luminescente Perkin Elmer et absorbance avec un spectrophotomètre (UV-160A)	Réservoir d'eau Daechung (République de Corée)	PC mesurée in vivo vs PC extraite PC mesurée in vivo vs Secchi deph PC mesurée in vivo vs Chl a PC mesurée in vivo vs Cyan (cellules/mL) PC mesurée in vivo vs *Microcystis* (cellules/mL) PC mesurée in vivo *Oscillatoria* (cellules/mL) En Log : PC extraite vs Chl a En Log : PC extraite vs Cyano (cellules/mL)	0,886 (p<0,001) -0,823 (p<0,001) 0,786 (p<0,001) 0,607 (p<0,001) 0,401 (p<0,01) 0,576 (p<0,001) 0,803 (p ??) 0,353 (p ??)	(Ahn et al., 2007)
Mesure de la phycocyanine faite avec la sonde TriOS qui est un fluoromètre miniaturisé et submersible Longueur d'onde d'excitation : 620 nm Longueur d'onde d'émission : 655 nm	Plan d'eau à l'Ouest de la France	En Log : Concentration en PC vs Cyan (cellules/mL) En Log : Cyan (cellules/mL) vs Chl a Contenu cellulaire en PC vs Cyan (cellules/mL) Contenu cellulaire en PC vs biovolume estimé Contenu cellulaire en Chla vs Cyan (cellules/mL)	r^2=0,7296 r^2=0,4285 r^2=0,74 (n=71, p<0,05) r^2=0,78 (n=71, p<0,05) r^2=0,68 (n=71, p<0,05)	(Brient et al., 2008)
Mesure faite avec la sonde de type Bio-Tek Flx 800 2 Longueurs d'onde d'excitation : 485 nm (algues eucaryotes) et 590 nm (cyanobactéries) Longueur d'onde d'émission : 680 nm	Réservoir d'eau Vir (République Tchéque)	À 10 m de la prise d'eau Cyan (cellules/mL) vs Fluorescence (r.u) À 30 m et 50 m de la prise d'eau Cyan (cellules/mL) vs Fluorescence (r.u)	r= 0,96 (n=32, p=??) r= 0,74 (n=79, p=??)	(Gregor et al., 2007)
Mesure de chl a faite avec la sonde bbe-Moldaenke. Sonde disposant de 6 longueurs d'onde d'excitation (370, 450, 525, 570, 590 et 610) correspondant à différents groupes algales (algues vertes, chlorophyta, cyanobactéries, chromophyta, dinophyta, et cryptophyta). Résultats Cells/mL obtenus suite a un comptage taxonomique	Réservoir d'eau Brno Réservoir d'eau Mostiste (République Tchéque)	Réservoir d'eau Brno Chl a vs biomasse M. aeruginosa et M. ichtyoblabe (cellules/mL) Chl a vs biomasse diatomées (cellules/mL) Réservoir d'eau Mostiste Chl a vs biomasse Staurastrumsp. (cellules/mL)	 r^2= 0,86 r^2=0,95 r^2=0,83	(Gregor et al., 2005)
Mesure faite online avec la fluoromètre AOA comportant 5 longueurs d'ondes : 450, 525, 570, 590 et 610 nm Limite de détection : 0,05 ugChl a /L	Réservoir d'eau de Sulejow (Pologne)	Biovolume Cyan vs Chl a Toxine intra (MC) vs Chl a Chl a : excitée à la longueur d'onde appropriée pour les cyanobactéries (???? nm)	r=0,68 (n=46, p<0,05) r=0,70 (n=46, p<0,05)	(Izydorczyk et al., 2009)
Sonde multi-paramétres : YSI phycocyanine : Longueur d'onde d'excitation : 590 nm Longueur d'onde d'émission : 660 nm Chlorophylle a Longueur d'onde d'excitation : 470 nm Longueur d'onde d'émission : 680 nm	Baie Missisquoi et réservoir d'eau Lemieux (Québec, Canada)	Biovolume (mm^3/L) vs microcystine-LR Log cyanobacteria vs microcystine-LR Log in vivo Phycocyanine vsmicrocystine-LR	r=0,742 (n=19, p=0,0003 r=0,72 (n=19, p=0,0004) r=0,634 (n=42, p=0,00001)	(McQuaid et al., 2011)

Cependant, les prises d'eau étant des points d'intérêt majeurs dans beaucoup de plans d'eau, il est impératif de pouvoir évaluer le risque associé à la présence de cyanobactéries en forte densité à ces endroits. En outre, cela implique une prise en compte de l'aspect positionnement géographique de la prise d'eau. Cet aspect n'est jusqu'ici pas disponible dans les outils de prédiction. Le chapitre 3 de cette thèse est consacré à cet aspect.

1.6 Distribution spatio-temporelle des cyanobactéries

Les recherches menées jusqu'ici se concentrent sur les conditions eutrophes propices à leur prolifération et les changements constatés sur la qualité de l'eau (Costa et al., 2006; Elliott, 2012; Fastner et al., 2007; Imamura, 1981; Jayatissa et al., 2006; Kotak & Kenefick, 1993; Lahti et al., 1997; McCarthy et al., 2013; Wang et al., 2002; Wu et al., 2008), même si l'on indexe l'influence de l'hydrodynamique du milieu aquatique quant à la distribution spatio-temporelle des cyanobactéries.

En effet, la distribution spatio-temporelle des espèces aquatiques (particulièrement le phytoplancton) est fortement influencée par les courants d'eau, les phénomènes des vagues et la turbulence. Deux principaux facteurs contrôlent l'abondance d'une espèce présente dans un écosystème aquatique. Il s'agit de l'advection et des processus biologiques tels que la croissance et la mortalité(Ji, 2008). Dans le cas de l'occurrence des cyanobactéries dans un plan d'eau, le caractère irrégulier de cet événement dans un endroit précis de ce milieu conduit à s'interroger sur la dominance d'un de ces facteurs. On pourrait avancer qu'il s'agit de celui qui présente la plus grande probabilité de varier aléatoirement. En effet, si l'on se fie aux mesures (**Figure 1.3 et 1.4**) faites par l'état du Vermont (Government, 2009) au niveau de la Baie Missisquoi sur les teneurs en éléments nutritifs jugés indispensables à la croissance de cyanobactéries, il apparait que ces conditions sont jusqu'ici propices à la prolifération des cyanobactéries. Cependant, des fleurs d'eaux n'ont pas été enregistrées dans le secteur Est de la Baie, durant l'année 2007, contrairement aux années précédentes et suivantes. Suite à cette analyse, les effets induits par le comportement l'hydrodynamique du plan d'eau pourrait être une éventuelle piste à intégrer entièrement si l'on veut comprendre réellement l'occurrence des fleurs d'eaux. Cet aspect hydrodynamique pourrait revêtir un caractère aléatoire dans la mesure où les conditions météorologiques telles que le vent (intensité-direction) l'affectent profondément.

La prise en compte de cet aspect hydrodynamique nous conduit à considérer l'approche déterministe pour mieux comprendre les mécanismes qui contrôlent la distribution spatio-temporelle des cyanobactéries. Pour cela les équations de continuité et de quantité de mouvement et de transport sont considérées.

Continuité :

$$\mathbf{\nabla.V=0} \tag{1.1}$$

Quantité de mouvement :

$$\boldsymbol{\rho_w \frac{\partial V}{\partial t} + \rho_w \nabla.(VV) = -\nabla p + \nu \nabla^2 V + \rho \vec{g}} \tag{1.2}$$

Où V est la vitesse du fluide (m/s); p est la pression dynamique (Pa); ρ est la densité de la suspension (kg/m^3); ρ_w est la masse volumique de l'eau (kg/m^3); g est l'accélération gravitationnelle (m^2/s), ν est la viscosité de l'eau (Pa.s), et t est le temps (s).

Équation de transport :

Le suivi de la distribution spatio-temporelle des cyanobactéries nécessite de tenir en compte l'équation de transport ci-dessous :

$$\boldsymbol{\frac{\partial C}{\partial t} + \nabla(VC) + \nabla(FC) = D\nabla^2 C} \tag{1.3}$$

Où C est la concentration phytoplanctonique (cellules/m^3); V est la vitesse du fluide (m/s), **D**est le coefficient de diffusivité du plancton (m^2/s) et F (m/s) est le terme représentant la flottabilité des cellules de cyanobactéries. Ce mouvement étant attribué à l'effet phototaxis.

En plus de cela, le mécanisme de flottabilité suite à l'effet phototactique tel que décrit dans les modèles énumérés au Tableau 1.3 et représenté par la variable F dans l'équation de transport devrait être intégré.

Tableau 1.3: Mise en équation du mouvement des cyanobactéries dans une colonne d’eau

Modèle	Équations mises en œuvre	Définition des paramètres	Auteurs
Mouvement le long de la colonne d’eau	$\rho_v = \rho_c - \alpha' V_f$ $V_{feq} = V_{fmax} \left(1 - \int_0^p f_n(\xi, \sigma)\, dP\right)$ $\frac{dP}{dt} = \alpha(P_{max} - P)Q_{o_2} - \beta(P - P_{\min})$	ρ_v : densité des colonies tenant compte des vésicules de gaz ρ_c : densité des colonies dépourvues de vésicules de gaz α' : coefficient empirique V_f : fraction volumique des vésicules de gaz V_{feq} : fraction volumique des vésicules de gaz en équilibre avec la pression de turgescence V_{fmax} : fraction volumique maximale des vésicules de gaz $\alpha\ et\ \beta$: constantes ; P : ? $P_{max}\ et\ P_{\min}$: maximum et minimum de la pression de turgescence Q_{o_2} : mesure de l’activité photosynthétique cellulaire en mL O_2/ (g h) t: temps $f_n(\xi, \sigma)$: fonction de distribution normale de la pression de turgescence	(Okada & Aiba, 1983a; Okada & Aiba, 1983b)
	$\frac{d\rho}{dt} = c_1 \left[\frac{I}{K_1 + I}\right] - c_3$ $\frac{dp}{dt} = c_2 I_a - c_3$ $I_0 = I_m sin\left(\frac{\pi t}{D_L}\right)$ $I_z = I_0 e^{\varepsilon z}$ $\bar{I}_z = \frac{I_{z2} - I_{z1}}{\ln(I_{z2} - I_{z1})}$ $\rho_t = \rho_{t-1} + P\left\{c_1 \left[\frac{\bar{I}_z}{K_1 + \bar{I}_z}\right] - c_2 I_a - c_3\right\}$ $v = 2gr^2 \frac{(\rho_c - \rho_e)A}{9\phi n}$	ρ : densité cellulaire I : intensité lumineuse I_a : intensité lumineuse antérieur I_0 : intensité lumineuse à la surface de l’eau I_m : intensité lumineuse maximale D_L : durée de la période d’éclairement K_1 : constante de demi saturation relative à l’intensité lumineuse c_1 ;c_2 ;c_3 : constantes $\bar{I}_z$: intensité lumineuse moyenne à la profondeur z P : pas de temps ρ_1 : densité cellulaire au temps t ρ_2 : densité cellulaire au temps t-1 v : vitesse de chute r : rayon moyen des cellules ρ_e : masse volumique de l’eau A : proportion de volume cellulaire ϕ : facteur de forme ; g : pesanteur n : viscosité de l’eau	(Kromkamp & Walsby, 1990)

Tableau 1.3: Mise en équation du mouvement des cyanobactéries dans une colonne d’eau (Suite)

Modèle	**Équations mises en œuvre**	**Définition des paramètres**	**Auteurs**
	$h^2 = \frac{W\ \rho\ v_*\ L}{g\ \Delta P}$ $v_*^2 = \frac{\rho_{air}\ c\ U^2}{\rho}$ $isurf = I_m \sin\left(\frac{\pi t}{D_L}\right)$ $I_z = isurf\ \times e^{-(\varepsilon\ z)}$ $I_0 = \frac{(1-b) \times c \times isurf}{218}$ Si $I_z\ < P_{max}\ / tan\alpha$ $P_{qi} =\ I_z\ \times tan\alpha$ Sinon $P_{qi} =\ P_{max}$ Si $P_{qi} - R \leq C_{gmax}\quad alors\ K = P_{qi} - R$ Si $P_{qi} - R > C_{gmax}\quad alors\ K = C_{gmax}$ $B = P_{qi} - R - K$ Cependant si $P_{qi} - R < 0\ alors\ K = 0$ $\Delta\rho_{cel} = \frac{B_g \times C_{cel}}{67}$ $\Delta\rho_{col} = \frac{colcell \times 67 \times\ \Delta\rho_{cel}}{(4/3) \times \pi \times r^3}$ $\rho_{col} = F \times \rho_{cell} + [(1-F) \times \rho_{muc}\,]$	h : profondeur de la couche de turbulence W : ? ρ : densité cellulaire v_* : vitesse moyenne de l’eau dans la couche de turbulence L : largeur du lac g : pesanteur ΔP : différence de densité entre l’eau dans la couche de turbulence et celle au dessous ρ_{air} : densité de l’air $b\ et\ c$: proportion de $isurf$ potentiellement active U : vitesse du vent $isurf$: intensité lumineuse à la surface de l’eau I_m : intensité lumineuse maximale D_L : durée de la période d’éclairement ε : coefficient d’extinction z : relatif à la profondeur de l’eau	(Howard et al., 1996)
Mouvement le long de la colonne d’eau	$\rho = a \times c + b$ $d_{(i)} = \left(\frac{N_0}{60}\right) I e^{I/I_0} + e$ $d_{(\rho)} = f_1 \times \rho_i + f_2$ Si $I_z \geq I_c\ :\quad \rho_2 =\ \rho_1 +\ t_x \times d_{(I)}$ $I_z < I_c\ :\ \rho_2 =\ \rho_1 +\ t_x \times d_{(\rho)}$ $z_2 = z_1 + 60 \times u \times t_x$	ρ : densité cellulaire $a, c\ et\ b$: paramètres relatifs au contenu en carbohydrate $d_{(i)}$: taux de changement de la densité cellulaire en condition éclairée $d_{(\rho)}$: taux de changement de la densité cellulaire en condition non-éclairée ; N_0 : ? I : intensité lumineuse I_0 : intensité lumineuse èa la surface I_z : intensité lumineuse èa la profondeur z I_c : intensité de compensation z : profondeur ; u : vitesse de chute t_x : pas de temps	(Visser et al., 1997)

Tableau 1.3: Mise en équation du mouvement des cyanobactéries dans une colonne d'eau (Suite)

Modèle	**Équations mises en œuvre**	**Définition des paramètres**	**Auteurs**
Mouvement le long de la colonne d'eau	$v_s(x,t) = \frac{gV_g}{6\pi k_D}(\rho(x,t) - \rho^{'})$ $\rho(x,t) = \rho^{'}\frac{-1 + \varepsilon\, f_2(G)}{1 - r f_1(G)}$	$v_s(x,t)$: vitesse de chute g : pesanteur V_g : volume cellulaire $\rho(x,t)$: densité cellulaire dans le temps et suivant les coordonnées x $\rho^{'}$: densité de l'eau k_D : facteur de forme $\varepsilon\ et\ r$: paramètres relatifs au contenu en carbohydrate $f_1(G)\ et\ f_2(G)$: fonctions (dépendantes de l'intensité lumineuse active) relatives aux vésicules gazeuses et au contenu en carbohydrate	(Belov & Giles, 1997)

Nous remarquons que seul l’effet phototaxis (relié à la lumière) est pris en compte dans les modèles jusqu’ici publiés et validé expérimentalement. En effet, le mouvement des cyanobactéries face à un gradient de nutriments n’est jusqu’ici pas représenté dans les modèles de flottabilité décrits ci-dessus (**Tableau 1.3**).

En ce qui concerne cet aspect de flottabilité des cyanobactéries, il faut retenir que dans beaucoup de logiciels disponibles et cités dans le **Tableau 1.4**, c’est un groupe algal qui a le même comportement que les autres types d’algues du point de vue de leur mouvement le long de la colonne d’eau. Ceci constitue une approximation grossière au vu des preuves existantes sur l’existence de la flottabilité.

Tableau 1.4: Quelques modèles actuellement disponibles sur le marché (espèces algales et toxines)

EUTROPHISATION : ESPECES ALGALES PRISES EN COMPTE :	**Cyanobactéries**	**Diatomées**	**Algues vertes**	**Regroupé ensemble (sous le vocable phytoplancton)**	**Production de Toxines**
WASP (Wool et al., 2002)	+	+	+		▨
CE QUAL-W2 (Cole & Wells, 2003)	+	+	+	+	▨
SWAMP (Covelli et al., 2001)	▨	▨	▨	+	▨
EFDC Water Quality Model (Tetra Tech Inc, 2007)	+	+	+	▨	▨
ECOHAM2 (Moll et al., 2003)	▨	▨	▨	+	▨
D-Water Quality (Deltares Systems, 2014)	+	+	+	+	▨
CAEYDIM (Hipsey et al., 2006)	+	+	+	+	+

\+ Prise en compte dans le logiciel (liste non-exhaustive : logiciels très utilisés)

En effet, comme énoncé précédemment, les cyanobactéries disposent d’une certaine capacité à se déplacer dans une colonne d’eau tenant compte de la disponibilité de la lumière et des nutriments. Cela est possible grâce aux vésicules de gaz dont elles disposent mais aussi à la variation de leur contenu en carbohydrate selon la disponibilité de la lumière (Kromkamp & Walsby, 1990; Reynolds & Irish, 1997; Visser et al., 1997). Dans un écosystème au repos (faible turbulence), les vésicules de gaz dont elles disposent et les variations du contenu en glucide (régulée par l’intensité lumineuse) définissent le positionnement d’une cellule de cyanobactérie (Guven & Howard, 2006; Kromkamp & Walsby, 1990).

Dans beaucoup de logiciels, une approche simplificatrice est adoptée pour connaître le taux de sédimentation de tout groupe algal. Cette dernière consiste à utiliser une valeur de vitesse de sédimentation à une température référence. Le logiciel CAEDYM (commercial) est jusqu’ici le seul qui tente de tenir en compte cet aspect de flottaison selon l’intensité lumineuse(Hipsey et al., 2006). En effet, dans ce logiciel, l’effet phototactique est utilisé pour évaluer la vitesse de sédimentation des cellules (Hipsey et al., 2006). Par contre, l’effet d’advection est considéré comme le principal facteur pour simuler leur remontée et remise en suspension. Cette simplification permet de contourner l’approche lagrangienne, mais elle ne s’accorde pas avec le fait que le comportement lié à la flottaison (sédimentation et remise en suspension) pourrait dépendre uniquement sur l’effet phototactique (Kromkamp & Walsby, 1990; Reynolds & Irish, 1997; Visser et al., 1997). Le **Tableau 1.5** ci-dessous donne des valeurs de vitesse de flottabilité qui ont été modélisées pour les cyanobactéries.

Tableau 1.5: Valeurs référentielles pour les vitesses de chute des cyanobactéries

Vitesse de chute (m/h)	Références
0,002 à 0,006	(Bierman et al., 1980)
0,008	(Lehman et al., 1975)
0,004	(DePinto et al., 1976)
0,003 à 0,008	(Porcella et al., 1983; Tetra Tech, 1980)
(-9,36) à (+10,8)	Espèces de ciblées: *Trichodesmium sp* (Walsby, 1978)
12	Espèces de ciblées: Large colonies de *Microcystis aeruginosa* (Reynolds et al., 1987)
(-0,2) à (+0,4)	Espèces ciblées:*Anabaena Circinalis sp* (Reynolds et al., 1987)
0,01 à 2,01	Espèces ciblées:*Anabaena Circinalis sp* (Brookes et al., 1999)
0,044	Diamètre des cellules:50 µm (sans taux de réponse)
0,13	Diamètre des cellules: 50 µm (taux de réponse considéré (4min)) (Wallace & Hamilton, 2000)
0,18	Diamètre des cellules: 100 µm (sans taux de réponse)
0,51	Diamètre des cellules: 100 µm (taux de réponse considéré (4min)) (Wallace & Hamilton, 2000)
3,96	Diamètre des cellules: 400 µm (sans taux de réponse)
6,01	Diamètre des cellules: 400 µm (taux de réponse considéré (4min)) (Wallace & Hamilton, 2000)
11,2	Diamètre des cellules: 800 µm (sans taux de réponse)
12,6	Diamètre des cellules: 800 µm (taux de réponse considéré (4min)) (Wallace & Hamilton, 2000)

L’approche qui consiste à considérer les CB comme des particules qui sédimentent ne reflète pas réellement leur comportement dans une colonne d’eau dans la mesure où seul le déplacement vers le fond de la colonne d’eau est pris en compte. En effet, il est décrit par beaucoup d’auteurs (Belov & Giles, 1997; Guven & Howard, 2006; Kromkamp & Walsby, 1990) que les cyanobactéries sont capables de se déplacer aussi bien vers le fond de la colonne d’eau que vers la surface libre, selon la disponibilité de la lumière.

Une autre approche, dont les premiers essais de modélisation ont été menés par Kromkamp and Walsby (1990), semble plus réaliste dans la mesure où elle prend en compte la possibilité de se déplacer le long de la colonne d'eau (vers la surface ou au fond). Les divers travaux qui ont été menés avec cette approche et cités par Guven et Howard (2006) sont regroupés dans le **Tableau 1.3**.

Une hypothèse majeure est faite dans les deux approches. Il s'agit de considérer que la loi de Stokes est valide. Ainsi, l'expression de la vitesse s'écrit comme suit :

$$\boldsymbol{V = \frac{2}{9}\frac{gR^2(\rho_c - \rho_e)}{\mu F_s}} \tag{1.4}$$

g: pesanteur (m^2/s)R: Rayon (m) ; ρ_c: densité de la cellule de cyanobactérie (kg/m^3)
ρ_e : densité de l'eau (kg/m^3); μ : viscosité de l'eau (Pa.s) ; F_s=facteur de forme
Dans ce contexte, seules les espèces unicellulaires peuvent être représentées dans la mesure où l'on ne peut pas prendre en compte toute la diversité des espèces présentes dans l'écosystème.

1.7 Présentation de la zone d'étude (la Baie Missisquoi)

La Baie Missisquoi est une grande étendue d'eau que se partagent le Québec et l'État de Vermont **(Figure 1.2)**. Sa superficie est de 77,5 km^2 avec une profondeur moyenne et maximale respectives de 2,8 et 4 m (Galvez & Levine, 2003; McQuaid et al., 2011). Les tributaires majeurs de la baie Missisquoi sont les rivières Missisquoi, Pike et Rock qui drainent un bassin versant de 3 105 km^2 et qui constituent les principales sources de phosphore vers le lac (Groupe de travail international de la Baie Missisquoi, 2004).

Le caractère eutrophe de cette étendue d'eau a été largement démontré et débattu (Smeltzer et al., 2012), ce qui a abouti à l'entente internationale entre la province du Québec (Canada) et l'État du Vermont (États-Unis) pour la réduction des teneurs en phosphore (Commission mixte internationale Canada et États-Unis, 2012; Groupe d'étude international sur la baie Missisquoi, 2012). En effet, dans le cadre d'un programme de suivi de la qualité des eaux du Lac Champlain (Vermont Department of Environmental Conservation Watershed Management Division (VTDEC), 2009), les analyses donnent une moyenne de concentration en phosphore de 0,053 mg/L de 1993 à 2013 **(Figure 1.3)** au niveau du point d'échantillonnage situé au centre de la Baie Missisquoi. En ce qui concerne l'azote total, la moyenne serait de 0,71 mg/L de 2006 à 2013 (**Figure 1.4**). Des densités élevées de cyanobactéries et de toxines y ont été relevées au cours des périodes estivales de 2001 à 2011 (excepté 2007). Malgré, l'ensemble des actions menées, visant une charge cible de phosphore de 0,025 mg/L à atteindre (Adhikari et al., 2010), la Baie Missisquoi n'est jusqu'ici pas à l'abri de proliférations abondantes de cyanobactéries (Ndong et al., 2014a; Zamyadi et al., 2013a). Une détérioration de la qualité de l'eau de la Baie, particulièrement marquée par une prolifération abondante de cyanobactéries durant l'été a entrainé des avis de non consommation de l'eau, des fermetures de plages publiques en plus d'autres restrictions sur les usages de ce plan d'eau (Fortin et al., 2010). D'après ce même auteur, la baie Missisquoi est la source d'eau potable des municipalités de Bedford et du secteur Phillipsburg de Saint Armand. Elle est d'une grande importance dans la mesure où, elle permet d'assurer l'alimentation en eau potable à une population de 4500 habitants (Organisme de bassin versant de la baie Missisquoi, 2011). **La Figure 1.5** illustre l'état de la Baie Missisquoi lors d'un événement de «fleur d'eau».

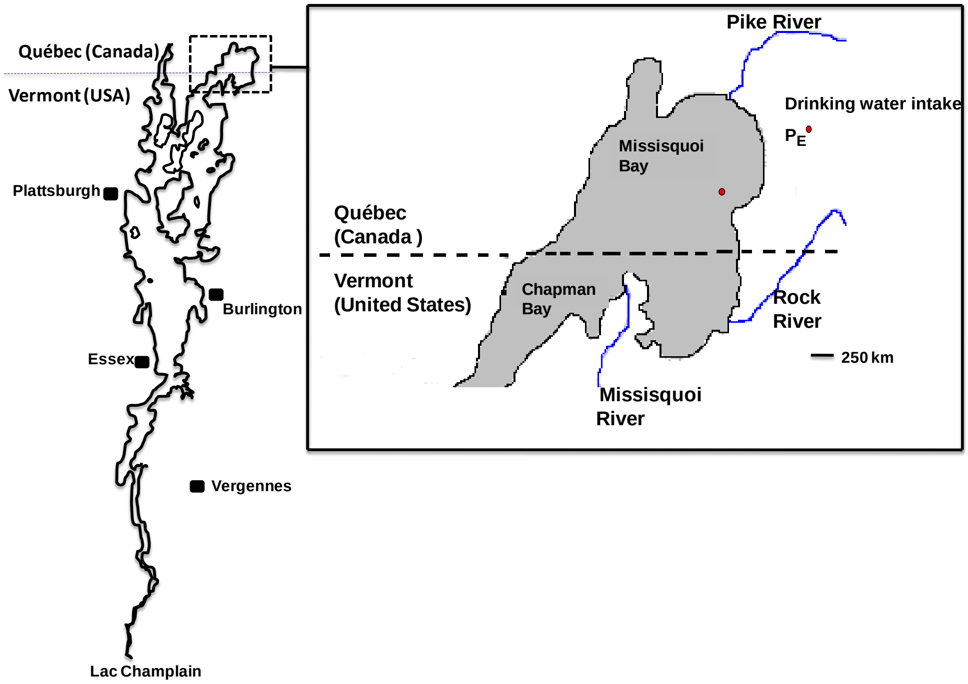

Figure 1.2: Principaux tributaires de la Baie Missisquoi(Ndong et al., 2014b)

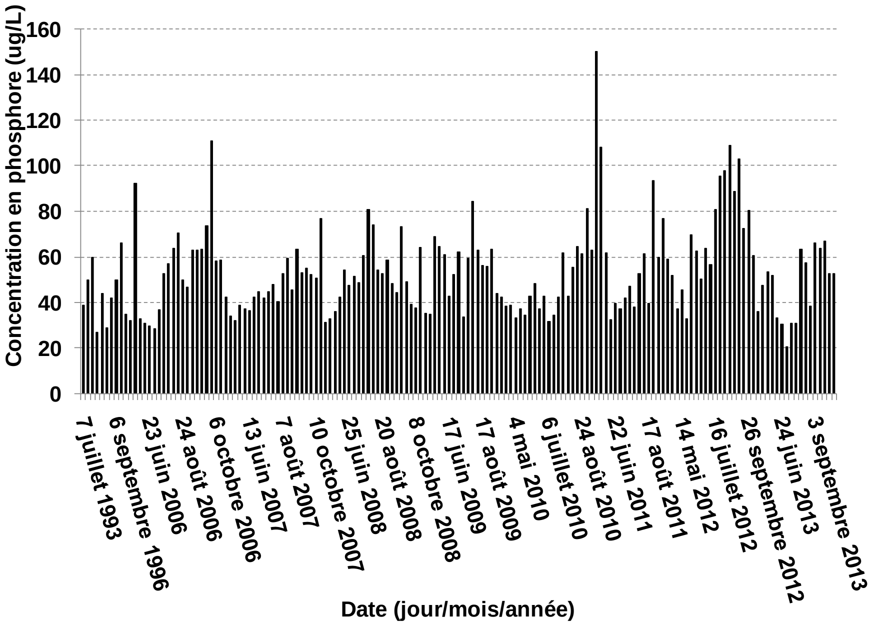

Figure 1.3: Concentration moyenne estivale en phosphore total au niveau de la Baie Missisquoi

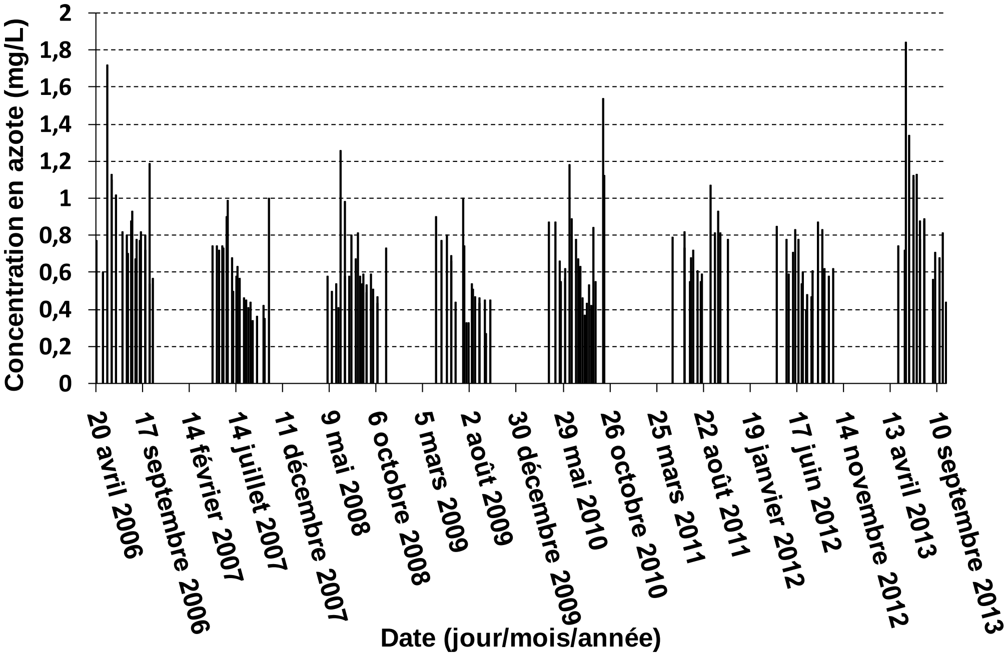

Figure 1.4: Concentration moyenne estivale en azote total au niveau de la Baie Missisquoi

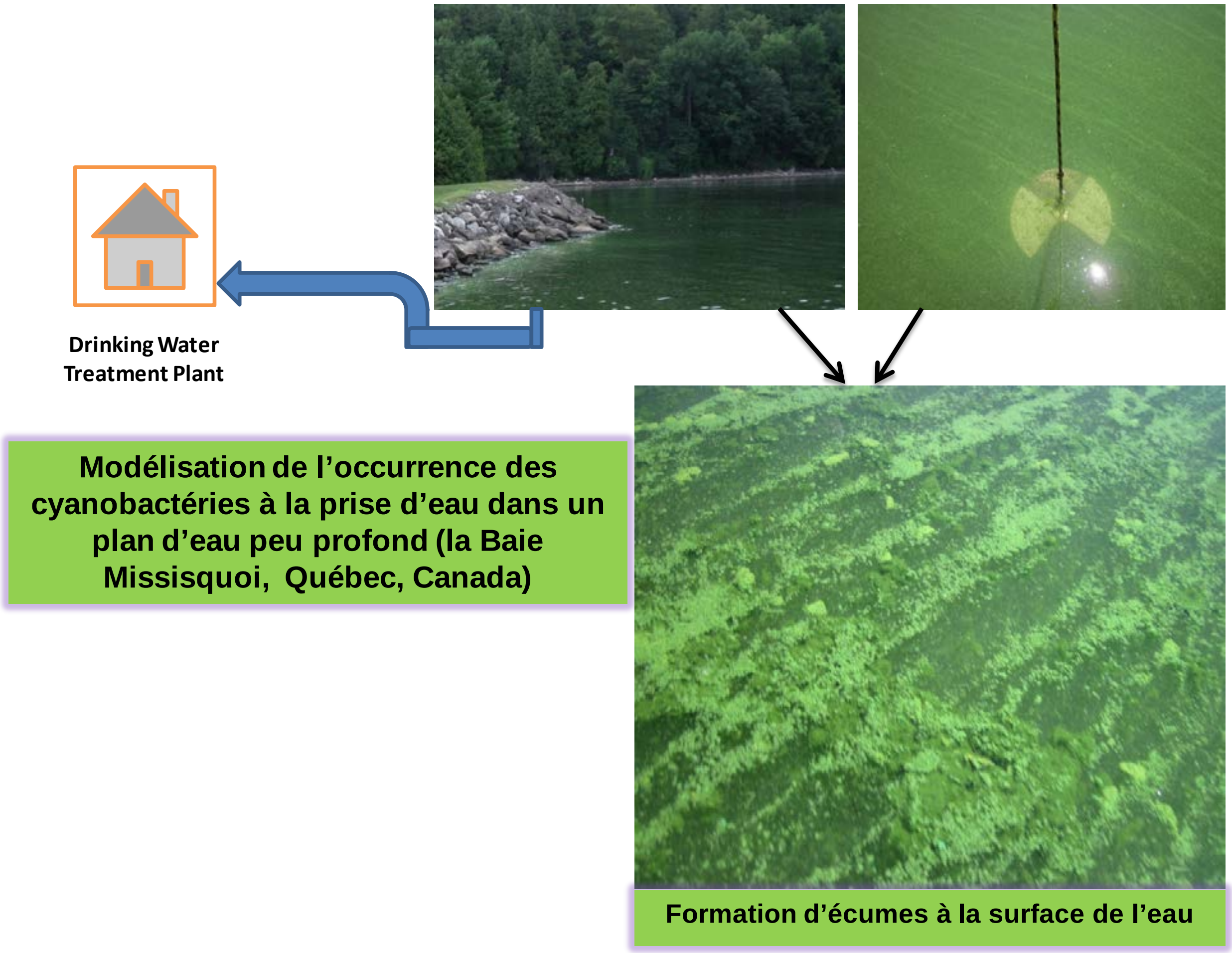

Figure 1.5: Événement d'occurrence de cyanobactérie à la Baie Missisquoi en 2010(Ndong et al., 2014b)

CHAPITRE 2 : OBJECTIFS DE RECHERCHE, HYPOTHÈSES ET DÉMARCHE DE L'ENSEMBLE DU TRAVAIL

2.1 Objectif général

L'objectif général de cette thèse est de développer des approches permettant d'évaluer le risque associé à certaines variables environnementales qui auraient une influence sur la prolifération et l'accumulation des cyanobactéries dans un plan d'eau et de bien comprendre le rôle des différents processus (advection et flottabilité) impliqués dans la distribution spatio-temporelle des cyanobactéries.

2.2 Objectifs spécifiques

- **Quantification de la probabilité d'occurrence**

Le premier objectif spécifique est d'analyser les données historiques recueillies au niveau de la Baie Missisquoi. Depuis l'été 2007, une équipe de la chaire en eau potable de l'école Polytechnique de Montréal a installé, au niveau de la Baie Missisquoi, des sondes de mesure en continu de certains paramètres tels que la chlorophylle a, la phycocyanine, le nombre de cellules de cyanobactéries par mL, le pH, l'oxygène dissout, la conductivité, la turbidité, la température de l'eau. À l'issue de cette analyse, nous développons une nouvelle approche pour quantifier la probabilité d'occurrence des CB associé à l'effet du vent et de la température de l'eau.

- **Modélisation**

Le deuxième objectif spécifique consiste à développer et valider un modèle mathématique intégrant les processus hydrodynamiques et un modèle de mouvement des cyanobactéries avec une approche eulérienne afin de pouvoir bien comprendre les mécanismes qui contrôlent la distribution spatio-temporelle des cyanobactéries.

Ce modèle intègre les données météorologiques réelles permettant de suivre la distribution spatio-temporelle des cyanobactéries.

- **Stratification thermique et distribution des cyanobactéries**

Enfin, il est prévu d’étudier le comportement des cyanobactéries exposées à la stratification thermique et à la pénétration de la lumière dans la colonne d’eau et de valider le comportement avec les données de terrain et les résultats du modèle.

2.3 Hypothèses scientifiques originales de cette contribution scientifique

a. Le risque d’occurrence des cyanobactéries à la prise d’eau située dans un endroit donné d’un plan d’eau est largement influencé par les variables qui contrôlent le comportement hydrodynamique, à savoir le vent (vitesse et direction) et la température de l’eau
   - *La validité de cette hypothèse pourrait vérifier si l’évaluation de la probabilité d’occurrence des CB est faible (en tenant uniquement compte de ces variables qui contrôlent le comportement hydrodynamique à savoir le vent (vitesse et direction) et la température de l’eau).*

b. Dans un milieu naturel, selon certaines conditions hydrodynamiques (présence ou absence de stabilité de la colonne d’eau), la distribution spatio-temporelle des cyanobactéries, leur forte accumulation en surface (présence d’écume) et au fond de la colonne d’eau seraient dépendantes de leur aptitude à la mobilité (présence ou absence de vésicules de gaz).
   - *Cette hypothèse pourrait être vérifiée si le comportement des CB dans la colonne d’eau est toujours régi par l’effet advection induite par les contraintes de vent à la surface du plan d’eau.*

c. Lors d’une fleur d’eau, la stratification thermique influence fortement la distribution spatio-temporelle des cyanobactéries dans une colonne d’eau.
   - *Cette hypothèse pourrait être vérifiée si la distribution spatio-temporelle des CB présente la même tendance que le gradient de température dans la colonne d’eau.*

2.4 Méthodologie et cohérence des articles par rapport aux objectifs spécifiques

Afin de pouvoir aborder notre premier objectif spécifique, l'ensemble des données recueillies de 2007 à 2011 ont été analysées afin de proposer une nouvelle approche statistique permettant d'évaluer quantitativement le risque associé à certains facteurs liés à l'occurrence des CB à la prise d'eau (article 1, publié dans *Water Research*).L'approche proposée a été inspirée par les travaux de Yu et al. (2002). Dans notre cas, les facteurs pris en compte ont été la température de l'eau, la direction et la vitesse du vent.

En effet, la température de l'eau est reconnue pour son rôle dans la croissance du phytoplancton en plus de son influence sur la densité et la viscosité de l'eau. Quant au vent, la prise en compte de sa direction, dans la nouvelle approche proposée, a été un point focal pour le développement de l'indice dans la mesure où cela implique l'angle de positionnement de la prise d'eau. De ce fait, la combinaison de ces facteurs à travers un indice a permis de quantifier le risque d'occurrence des CB à la prise d'eau. Cependant, l'approche proposée est statistique et ne permet pas de comprendre les différents mécanismes associés à la distribution spatio-temporelle des CB. C'est ainsi que l'approche déterministe, à travers le développement d'un modèle mathématique, a été abordée dans le deuxième thème décrit dans le chapitre 4 (article 2, soumis à *Environmental Science and Technology*). Dans cette section, nous étudions l'effet du mouvement d'advection de la masse d'eau et de la flottabilité des CB à travers leur changement de densité quand elles sont exposées ou non à la lumière. Un ensemble de codes de calcul a permis de tenir en compte l'hydrodynamique et la flottabilité, tout en intégrant une lecture des mesures météorologiques (température de l'air, radiation photosynthétiquement active, humidité, pression atmosphérique, vitesse et direction du vent).

Afin d'investiguer davantage les éventuelles causes jusqu'ici citées dans la littérature, nous avons tenté de modéliser la température de l'eau et de décrire la stratification thermique afin de mieux comprendre la distribution spatio-temporelle des CB dans le cas d'un lac peu profond comme la Baie Missisquoi subissant aussi des effets de réchauffement de la masse d'eau durant l'été. C'est ainsi que le troisième et dernier thème, relatif à l'aspect stratification thermique et distribution des CB, a été initié à travers le chapitre 5 (article 3, soumis à *Water Research*) de cette thèse.

CHAPITRE 3 ARTICLE 1: ESTIMATING THE RISK OF CYANOBACTERIAL OCCURRENCE USING AN INDEX INTEGRATING METEOROLOGICAL FACTORS: APPLICATION TO DRINKING WATER PRODUCTION

Ce chapitre décrit l'approche développée pour évaluer la probabilité d'occurrence des CB à la prise d'eau en tenant compte des facteurs tels que le vent (vitesse et direction) et la température de l'eau. Les résultats issus de cette approche y sont présentés. L'importance des nutriments a été également mis en évidence à travers le rapport azote inorganique dissout/phosphore total qui serait également un bon indicateur de l'occurrence des CB. Ce chapitre a été publié dans *Water Research* en Février 2014.

ESTIMATING THE RISK OF CYANOBACTERIAL OCCURRENCE USING AN INDEX INTEGRATING METEOROLOGICAL FACTORS: APPLICATION TO DRINKING WATER PRODUCTION

Mouhamed Ndong[1],*, David Bird[2], Tri Nguyen-Quang[3], Marie-Laure de Boutray[1], Arash Zamyadi[1], Brigitte Vinçon-Leite[4], Bruno J. Lemaire[4,5], Michèle Prévost[1], Sarah Dorner[1]

[1] École Polytechnique de Montreal, Civil, Mineral and Mining Engineering Department, P.O. Box 6079, Station Centre-ville, Montreal, Quebec, Canada, H3C 3A7

[2] Department of Biological Sciences, Université du Québec à Montréal, C.P. 8888, succ. Centre-ville, Montréal (Québec), Canada, H3C 3P8

[3] Department of Engineering, Faculty of Agriculture, Dalhousie University, PO Box 550, Truro-Bible Hill (Nova Scotia), Canada, B2N 5E3

[4] LEESU, Ecole des Ponts ParisTech, Université Paris-Est, 6 et 8 avenue Blaise Pascal, Cité Descartes, 77455 Marne la Vallée Cedex 2. France

[5]AgroParisTech, 16 rue Claude Bernard, 75005 Paris, France

3.1 Abstract

The sudden appearance of toxic cyanobacteria (CB) blooms is still largely unpredictable in waters worldwide. Many post-hoc explanations for CB bloom occurrence relating to physical and biochemical conditions in lakes have been developed. As potentially toxic CB can accumulate in drinking water treatment plants and disrupt water treatment, there is a need for water treatment operators to determine whether conditions are favourable for the proliferation and accumulation of CB in source waters in order to adjust drinking water treatment accordingly. Thus, a new methodology with locally adaptable variables is proposed in order to have a single index, f(p), related to various environmental factors such as temperature, wind speed and direction. The index is used in conjunction with real time monitoring data to determine the probability of CB occurrence in relation to meteorological factors, and was tested at a drinking water intake in Missisquoi Bay, a shallow transboundary bay in Lake Champlain, Québec, Canada. These environmental factors alone were able to explain a maximum probability of 68% that a CB bloom would occur at the drinking water treatment plant. Nutrient limitation also influences CB blooms and intense blooms only occurred when the dissolved inorganic nitrogen (DIN) to total phosphorus (TP) mass ratio was below 3. Additional monitoring of DIN and TP could be considered for these source waters prone to cyanobacterial blooms to determine periods of favourable growth. Real time monitoring and the use of the index could permit an adequate and timely response to CB blooms in drinking water sources.

Keywords: cyanobacteria, meteorological index, drinking water intake, early warning systems, wind, nutrient mass ratios

* Corresponding author. Current address: École Polytechnique de Montréal, Civil, Mineral and Mining Engineering Department, P.O. Box 6079, Station Centre-ville, Montreal, Quebec, Canada, H3C 3A7

* Corresponding author Phone: 514-340-4711 extension 2983; Fax: 514-340-5918

E-mail: mouhamed.ndong@polymtl.ca

3.2 Introduction

Harmful cyanobacteria (CB) blooms have been noted worldwide. CB blooms may release toxins, which can be harmful for aquatic communities (Bartram & Chorus, 1999), limit recreational and economic activities (Steffensen, 2008) and constitute a threat to drinking water sources (Zamyadi et al., 2012). Long-term solutions for restoring water bodies require an understanding of the factors that are contributing to the increase of CB blooms (Wongsai & Luo, 2007). Thus, considerable efforts have been made globally in order to understand the environmental factors related to these phenomena for better management of the affected water bodies (Falconer, 2005; Le Vu et al., 2010; Trojanowska & Izydorczyk, 2010). Both endogenous factors (e.g. nutrients, water temperature) and exogenous factors (air temperature, solar radiation, wind speed and wind direction) can be considered to play a role in CB bloom development (Howard, 1994). Short term fluctuations of meteorological variables play an important role with regards to CB occurrence (Wu et al., 2013).

Generally, the principal focus of past studies has been on the effects of nutrients. Thus, the mass ratio (TN/TP) of total nitrogen (TN) to total phosphorus (TP) in water and in biomass has been studied as an index for its relationship to CB blooms (Havens et al., 2003; Lilover & Stips, 2008; Schindler, 1977; Smith, 1986). However, others have had concerns (Ferber et al., 2004) or do not support the use of TN/TP mass ratio (Jayatissa et al., 2006). It has been suggested that eutrophication generated by phosphorus is the main cause of CB blooms (Christian et al., 1988), but this view has been qualified of overly simplistic and is not applicable to all water bodies (e.g. Vincent, 1981). Thus, the TN/TP mass ratio is not the only indicator to predict CB blooms and a consensus does not exist with regards to a quantitative value. Another approach related to the mass ratio of Dissolved Inorganic Nitrogen (DIN) to total phosphorus (TP) has also been proposed and was shown to be a better predictor of CB biomass than the TN/TP mass ratio with CB bloom occurrences observed when the DIN/TP mass ratio was below 2 (Bergström, 2010; Ptacnik et al., 2010).

In addition to nutrients, meteorological conditions are required to explain CB bloom occurrences. Meteorological variables are known to have a significant influence on CB development (Elliott, 2012; Liu et al., 2012a; Reichwaldt & Ghadouani, 2012). Many authors have explored the relationships among meteorological variables and CB (e.g. Bormans et al., 2005; Kanoshina et al., 2003; Lilover & Stips, 2008; Liu et al., 2012; Liu et al., 2013). Various weather variables have been related to CB blooms such as air temperature (Elliott, 2012; Reichwaldt & Ghadouani, 2012; Zhang et al., 2012), rainfall (Reichwaldt & Ghadouani, 2012), wind (Liu et al., 2012a; Liu et al., 2013b; Zhang et al., 2012) and sunshine hours (Zhang et al., 2012). Wind in particular may play both direct and indirect roles in determining cyanobacterial densities (Falconer et al., 1999). Wind can generate complex physical processes, such as internal waves or seiches, which produce periodic motion of the water layers in stratified lakes (e.g. Lemmin & Mortimer, 1986). These internal waves affect the spatial distribution of phytoplankton in the epilimnetic layer (Marce et al., 2007). In deep lakes, they have a great impact on the distribution of cyanobacteria proliferating in the metalimnion and on their growth though a direct influence on light availability (Cuypers et al., 2011). As CB are buoyant, wind can result in accumulation of cyanobacteria at specific locations during a bloom (Cao et al., 2006; Kanoshina et al., 2003; Ostos et al., 2009), but it may also indirectly influence nutrient availability through mixing processes of the water column (e.g. Livingstone, 2003; MacIntyre et al., 1999; Schmittner, 2005). Other meteorological variables such as the relative humidity, minimum daily air temperature and the amount of solar radiation (sunspots) have also been related to CB density (Hu et al., 2009). It has been hypothesized that the increase in the number of CB blooms is at least partly related to global climate change and increasing air temperatures (Mooij et al., 2007; Wagner & Adrian, 2009; Zhang et al., 2012). Although the effect of water temperature on growth is species-specific (Mehnert et al., 2010) some generalizations can be made for the CB native to temperate environments. Seaburg et al. (1981) found that the majority of CB have an optimal growth temperature of 25°C. However, many bloom forming CB show optimal growth rates at temperatures of 25°C or higher (Robarts & Zohary, 1987). Tang et al. (1997), in studying the predominance of CB in freshwater in polar environments, showed that the growth was undetectable when the temperature of the aquatic environment in which the CB living was less than or equal to 5°C or greater than 35°C.

Consideration of meteorological variables is important when implementing an early warning system for the proliferation of CB in drinking water sources (Hu et al., 2009). In the United States, National Oceanic and Atmospheric Administration (NOAA) issues weekly harmful algal bloom reports based upon satellite imagery and meteorological conditions (Wynne et al., 2013). Early warning systems are needed for drinking water treatment plant operators who must adjust treatment according to the biovolume and species of CB present, including such measures as changing coagulant, or adjusting the doses of treatment chemicals to be added (Zamyadi et al., 2013b). For drinking water treatment, in sources highly impacted by cyanobacteria, operational decisions must be made in real time. Thus, weekly forecasts can provide useful information, but higher resolution forecasts are required (i.e. daily or sub-daily).

For the development of a reliable index which can serve as a ‘universal threshold’ for the occurrence of CB blooms in the aquatic environment, the effects of endogenous factors and exogenous parameters must be investigated. It is anticipated that the threshold for CB bloom occurrence will be based on the coupled effects of these external and internal factors. Thus, the objectives of this study are to: (1) through a new approach, propose an index in the form of a unique factor that integrates the effects of exogenous factors such as meteorological variables and water temperature on CB occurrence at a drinking water treatment plant intake, (2) evaluate this index to determine the probability of CB occurrence as an aid to operational decision making for water treatment plants, and (3) assess the role of nutrient limitation and the DIN/TP mass ratio as additional variables to be monitored along with phycocyanin at drinking water intakes. This paper proposes a novel index approach integrating meteorological factors and continuous phycocyanin probe measurements to determine drinking water intake risk as a result of intense cyanobacterial blooms.

3.3 Methodology

3.3.1 Site description

The research was performed at Missisquoi Bay, a large bay (77.5 km^2 at the latitude and longitude coordinates of 45°01’37.63’’ North and 73°07’34.84’’ West) of Lake Champlain, which straddles the Canada - United States border (Supplemental Information Section 3.8.1,**Figure 3.5**). The characteristics of tributaries are as described by Medalie et al. (2012) and Adhikari et al. (2010). Missisquoi Bay is a shallow water body with a mean depth of 2.8 m (Galvez & Levine, 2003). Myer and Gruendling (1979) reported that in areas without rooted aquatic vegetation, the wave base can be deep enough during storms to cause mixing of bottom sediments. It is also the principal source of drinking water for a population of approximately 4100 residents (Statistics Canada, 2006). From 1992 to 2009, total phosphorus seasonal mean concentrations (sampling from June to September) increased in Missisquoi Bay by 72% (representing an increase of 20 µg/L from an initial seasonal mean concentration of approximately 28 µg/L). In contrast, total nitrogen seasonal mean concentrations decreased by approximately 25% (representing a decrease of approximately 0.15mg/L from an initial seasonal mean concentration of approximately 0.65 mg/L) over the same period, possibly related to a reduction in atmospheric nitrogen deposition (Smeltzer et al., 2012). The reduction of the phosphorus is critical for the health of Missisquoi Bay and has led to a bilateral agreement between the province of Québec (Canada) and state of Vermont (United States) to take action on reducing phosphorus to an acceptable limit of 25 µg/L (Comité Interministériel de Concertation sur la Baie Missisquoi, 2003) and to guide related research activities (Adhikari et al., 2010).

3.3.2 Field sampling and laboratory analyses

In 2007, a real-time monitoring program was developed and implemented in Missisquoi Bay using an online multi-probe system from YSI (YSI, Yellow Springs, Ohio) as described by McQuaid et al. (2011). The multi-probe system consists of eight sensors: temperature, depth, conductivity, turbidity, pH, dissolved oxygen, chlorophyll fluorescence (excitation: 470 nm; emission: 680 nm) and phycocyanin fluorescence (excitation: 590 nm; emission: 680 nm). It was installed to monitor the raw water intake of the drinking water treatment plant on the eastern shore of Missisquoi Bay every hour. Information on additional sampling and laboratory analyses of phycocyanin, chlorophyll, taxonomic counts and nutrients are provided in supplemental information (Section 3.8.1).

3.3.3 Meteorological data collection and treatment

Meteorological data were obtained from the weather station in Frelighsburg situated close to Missisquoi Bay. Frelighsburg data (Station name: FRELIGHSBURG; Province: QUEBEC; Latitude: 45.05°North; Longitude: -72.86°West; Altitude: 152.4m; climate identification: 7022579), provided by the National Climate Data and Information Archive (2013), were used to develop the model relating meteorological variables with cyanobacterial biovolume (CBV). Hourly data were available, thus the daily means of wind speed and direction were calculated using the method proposed in Stull(2000). Statistica 9.0 (StatSoft.Inc, Tulsa, OK USA), Matlab (version 7.1.0.246 (R14) Service Pack 3, MathWorks, Inc.) and MS Excel (Microsoft, Redmond, WA, USA) were used for statistical analyses.

3.3.4 Development of a Meteorological Index

a) Description of the approach

In order to evaluate the effects of meteorological factors on CB biomass, the development of this simple index is based on similar approach from Yu et al. (2002) for integrating the influence of climate components on rice biomass accumulation. Yu et al. (2002) proposed using a classical logistic growth model in which the maximum relative growth rate (μ) is defined as shown in equation (3.1):

$$\mu = \mu_0 \times f(p) \qquad 3.1$$

where μ_0 is the growth rate when meteorological factors are most favourable for population growth. The function *f(p)* reflects the meteorological factors being considered and can take on values between 0 and 1 with *f(p)* = 1 signifying growth without the constraint of meteorological factors and *f(p)* = 0 signalling the end of growth because of completely unfavourable conditions.

However, different from the approach by Yu et al. (2002), in this paper, our focus is on the parameterization of f(p) and the relationship between this index and observed biomass accumulation in Missisquoi Bay to provide a functional index at the drinking water treatment plant and to assess the importance of meteorological factors in driving CB blooms. Yu et al. (2002) integrate *f(p)* directly into their logistic growth model and use multiple linear regressions to fit model parameters for the prediction of biomass growth. Our objective in this study was not to predict the amount of cyanobacterial growth, which would require continuous data on nutrient limitation which are not available and are not typically monitored at high frequency at drinking water treatment plant, but rather to estimate the probability of CB blooms occurrence that can be explained by a series of easily measured meteorological parameters.

The meteorological index does not distinguish between the direct and indirect influences that meteorological conditions play on biomass accumulation and it is not possible to directly distinguish accumulation from growth. However, the primary objective is to determine the probability of bloom occurrence given meteorological conditions influencing their presence at a drinking water treatment plant intake. In this context, our expectation is to develop an approach that can easily integrate meteorological factors into an index to adequately describe both CB growth and accumulation under various environmental conditions.

The meteorological index was developed in three stages:

Stage 1) Meteorological index development: Data collected during the years 2007 and 2008 were used to define functions and calibrate all the parameters. The first two years of the 5 years of data were selected for model calibration because they represented a broad range of bloom conditions. In 2007, there was little accumulation of cyanobacteria at the drinking water intake in contrast to 2008 when intense blooms were observed. Additional data were not used in calibration in order to avoid -over-fitting parameters. The definition of this function f(p) takes into account the physical position of the drinking water intake relative to the wind direction.

Stage 2) Model validation: Data recorded from 2009 - 2011 (YSI probe and Frelighsburg weather station) were used to confirm the link between the function of factor f(p) on cyanobacteria biovolume (CBV). Similar model parameters found for 2007 and 2008 were used for the validation of the following years (2009 - 2011).

Stage 3) Logistic regression model development: the logistic regression was developed with five years of data (2007-2011) in order to estimate the probability of CB blooms occurrence given the meteorological conditions included in the f(p) function.

b) Selection of Meteorological Parameters for f(p)

The selection of meteorological variables was based upon local considerations (position of drinking water intake) and literature review. Wind direction measured in degrees is not monotonically related to CBV because only a specific range of wind directions can physically have an impact on the drinking water treatment plant based on its location. Even with strong winds, if the wind is moving in the direction away from the plant, CB accumulation at the intake is unlikely. There exists an optimal wind direction that could transport CB towards the plant. Thus, wind direction was included in the model based on physical rather than statistical considerations.

The model used water temperature (as opposed to air temperature) because it more directly represents the environmental conditions experienced by the cyanobacteria. Similar variables (wind speed and direction, and water temperature) were used by Liu et al. (2012b) for the development of a model to estimate the probability of bloom occurrence. The measurements of

CBV at the drinking water intake represent CB that are at the bottom of the water column, and thus, lower water temperatures can also be related to the presence of cyanobacteria in the lower depth of the water column because of additional processes not considered in the index model (mixing, cyanobacteria behavior with regards to light intensity, cloud cover, etc.). It has been reported that cyanobacteria move towards the bottom of the water column at night when water temperatures are lower (Walsby et al., 1989). Thus, when cyanobacteria are abundant, the dominant risk factors for a drinking water intake are related more to transport phenomena than to cyanobacterial growth. However, over the course of a season, the temperature becomes important when it falls outside of the optimal range for cyanobacterial growth. The model was constructed such that it would be possible to modify parameters according to local conditions. For example, various water bodies will have different dominant CB species. As such, optimal water temperatures could be adapted according to CB species present. However, this approach remains to be tested for systems other than Lake Champlain.

c) Definition of parameter functions for f(p)

Following the selection of the variables, f(p) was defined as follows:

$$\mathrm{f(p_i) = g\left(T_{Wtemp}\right) \times g(p_i)} \qquad 3.2$$

$$\mathrm{g(p_i) = g(Wind\,Speed) \times g(Wind\,direction)} \qquad 3.3$$

where T_{Wtemp} represents the water temperature as measured by the probe installed at the drinking water intake, $\mathrm{g\left(T_{Wtemp}\right)}$ is the function describing the influence of water temperature on CB growth, $\mathrm{p_i}$ is the meteorological parameter and $\mathrm{g(p_i)}$ is the function representing the influence of wind speed and wind direction on CB accumulation and growth.

Considering meteorological parameters X_1, X_2, $X_3 \ldots X_N$ for a given time series, the function $\mathrm{g(p_i)}$ at a given time can be written in the form of:

$$\mathrm{g(p_i) = K(i)/K_{MAX}} \qquad 3.4$$

With

$$K(i) = \sum \left[F(X_1) \times F(X_2) \times F(X_3) \times \ldots \times F(X_N) \right] \qquad 3.5$$

$$\text{And} \quad K_{MAX} = \max(K(i)) \qquad 3.6$$

From equation (3.4) we can see that $g(p_i)$ will have a value between 0 and 1.

Hence, the expression for the growth and accumulation rate of CB integrating meteorological parameters and water temperature is:

$$\mu = \mu_0 \times g\left(T_{Wtemp}\right) \times g(p_i) \qquad 3.7$$

and $f(p_i)$ is therefore equal to μ.

The procedure for f(p) calculation is provided in **Figure 3.6**.

Function for water temperature

For conditions where water temperature exhibits a large range of variability, the description of the function $g\left(T_{Wtemp}\right)$ can adopt the following form (Bouarab & Dauta, 2002; Bowie et al., 1985; Lehman et al., 1975):

$$g\left(T_{Wtemp}\right) = \exp\left[-a \times \left(\frac{T_{Wtemp} - T_{opt}}{T_x - T_{opt}} \right)^2 \right] \qquad 3.8$$

$$\text{with}\, T_x = \begin{cases} T_{min} \text{ for less than or equal to } T_{opt} \\ T_{max} \text{ for higher than or equal to } T_{opt} \end{cases} \qquad 3.9$$

a is a dimensionless calibration parameter. This approach takes into account three different levels of water temperature: (1) minimum growth temperature T_{min} (^{o}C), (2) optimum growth temperature T_{opt} (^{o}C) and (3) maximum growth temperature T_{max} (^{o}C).
As $T_{min}<T_{opt}<T_{max}$, these temperature levels will define four distinct intervals on which i) negligible growth occurs below T_{min} or above T_{max}; ii) increasing growth occurs from T_{min} or T_{max} to T_{opt} ; and iii) decreasing growth occurs from T_{opt} to T_{min} or to T_{max}(Bowie et al., 1985).

By adjusting parameters, equations 3.8 and 3.9 can be applied for the environmental conditions at Missisquoi Bay or other source waters where there is a large variation of temperatures. Based on studies of Mooij et al. (2007), Tang et al. (1997) and Seaburg et al. (1981) minimum, optimal and maximum growth temperature are approximately 0°C, 25°C and 35°C, respectively. These studies have demonstrated that out of this temperature range, the growth is undetectable and that the majority of cyanobacterial species have an optimal growth temperature of 25°C. Additional information on the cyanobacterial species present in the Bay and their optimal growth temperatures are provided in supplemental information (Section 3.8.1, **Table 3.3**).

Functions for wind speed and wind direction

The function describing the effect of wind direction (RDIR) is

$$F(\mathrm{RDIR}) = \exp[-a \times C] \tag{3.10}$$

$$C = \frac{(\mathrm{Wind}_{\mathrm{dir\_X}} - \mathrm{Wind}_{\mathrm{dir\_opt}})^2}{(\mathrm{Wind}_{\mathrm{dir\_X}} - \mathrm{Wind}_{\mathrm{dir\_Min}})(\mathrm{Wind}_{\mathrm{dir\_Max}} - \mathrm{Wind}_{\mathrm{dir\_X}})} \tag{3.11}$$

Where $Wind_{dir\_X}$ is the wind direction (°), $Wind_{dir\_Min}$ and $Wind_{dir\_Max}$ are its minimal and maximal values, $Wind_{dir\_opt}$ is its optimal value for CB accumulation, and *a* is a dimensionless calibration parameter.

The forms of equations 10 and 11 are similar those of equations 8 and 9. Similar to water temperature, wind direction is expected to have an optimal value in relation to the position of the drinking water treatment plant intake (the treatment plant is situated in the north-east region of the bay, at around 30 degrees). A similar procedure is used for describing the effect of wind speed.

The function describing the effect of wind speed (RWND) is defined as

$$F(\mathrm{RWND}) = \exp[-a \times B] \tag{3.12}$$

$$B = \frac{(\mathrm{Wind}_{\mathrm{speed\_X}} - \mathrm{Wind}_{\mathrm{speed\_opt}})^2}{(\mathrm{Wind}_{\mathrm{speed\_X}} - \mathrm{Wind}_{\mathrm{speed\_Min}})(\mathrm{Wind}_{\mathrm{speed\_Max}} - \mathrm{Wind}_{\mathrm{speed\_X}})} \tag{3.13}$$

Where $Wind_{speed\_X}$ is the wind speed (m/s), $Wind_{speed\_Min}$ and $Wind_{speed\_Max}$ are its minimal and maximal values, $Wind_{speed\_opt}$ is its optimal value for CB accumulation, and a is a dimensionless calibration parameter.

Weak or intense hydrodynamic fluctuations influence cyanobacteria (Wu et al., 2013). Additional information on the influence of wind speed on cyanobacterial drift for the parameterization of the model is provided in supplemental information (Section 3.8.1). Based on the reported values in the literature, model calibration was performed to obtain the appropriate values for wind speed (**Table 3.1**).

Table 3.1: Calibrated Parameters values for 2007 and 2008

Model parameters	**Calibrated Parameters**			
	a	**Minimum**	**Optimum**	**Maximum**
Wind direction (º)	7	190	200	310
Wind speed (m/s)	0,1	2	3	6
Temperature (°C)	7	10	20	35

Equations 3.8, 3.10, and 3.12 rely on optimal ranges for the various variables. If measured values of a given factor fall outside of its optimal range, the index would predict no risk to the drinking

water intake. For example, if wind speed were too low, minimal transport of CB towards an intake would occur. Thus, when variables fall outside of their optimal ranges, the risk that CB would be present at an intake is expected to be low and controlled by other factors not considered in the index such as light intensity, nutrients, and the vertical movement of CB in the water column. Model parameters were calibrated with data for 2007 and 2008 and were used for validation with data for 2009, 2010 and 2011. Logistic regression was performed on all data (2007 to 2011) in order to evaluate the probability that a CB bloom occurs at the drinking water intake in relation to the f(p) factor.

3.4 Results and Discussion

3.4.1 Meteorological parameters and cyanobacterial biovolume: model parameters

In this paper, our hypothesis is that exogenous factors dominate and drive the appearance of CB blooms at a drinking water intake where nutrients are not limiting. A simple model was proposed to evaluate easily monitored exogenous variables on CB blooms occurrence in a water body via a meteorological index which assembles different weather variables into a unique index. This study proposes a simple, novel, but highly applicable index approach to evaluate drinking water intake exposure to cyanobacterial bloom occurrences due to their position in the water body.

As described in Section 2.4, the years 2007 and 2008 were used for calibration in order to determine the best values for the minimum, maximum and optimum values of water temperature, wind speed and direction and the factor ‘a’ to include in equations 3.8 to 3.12.A low value of f(p) was expected for most of 2007 when CB blooms were not observed at the drinking water intake (CBV < 1 mm^3/L), in contrast to 2008 when many CB blooms were observed. Detailed data with regards to taxonomic counts for 2007 and 2008 are available in McQuaid et al. (2011). Approximately 98% of the CBV in 2007 and 2008 consisted of various species of *Microcystis* and *Anabaena*. The year 2007 was an exceptional year for Missisquoi Bay because no CB blooms had been observed until September (Fortin et al., 2010) and no CB were present in large densities at the drinking water intake situated on the north-east side of the Bay. The probe was installed in the north-eastern region of the study site, thus even if a bloom occurred in Missisquoi Bay, the risk to the north-eastern region, where the probe was installed was low. The wind direction was such that CB would be transported to the outlet (south-western side of the bay) when CB blooms occurred and wind from the north and east were dominant. This flushing phenomenon is observed in many lakes (Dillon, 1975) was dominant during the entire monitored period of 2007. In contrast, in summer 2008, the factor f(p) increased during (or one day prior) to high CBV values. The relationship of the meteorological factor f(p) with CBV at the drinking water intake is shown in **Figure 3.1a and b**. It should be noted that CBV values below the threshold of $1 mm^3/L$ represent low concentrations of CB and thus can be considered as periods of low risk to the drinking water treatment plant despite greater uncertainty with regards to their exact concentrations (McQuaid et al., 2011). The evolution of all the three functions calculated (for water temperature, wind speed and direction) was compared with CBV in order to observe the influence of each meteorological parameter (**Figure. 3.1a and b**). The relative importance of the factors was not considered in the analysis and all factors were given equal weighting. No single function could explain a CBV, but through f(p), all of these variables demonstrated an effect on the variation of CBV at the drinking water intake.

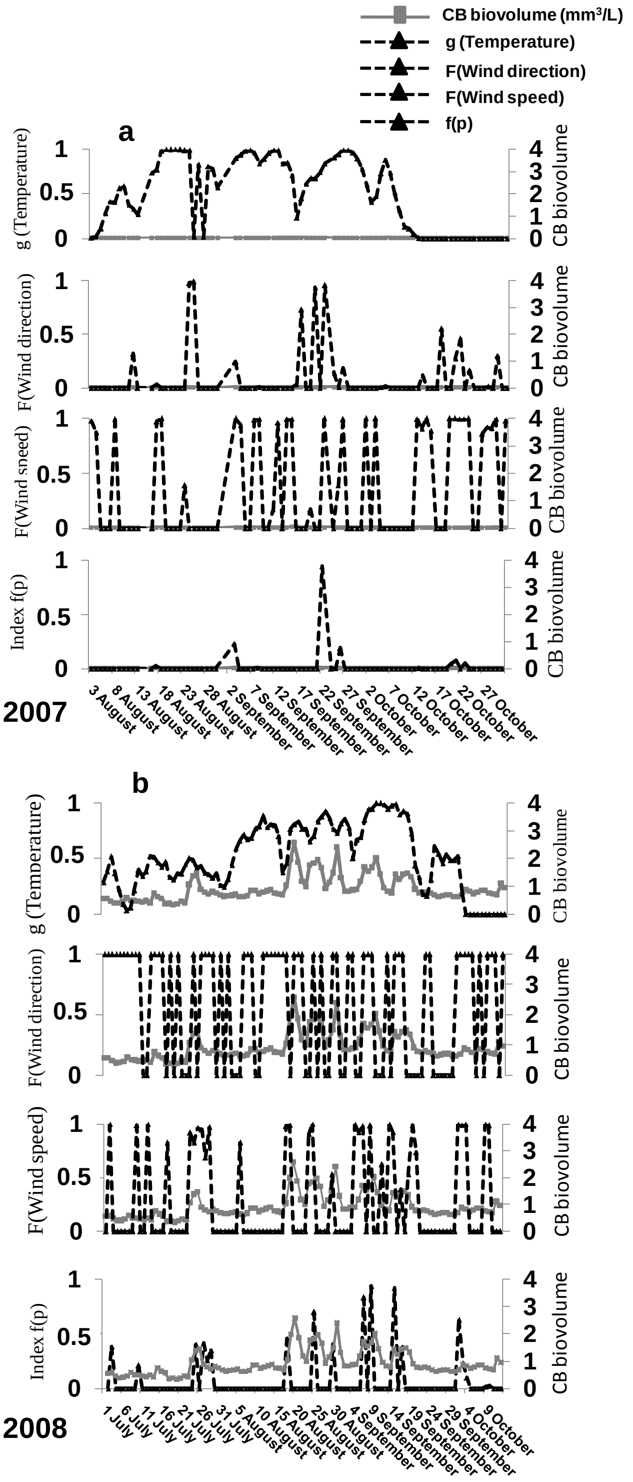

Figure 3.1: Functions defined from weather parameter versus CBV (model development): a) for 2007 and b) for 2008

Few explanations have previously been available with regards to the non-existence of CB blooms observed during the summer 2007 at the drinking water intake at Missisquoi Bay. Based on this study, we can propose as an explanation that, for 2007 the value of f(p) which was very low except for a few days, clearly demonstrated that 2007 had meteorological conditions that were not conducive for CB growth or accumulation near the drinking water intake. This supports our theoretical model of the importance of wind (speed and direction) and water temperature as explained in supplemental information (Section 3.8.1).

Given that 2007 was not conducive for CB growth or accumulation, it is interesting to note that the flushing effect could also have prevented large blooms from forming, dying, settling to the bottom sediments and releasing additional nutrients that would have become available to create a new cycle of CB blooms. Redox conditions in the sediments (Pant & Reddy, 2001) for 2007 at Missisquoi Bay showed that anaerobic conditions did not occur as is typical for other years when large cyanobacterial blooms occur (Smith et al., 2011). Through the use of a combination of different variables in one index (f(p)), it is possible to improve explanations of environmental conditions that contribute to CB bloom occurrences. This has been highlighted by other studies using statistical methods to explain CB bloom occurrence (Hu et al., 2009; Liu et al., 2012b).

The investigating results demonstrated that the effects of wind and water temperature cannot be ignored with regards to CB bloom occurrence at any considered position in the water body as the spatial distribution of CB is affected by wind direction and speed and water temperature (Kanoshina et al., 2003). The importance of wind has been emphasized by Izydorczyk et al. (2005) although they did not quantitatively demonstrate the wind effect on cyanobacteria. The wind speed can induce mixing in the water column and influence nutrient availability (e.g.Livingstone, 2003; MacIntyre et al., 2010; O'Reilly et al., 2003; Schmittner, 2005).

3.4.2 Meteorological parameters and cyanobacterial biovolume: Model application

Model application for 2009, 2010 and 2011 show a similar trend between f(p) and CBV. As seen in **Figure. 3.2a, b and c**, the f(p) index is low but CBV is high in some cases (false negatives). However, the false negatives were frequently related to bloom events that occurred over multiple days when the meteorological index decreased faster than the CBV (returning to a state without a bloom). In other instances, false negatives were likely related to endogenous and exogenous factors optimal for cyanobacterial growth but not considered in the index (e.g. solar radiation, nutrients). The benefit of the current index approach is its potential applicability to cyanobacteria impacted drinking water intakes with data that can be easily and reliably obtained in real time. Thus, drinking water treatment plants can evaluate their vulnerability (the probability of bloom occurrence, a maximum probability occurs with a maximum f(p)) using meteorological conditions and water temperature without the need to wait for satellite imagery.

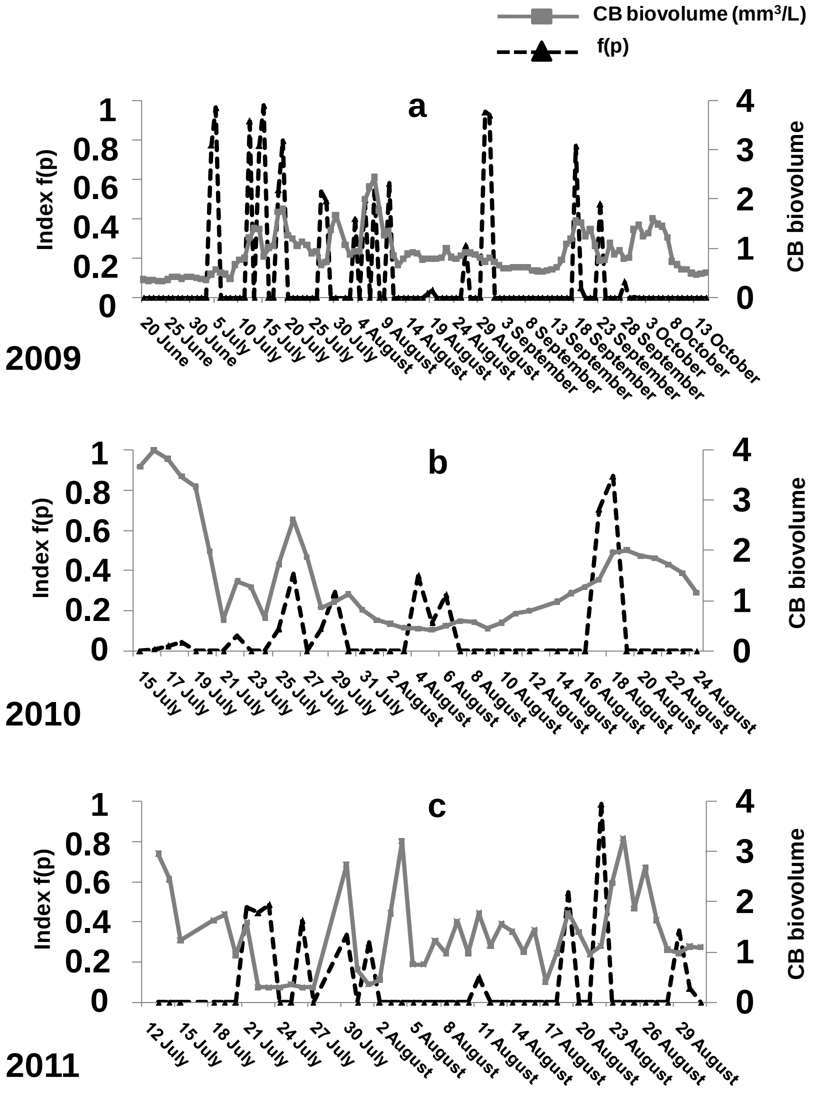

Figure 3.2: Meteorological parameter f(p) versus CBV (model application): a) for 2009, for b) for 2010 and c) for 2011

3.4.3 Logistic model: Relationship between f(p) and cyanobacterial bloom occurrence

CB occurrence is a complex phenomenon due to the non-linearity of the variables, as described previously. Thus, a logistic regression model was used to estimate the probability of CB bloom occurrence given by the calculated index (f(p)). In order to develop a logistic regression model, a CBV of 1 mm^3/L was considered as a threshold value for when the drinking water treatment intake is at risk. The 1 mm^3/L is a locally adapted threshold value and was proposed as the monitoring threshold (alert level) for Missisquoi Bay by McQuaid et al. (2011). McQuaid et al. (2011) found that $1mm^3/L$ corresponded to a maximum potential microcystin concentration of 13µg/L in Missisquoi Bay. The McQuaid et al. (2011) threshold falls between alert level 1 (biovolume: $0.2mm^3/L$; maximum potential microcystin concentration (MPMC): 2.6µg/L) and alert level 2 (biovolume: 10 mm^3/L; MPMC: 130µg/L) proposed by Bartram et al. (1999) and also represents the lowest biovolume value for which phycocyanin probes provided reliable estimates in Missisquoi Bay. For CB blooms to develop, it is likely that conditions must be favorable for more than one consecutive day. The logistic model developed was based on f(p) and CBV data from the five years (2007 to 2011). All the parameters values of the model are significant with p-value equal to 0.006 with an odds ratio of 6.03 (**Table 3.2**).

Table 3.2: Logistic regression between cyanobacterial occurrence bloom and f(p) during the five years (2007 to 2011)

Year	Model Equation	p-value	Odds ratio	Wald's Chi-square	Weather datas sources
2007 to 2011	$t = -0.018+1.845\times f(p)$	0.006 (n=393)	6.03	11.76	Freligsburg weather station

$t = \log\left(\frac{P}{1-P}\right)$; P=probability of occurrence

As expected, meteorological conditions were observed to have a large influence on CBV increases at the drinking water intake. The odds ratio found for a logistic regression model demonstrated a significant relationship between f(p) and the probability of CB occurrence above the CBV threshold of 1 mm^3/L. Thus, increasing values for f(p) coincide with CB blooms at the drinking water intake. As seen in Fig.3, a maximum probability of 68% of CB bloom occurrence can be explained by the increase of f(p). An f(p) value of 1 means that the combined effects of wind speed and direction, and water temperature are optimal for CB accumulation at the drinking water intake. It is also interesting to note that at low f(p) values, there is a low probability (less than 26%) of a CB bloom at the intake. Thus, the probability of a false negative is less than 26%.

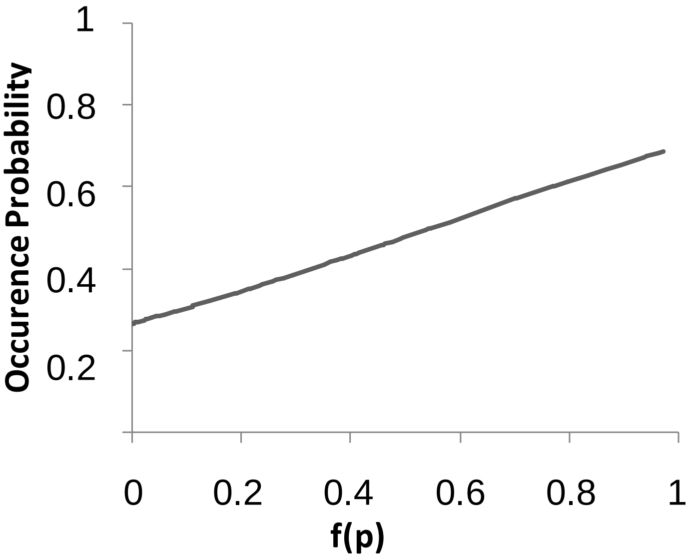

Figure 3.3: CB blooms occurrence probability versus meteorological factor f(p)

As described in Section 3.4.2, false negatives were related to the index decreasing faster than the CBV, and both false positives and negatives also arose potentially from the exclusion of factors such as light intensity and nutrients from the index. Our index approach can be discussed within the context of other statistical approaches that have included regression models (Smith, 1985; Smith et al. 1987), correlations (Varis, 1991), classification and regression trees (Hu et al., 2009), artificial neural networks (Teles et al. 2006; Wei et al. 2001; Maier et al. 1998; Recknagel et al. 1997), and conditional probabilities (Peretyatko et al. 2010). For many statistical approaches it is not possible to distinguish factors that are drivers of CB blooms from those that are merely correlated with CB blooms. For example, although pH is typically correlated with CBV and has often been included in regression models, it cannot be predictive because changes in pH are driven by changes in CBV (Zamyadi et al. 2012b). By studying the probability of CBV conditioned on environmental factors (not including history of CBV), Peretyatko et al. (2010) reached a maximum probability of 0.5. In addition, some of the environmental factors, such as pH, were not drivers of CB blooms. In contrast, our index approach found a maximum probability of 0.68 with the maximum index value using only variables that can be viewed as potential drivers of CB accumulation at a drinking water intake. Thus, the index approach provides a robust estimate of the potential for CB accumulation at a drinking water intake without relying on variables that cannot be monitored continuously, or that are correlated with CB because the CB themselves were the drivers of the change. Although artificial neural networks and classification and regression trees are powerful techniques for highly non-linear problems, they are black box approaches that do not necessarily encode the available physical knowledge of the system. Using the index approach, we were able to include information and factors based on the physical environment (e.g., the specific location of the drinking water intake) to obtain reliable results for operational decision-making at drinking water treatment plants.

For our model based on the assumption that nutrients are not limiting for CB, a better estimate is not expected given that only limited meteorological variables were considered and major endogenous factors related to growth like nutrients were not included in the model. The unexplained part of CB occurrence is related to endogenous factors such as nutrient availability and limitation. Thus, we explored the use of a nutrient mass ratio that could be used to augment continuous phycocyanin monitoring at the drinking water intake. CB abundance was compared to the DIN/TP mass ratio. Total, rather than soluble reactive phosphorus was used in the ratio because the algae and cyanobacteria population can store sufficient phosphate to increase 10-fold, even if no dissolved phosphate can be detected (Chorus and Cavalieri, 2000). The mass ratio DIN/TP provides additional information on nutrient limitation that will impact cyanobacterial growth (Bergstrom, 2010; Ptacnik et al. 2010). We found a significant negative correlation between mass ratio DIN/TP and extracted CB phycocyanin pigment ($r^2=-0.48$, *p-value* < 0.05). This correlation suggests that CB abundance is likely to be limited by either the DIN *or* TP. Two hypotheses are proposed *1)* CB dominate under nitrogen limitation due to their efficiency to use trace levels of *DIN, and2)* CB are more competitive for phosphorus than other algal species as

CB are efficient at nutrient uptake and storage (Sorokin and Dallocchio, 2008). Low heterocystes in Missisquoi Bay during summer bloom periods suggests that nitrogen fixing cyanobacteria do not rely on atmospheric N_2 (McCarthy et al., 2013). **Figure 3.4** shows the nutrient mass ratio, DIN/TP, from weekly duplicate samples in 2011 from all sites described (**Figure 3.5**) and its correlation with CB phycocyanin pigment. It shows that when the mass ratio DIN/TP is low, the phycocyanin concentration, related to CBV, can reach high values.

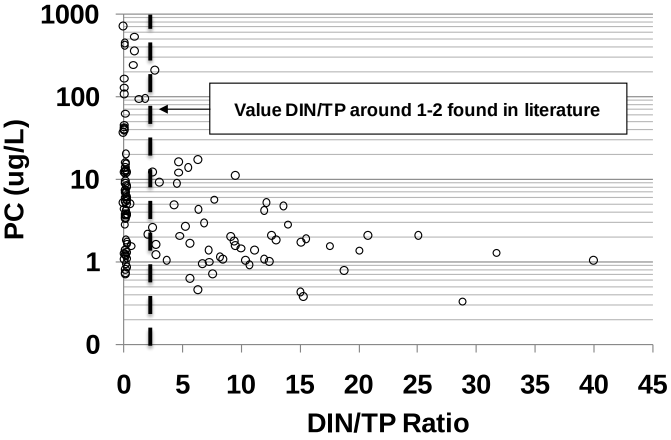

Figure 3.4: Changes in the mass ratio of dissolved inorganic nitrogen (DIN) to total phosphorus (TP) concentration, and cyanobacteria phycocyanin (PC) concentration Missisquoi Bay in 2011 (measured in lab)

Furthermore, it shows that nutrient limitation does occur and could explain the false positives in the index model. To improve index predictions further, it would be useful to consider the addition of continuous nutrient and light intensity data that were not available in this study. In **Figure 3.4**, the critical zone where CB abundance in Missisquoi Bay can be high, is for a DIN/TP mass ratio below 3 and it descends exponentially, similar to values reported between the range of 1-2 by Bergstrom (2010) and Ptacnik et al., (2010). Thus, DIN/TP is potentially a useful indicator of nutrient limitation, although nutrient availability may be driven by phytoplankton dynamics (McCarthy et al., 2013). The critical value of 3 obtained in our study could be used as an additional monitoring index for CB abundance, albeit not in real time and not necessarily for prediction. However, it could be useful when the meteorological index indicates a high vulnerability to CB occurrence at the intake.

The meteorological index proposed in this study is most important for determining initial conditions that could lead to a bloom rather than for explaining when the bloom will disappear. This is related to practical considerations at the drinking water plant intake with regards to operational decision-making. For example, drinking water treatment plant operators could take samples to determine optimal coagulants and doses (Zamyadi et al., 2013), or they could opt to close their drinking water intake and use stored water should CBV increase rapidly. At the study site, current practice involves the use of phycocyanin monitoring exclusively for assessing on-site CB vulnerability. With the use of real-time phycocyanin monitoring and the meteorological index, the operators would have important information to determine whether or not optimal bloom conditions are occurring or are likely to occur that will enable them to plan and to closely monitor the CBV at the drinking water intake.

Although the demonstration of the approach was conducted at Missisquoi Bay, this index approach for surface waters other than Lake Champlain could be applied and validated using locally adapted threshold values and variables. The different variables used to calculate this index can easily be collected for any water body affected by CB and used to evaluate the risk of CB blooms affecting a zone of interest. Findings from the meteorological index model in our research strongly reinforce our further investigation on a coupled hydrodynamic-cyanobacterial growth model to fully consider meteorological variables and their influence on lake hydrodynamics and cyanobacterial transport.

3.5 Conclusions

An early warning system for drinking water treatment plants should consider meteorological factors in addition to in vivo phycocyanin monitoring in order to adequately respond to CB events. Wind (speed and direction) and water temperature are related to CB blooms, both directly with regards to accumulation near a drinking water intake and indirectly on factors related to CB growth. This study shows that all the variables have an effect on CBV at drinking water intake and must be analysed together to understand their effect on CBV at drinking water intakes. As nutrient limitation is related to CB occurrence, the DIN/TP mass ratio could be monitored in conjunction with phycocyanin and meteorological variables.

Favourable meteorological conditions (high f(p) value) was related to maximum probability of 68% that a bloom event with CBV exceeding 1 mm^3/L would occur. As CB occurrence at drinking water treatment intakes are largely driven by exogenous factors, the use of hydrodynamic models could be used to more accurately predict CB events at drinking water intakes and to propose solutions to avoid breakthrough of cyanobacteria into drinking water treatment plants.

3.6 Acknowledgment

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3.8 Supporting Information (SI)

ESTIMATING THE RISK OF CYANOBACTERIAL OCCURRENCE USING AN INDEX INTEGRATING METEOROLOGICAL FACTORS: APPLICATION TO DRINKING WATER PRODUCTION

Mouhamed Ndong[1],*, David Bird[2], Tri Nguyen-Quang[3], Marie Laure Deboutray[1], Arash Zamyadi[1], Brigitte Vinçon-Leite[4], Bruno J. Lemaire[4,5], Michèle Prévost[1], Sarah Dorner[1]

[1.] Department of Civil, Geological and Mining Engineering. École Polytechnique de Montréal, C.P. 6079, succ. Centre-ville, Montréal (Québec), Canada, H3C 3A7

[2.] Department of Biological Sciences, Université du Québec à Montréal, C.P. 8888, succ. Centre-ville, Montréal (Québec), Canada, H3C 3P8

[3.] Department of Engineering, Faculty of Agriculture, Dalhousie University, PO Box 550, Truro-Bible Hill (Nova Scotia), Canada, B2N 5E3

[4.] LESSU, Ecole des Ponts ParisTech, Université Paris Est, 6 et 8 avenue Blaise Pascal, Cité Descartes, 77455 Marne la Vallée Cedex 2. France

[5.] AgroParisTech, 16 rue Claude Bernard, 75005 Paris, France

* Corresponding author. Current address: Department of Civil, Geological and Mining Engineering. École Polytechnique de Montréal, C.P. 6079, succ. Centre-ville, Montréal (Québec), Canada, H3C 3A7.

Tel.: (+1) 514 994 6872

E-mail address: mouhamed.ndong@polymtl.ca

Supplementary data (SD)

Number of pages: 8

Number of figures: 2

Number of table: 1

3.8.1 Materials and Methods

a) Sampling locations and laboratory analyses

The probe was also used to measure vertical depth profiles at three sampling points as shown in **Figure 3.5** (points P_0, P_E and P_1). P_0 is situated in the Bay approximately 10 m from the shoreline near the drinking water treatment plant (depth of 3 meters). P_E is located above the raw water intake of the drinking water treatment plant (depth of 4 meters). P_1 is a pelagic sampling point 500 m from P_E (depth of 5 meters).

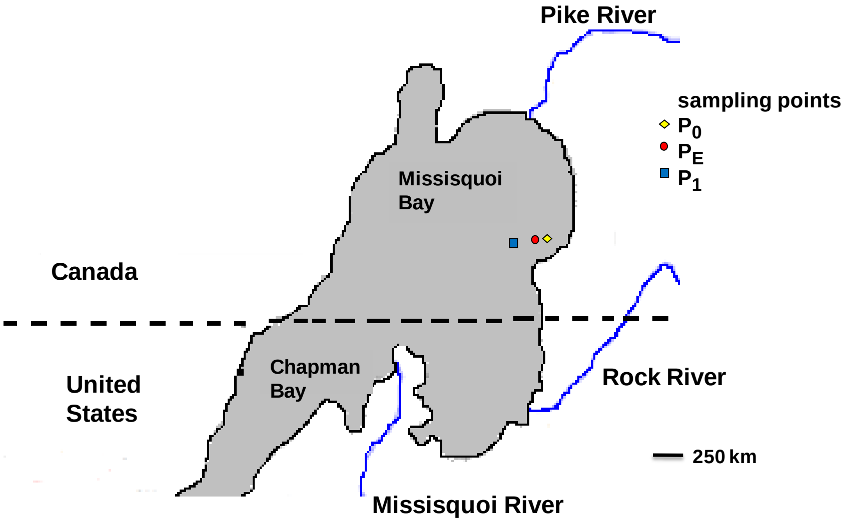

Figure 3.5: Missisquoi Bay and sampling points

In addition, water samples were also collected once per week at these locations. At each sampling point, water samples were taken in duplicate every meter in clean 500 mL plastic bottles for chemical analysis and biological extractions, and in sterile 20 mL vials for taxonomic counts and phycocyanin analyses. The bottles were rinsed three times with sampled water before they were filled completely and tightly closed. Lugol's iodine was added in vials for taxonomic counts according to Lund et al. (1958). All the samples were preserved on ice in coolers for transport and processed within 24 hours, with the exception of the taxonomic counts for CB that were preserved in Lugol's iodine. Vials with Lugol's iodine were sent to Quebec Environmental Analysis Expertise Centre or to Université du Québec à Montréal's (UQAM) Biological Sciences

Department for species identification, taxonomic counts, biomass and biovolume calculations using inverted microscopy according to Lund et al. (1958). Phycocyanin and chlorophyll analyses were performed with a Turner Designs 10AU™ Field Fluorometer (Turner Designs, Sunnyvale, CA, USA) using EPA Method 445.0 (Arar & Colling, 1997). Nutrient analyses were performed according to Standard Methods 4500 NO_3-I for DIN (filtered samples of NO_2-N and NO_3-N) and 4500 N_{org}-D for TKN (unfiltered samples) (American Public Health Association et al., 2005)as well as EPA method 365.4 for TP.

Cyanobacterial biovolume (CBV) with units of mm^3/L, representing the CB abundance in Missisquoi Bay was calculated by using the correlation between RFU (ratio fluorescence units) of the phycocyanin probe and the CBV obtained in environmental conditions according to McQuaid et al. (2011). The relationship established from the two study sites including the Missisquoi Bay was a linear function over the range encountered:

$$\mathrm{Log(Biovolume)} = -0.4768 + 1.089 \times \mathrm{Log(RFU)} \tag{3.14}$$

The importance of using CBV rather than cell counts (cells mL^{-1}) is that abundance is quantified in a manner that is independent of cell shape, form or volume and accounts for CB heterogeneity in source waters.

b) Cyanobacteria and wind speed

Wind speed and direction can cause horizontal drift of CB colonies in water bodies and entrainment and drift of CB colonies is noted for wind speeds exceeding 1 m/s(Baines & Knapp, 1965). CB colonies' aggregation can be a result of intense mixing. Kanoshina et al. (2003) found that wind forced advection influenced the distribution of the dominant species of CB colonies which were different during warm and calm weather than in cold and windy conditions. Webster and Hutchinson (1994) observed through experiments that winds speed greater than 2-3 m/s lead to phytoplankton mixing cells (or colonies). There was a critical wind speed which defined the nature of mixing process (with or without turbulence). The wind speed influences the horizontal distribution of phytoplankton populations in lakes. Low wind speed was defined as <2m/s and high wind speed as>3m/s. Horne and Wrigley (1975) noted that CB blooms disappeared from the surface for wind speeds greater than 3.6 m/s over the course of 4 hours.

c) Cyanobacteria and water temperature

According to Reynolds and Walsby(1975), the optimum water temperature for cyanobacterial growth to be 25°C to 35°C. These authors reported that Nicklish and Kohl (1983) found a very slowly grow at temperatures below 13-15°C for *Microcystis*. The main cyanobacteria species dominant at Missisquoi Bay are reported in Table 3.3 and show their optimal growth temperature. The minimum, maximum and optimum values of temperature for CB growth were thus assumed to be 10°C, 35°C and 20°C (by model calibration), respectively. At Missisquoi Bay, water temperatures recorded during our sampling period ranged from a minimum of 10°Cin 2007 to a maximum of 29.1°C in 2011 with mean temperatures ranging from 18°C in 2007 to 23.7°C in 2011. Calibration done for 2007 and 2008 data permit to obtain the good value for our model, taking account range value found in the cited literature.

Table 3.3: Optimum growth temperature of dominant CB species at Missisquoi Bay

Dominant species Cyanobacterial genus	**Biovolume (mm3/L)**				**Percentage (%) (N = 76)**				**optimum temperature of dominant species**
	2008	2009[a]	2010	2011	2008	2009[b]	2010	2011	
Microcystissp.	1959	1600	41	747	63	83	52	67	32.5^{o}C Lake Kasumigaura,Japan (Imamura N. (1981)) 15^{o}C-30^{o}C (Chorus and Bartram, 1999) 28^{o}C (Zehnder and Gorham, 1960)
Anabaenasp.	1031	-	27	312	33	-	35	28	25^{o}C Lake Kasumigaura,Japan (Imamura N. (1981)) 30^{o}C Missouri, USA Novak J.T., and Brune D.E. (1985)
Aphanizomenonsp.	109	0.3	5.1	45	4	16	6	4	25^{o}C Lake Kasumigaura,Japan Imamura N. (1981)

a: McQuaid, N., Zamyadi, A., Prevost, M., Bird, D., Dorner S., (2011) Use of in vivo phycocyanin fluorescence to monitor potential microcystin producing cyanobacterial biovolume in a drinking water source. J.Environ. Monit., 13(2), 455–463.

b: Zamyadi, A., MacLeod, L. S., Fan, Y., McQuaid, N., Dorner, S., Sauvé, S., Prévost, M., (2012). Toxic cyanobacterial breakthrough and accumulation in a drinking water plant: A monitoring and treatment challenge. Water Res., 46 (5), 1511-1523.

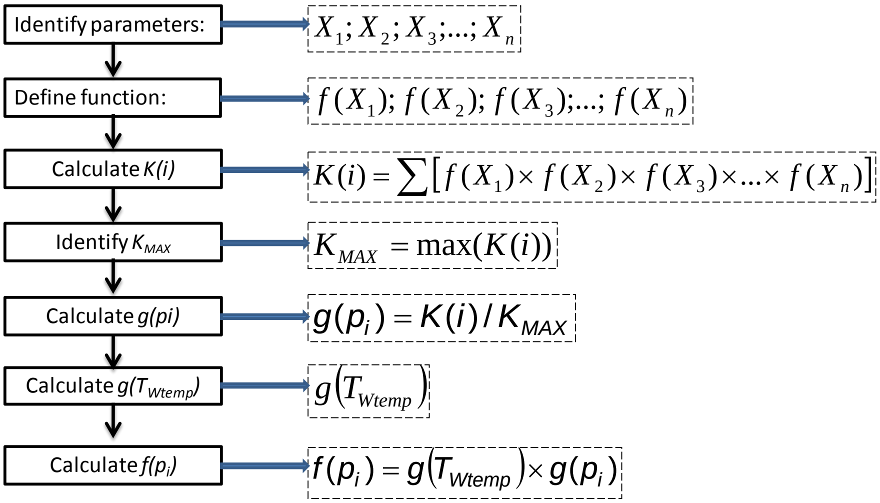

Figure 3.6: Description for meteorological index f(p) calculation

d) References

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CHAPITRE 4 ARTICLE 2: HYDRODYNAMIC MODELING OF LIGHT INTENSITY AND WIND EFFECTS ON THE SPATIAL DISTRIBUTION OF CYANOBACTERIA

Ce chapitre présente l'approche eulérienne et déterministe développée en tenant en compte la flottabilité des cyanobactéries. Ce chapitre a été abordé pour mieux comprendre la distribution spatio-temporelle des CB qui ne pouvait pas être expliquée avec l'approche statistique présentée dans le chapitre précédent. Ce chapitre met en exergue l'importance des processus de changement de densité des CB selon l'intensité de la lumière et d'advection sur la distribution spatio-temporelle des CB. Les résultats présentés dans ce chapitre ont été soumis à *Environmental Science and Technology* en Septembre 2014.

HYDRODYNAMIC MODELING OF LIGHT INTENSITY AND WIND EFFECTS ON THE SPATIAL DISTRIBUTION OF CYANOBACTERIA

[a]Mouhamed Ndong*, [b]David Bird, [c]Tri Nguyen-Quang, [a]René Kahawita, [a]Michèle Prévost, [a]Sarah Dorner

a. Department of Civil, Geologic and Mining Engineering. École Polytechnique de Montréal, C.P. 6079, succ. Centre-ville, Montréal (Québec), Canada, H3C 3A7

b. Department of Biological Sciences, Université du Québec à Montréal, C.P. 8888, succ. Centre-ville, Montréal (Québec), Canada, H3C 3P8

c. Department of Engineering, Faculty of Agriculture, Dalhousie University, PO Box 550, Truro-Bible Hill (Nova Scotia), Canada, B2N 5E3

KEYWORDS

Cyanobacteria bloom, hydrodynamic model, eulerian model, phototaxis, wind effects, water intake, drinking water.

4.1 Abstract

An increasing number of water bodies are affected by cyanobacteria (CB) occurrences. CB blooms can be toxic and may disrupt drinking water (DW) treatment. For DW sources impacted by CB, in addition to long term management plans, short term operational decision making tools are needed that enable an understanding of ecological aspects related to CB. In this paper, we propose a new conservative model based on an eulerian framework and compared results with data from CB blooms in Missisquoi Bay (Québec, Canada). The hydrodynamic model considering the effects of wind and light intensity demonstrated that the photosynthetic effect on CB buoyancy plays a major role in the formation of a thin surface layer and that the wind contributes to the accumulation of CB. The risk due to CB bloom at a DW intake could be cyclic depending on the light intensityand wind stresses. Lake recirculation effects have a tendency to create zones of low CB concentrations in a water body. Monitoring efforts at DW intakes should focus on short-term temporal variation of CB throughout the water column as this is critical for understanding the risk of breakthrough into treatment plants.

4.2 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). Therefore, knowledge of the relationship of CB growth and accumulation with 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). However, determining causes of CB occurrences and their effects considering their spatial and temporal distributions in lakes and reservoirs are not easy tasks (Wallace & Hamilton, 1999). Computational modelling is hence a useful tool for water managers and DW treatment plant operators to better understand mechanisms controlling CB movement (Visser et al., 1997).

Understanding ecological aspects of CB formation such as the development of a thin layer near the surface or bottom of a water-body during bloom occurrences as well as the importance of water movement and recirculation is needed for choosing an appropriate location for a DW intake and identifying periods of risk of CB breakthrough into treatment plants. However, in general, DW intake design has not integrated phytoplankton risk. Given that intense CB blooms are relatively recent occurrences in many water bodies, plant managers must now consider whether or not changing the location of an intake could minimize the risk to DW. Better prediction of blooms could lead to improved operational decision-making at DW treatment plants (Ndong et al., 2014a; Wynne et al., 2013; Zamyadi et al., 2013c).

The thin phytoplankton layer at the water surface is generally observed in a wide variety of environments (Wang & Goodman, 2010). The thickness of this layer can vary from a few centimeters to a few meters and can cover a surface from meters to kilometers square (Ryan et al., 2010). This thin layer may be composed of many different organisms living or non-living and their formation and maintenance are strongly dependent on organism behaviours (Ross & Sharples, 2008) and on physical and biological processes controlling the bloom formation. Buoyancy and turbulence factors facilitate organisms' accumulation (Franks, 1992; Steinbuck et al., 2009). The initiation and development, maintenance, decline and vertical distribution of a thin layer is 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 straining and buoyancy play an important role in phytoplankton thin layer formation and maintenance (Velo-Suárez et al., 2010). Local circulation patterns and episodic changes in a water body driven by wind and tidal forcing (in the case of marine environments) can also govern the vertical distribution of thin layers 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 (advection, wave…) is important (Hu et al., 2009; Moreno-Ostos 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 (Ghorai & Hill, 2005; Nguyen-Quang & Guichard, 2010; Wallace & Hamilton, 1999; Webster, 1990; Webster & 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, turbulent mixing and light intensity

(Moreno-Ostos et al., 2006). CB buoyancy regulation is affected by water temperature (Kromkamp et al., 1988), light intensity (Howard et al., 1996; Kromkamp & Mur, 1984; Kromkamp & Walsby, 1990), nutrient limitation (nitrogen and phosphorus) (Kromkamp & Walsby, 1990; Wallace & Hamilton, 2000), and colony size (Howard et al., 1996; Kromkamp & Walsby, 1990; Rabouille et al., 2003; Visser et al., 1997). In general, light intensity has been the most studied factor with regards to modeling CB buoyancy (Chen et al., 2009; Howard, 1997; Kromkamp et al., 1988; Wallace & Hamilton, 1999). Light intensity varies in time and space and is a major and essential resource for phytoplankton (Litchman & Klausmeier, 2001). CB are photosynthetic microorganisms that must remain near the surface water layer for sunlight (Reynolds et al., 1987).

For modeling, statistical methods and Lagrangian based approaches have been commonly used to study 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, 1985; Smith et al., 1987; Teles et al., 2006; Wei et al., 2001). 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 (Belov & Giles, 1997; Kromkamp & Walsby, 1990; Porat et al., 2001; Verhagen, 1994; Visser et al., 1997; Wallace et al., 2000; Webster, 1990; Webster & Hutchinson, 1994) have also attempted to understand the spatio-temporal distribution of CB. A Lagrangian deterministic approach, where by the position of a CB colony is followed in the water column has been used at the laboratory scale (Kromkamp et al., 1988; Kromkamp & Mur, 1984; Kromkamp & Walsby, 1990; Visser et al., 1997). The results from these studies enable the development of mathematical models to describe variations in CB density. Kromkomp et al.(1990) found that the variation of density of CB cells in the dark is proportional to 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 proportional to its previous density (without considering gas vesicles). This last approach is easier to implement and is realistic, but it requires a correction to take into account the presence of gas vesicles in the cells of CB.

There is a need to have a global view of CB distribution in a water body to observe changes at a particular location through time (e.g. at a DW intake). Although other more complex and complete ecological CB models exist such as CAEDYM (Hipsey et al., 2006), none have explicitly considered the effects of buoyancy in relation to phototaxis. As such, the upwards movement has generally been considered a process related to resuspension as a function of critical shear stress rather than a process intrinsic to the cells as a density change according to light. Furthermore, the Visser et al.(1997) model is an improved version based on Kromkomp et al. (1990) model.

This paper presents a novel 2D computational model based on the eulerian approach with a numerically conservative scheme to simulate the spatial variability of CB concentrations. The objectives of the research were to investigate: 1) the light effects on the spatio-temporal distribution of CB in a water body via phototactic behaviour; 2) the combination of light and wind effects on the distribution of CB, and3) the coupled biological and physical effects related to CB formation such as thin layers near the water surface and at the bottom of the water-body during bloom occurrences. We expect that these results can be applied to explain the cyclic risks of CB blooms at DW treatment plant intakes and will contribute to improved decision making with regards to CB monitoring, the selection of water intake positions in source waters affected by cyanobacteria, and the operation of treatment plants in order to minimize disruption of DW treatment from CB breakthrough. To our knowledge, the computation framework developed is the first model of CB transport using an eulerian framework with comparison to full-scale field data.

4.3 Theoretical Calculations: Hypotheses

Our model was developed for the general case of a homogeneous suspended CB population in a water body considering light and wind effects. We assumed that all physical properties of the fluid were constant even for 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 the CB population reacts actively to the effects of light with regards to their phototaxis behavior. Thus, they will move positively towards the light sources.

The computational model constructed was based on the system of equations and boundary conditions detailed in Section 4.9.1, in Supporting Information (Section 4.9). The numerical resolution of the transport equation including CB buoyancy is described in section 2 (Supporting Information). 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 4.9.3 (Supporting Information, Section 4.9). Many have proposed approaches to calculate the velocity of CB as a function of light (Belov & Giles, 1997; Kromkamp et al., 1988; Kromkamp & Mur, 1984; Kromkamp & Walsby, 1990; Visser et al., 1997; Walsby, 2005).The system of equations describing the phototaxis behaviour of cyanobacteria is described in Section 4.9.4 (Supporting Information, Section 4.9).

4.4 Site Selection and Application of the eulerian Model to real 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 (Equation (4.21) in Supporting Information-section 4) with the maximum value of photon irradiance at noon (I_m) equal to 1800 µmol photons $m^{-2}s^{-1}$and the length of the photoperiod (D_L) of 12 hours. For real CB blooms, Missisquoi Bay in Québec, Canada, was selected as the test site for the model. The site description and monitoring data are described in Supporting Information-Section 4). It is also the principal source of DW for a population of approximately 4500 residents(Organisme de bassin versant de la baie Missisquoi, 2011) and has experienced serious disruption of DW treatment as a result of CB blooms (Zamyadi et al., 2013c; 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). Dominant genera of CB in Missisquoi Bay vary widely with regards to cell biovolume (Ndong et al., 2014a). The model was developed generically for all cyanobacteria species occurring in the Missisquoi Bay to study the dominant processes affecting CB movement and transport at the lake-scale and did not consider differences in movement and transport related to different species.

4.5 Results and discussion

4.5.1 Effects of light and wind

Simulation results: Results obtained from our mathematical model for Missisquoi Bay show the phototactic behaviour of CB as a function of light sources under the effects of wind are presented in **Figures 4.1** to**4.4**.

Figures 4.1 to**4.3** show the model’s results using simulated light intensity and wind speed.

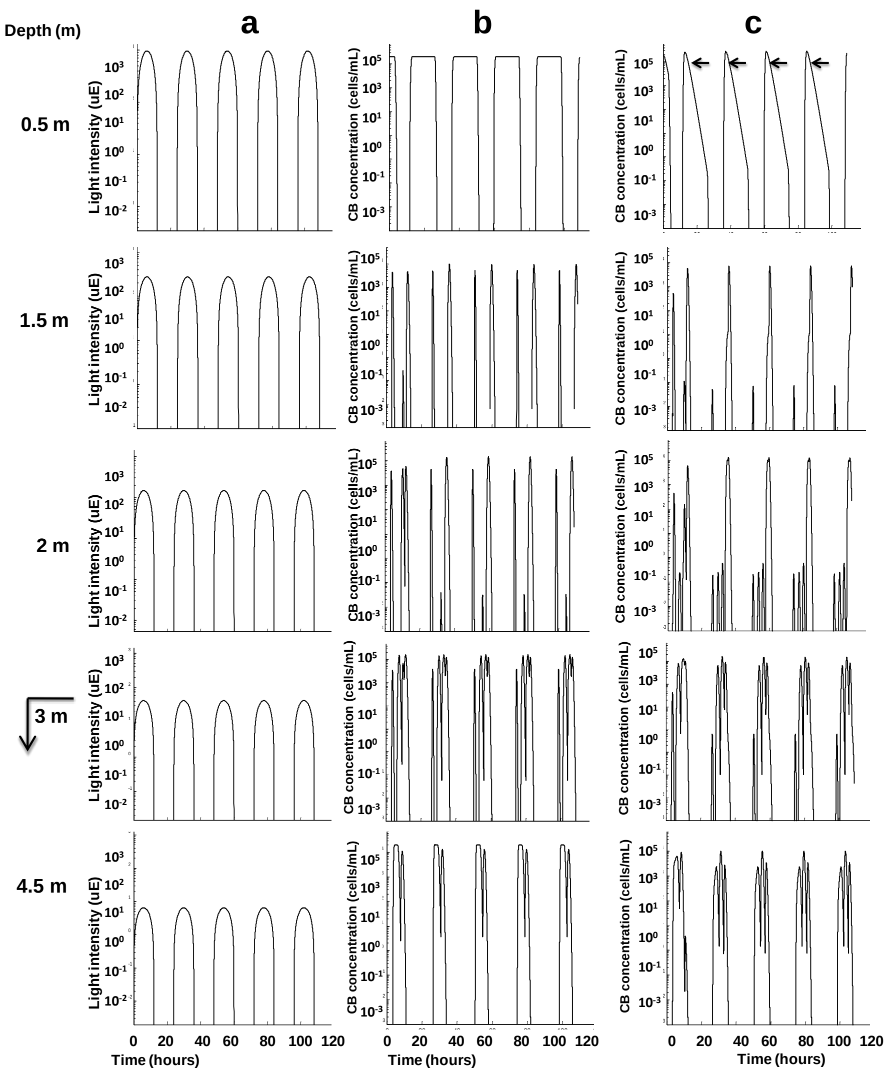

Figure 4.1: a) Light intensity penetration in water column, b) Cyanobacteria concentration according to light intensity only and c) Cyanobacteria concentration according to coupled effect of wind and light intensity

Figure 4.1a shows the light distribution as a function of water depth according to Beer-Lambert`s law. **Figure 4.1b** demonstrates that various states of CB distribution are strongly associated with the light distribution shown in **Figure 4.1a**. The distributions of CB, varying at each value of water depth, are also cyclic according to the periodicity of the light distribution as explained by 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 0.5m, **Figure 4.1b**). As can be seen in **Figure 4.1b**, the distributions of cells below 1.5 m are less exposed to the effects of light. These phototactic distributions (with light stimuli only in **Figure 4.2b**) are clearly affected by wind forces introduced in the system as shown in **Figure 4.2c**: The curves of CB cell distribution are still cyclic but change in form with the wind intensity. At the water surface, 0.5m and 1.5m depth (**Figure 4.1c**), the CB distribution curves are more deformed by the effects of wind while at the deeper positions (more than 3 m), CB cell distribution curves are less modified (**Figure 4.1c**).

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 stimuli. 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 group dynamics. 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). The lag time can be seen in **Figure 4.1** when the light intensity reaches its maximum value, the CB population do not yet reach their maximum concentration as a result of the time needed to reach a critical mass. When the light intensity continues along its sinusoidal function and decreases to zero, the CB concentration in turn reaches its maximum value as shown in Figures 4.1b and c. This effect was also observed in simulations with real 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. Their redistribution is the result of two processes: (1) vertical advection from wind effects that results in an accumulation of CB at the right (east) side of the Bay as shown in **Figure 4.2** *at t=67*minutes; 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 **Figures 4.2a, b** and **c** presenting 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 **Figure 4.2a**, the light intensity diffuses within the water column according to Beer-Lambert's law. After a certain accumulation time, CB reach a critical mass and move towards the maximum light intensity (t=67 min and t=1000 min, **Figure 4.2b**). If the wind effects are taken into account, the CB population is affected, blown out and collected in larger numbers along one side of the water column (t=67 min). Due to the recirculation effects induced by wind, the accumulated CB will be blown out again over a long period of time as a function of light intensity and the convective motion in the water column (**Figure 4.2c**).

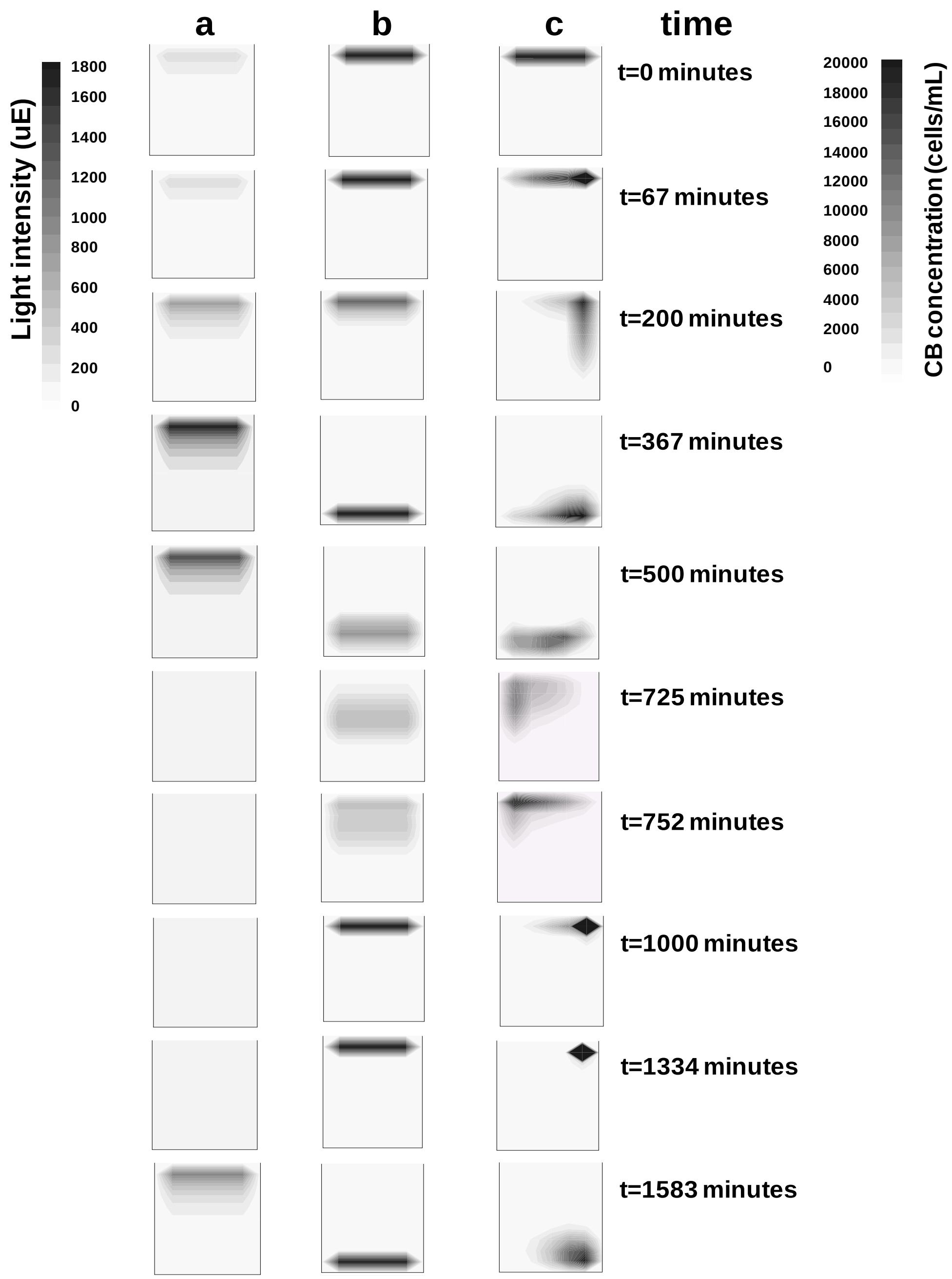

Figure 4.2: a) Light penetration in water column and Cyanobacteria movement according to: b) Light intensity effect only, c) Wind and Light intensity effect

4.5.2 The formation of a thin layer of CB during a bloom

According to our results presented in **Figure 4.3b** and **c**, a thin layer of CB appears near the water's surface. Phototaxis and wind effects strongly influence the formation of the thin layer. Indeed, by considering the phototaxis effect only (**Figure 4.3b**), we observe a formation of large thin layer of CB at the water surface and at the bottom of water body. This accumulation trend can be prevented by wind effects as illustrated by the results obtained in **Figure 4.3c**.

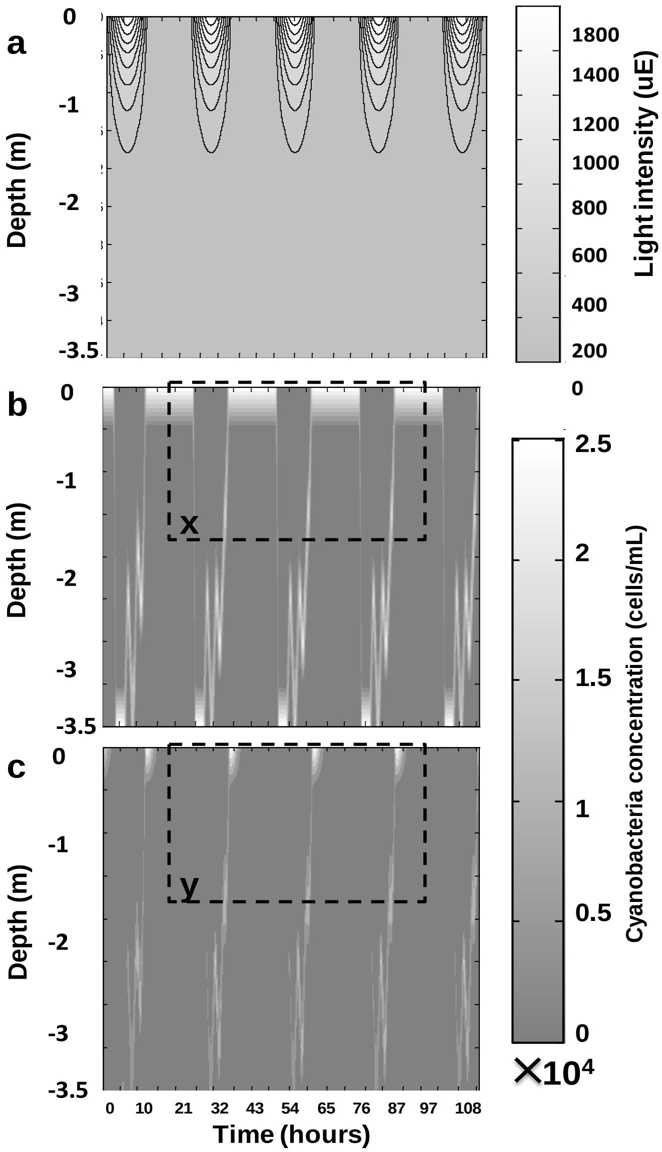

Figure 4.3: Spatio-temporal distribution of: a) Light penetration in water column and Cyanobacteria according to: b) Light intensity effect only, c) Wind and Light intensity

From an ecological point of view, the thin layer formation is a consequence of CB phototaxis behaviour in a low dynamical environment, e.g. with weak turbulence and would also be expected to be related to the species of cyanobacteria. Wind has a tendency to disperse this layer through its transport vector and creates other various thin layers near the shoreline.

Figure 4.3 shows the spatial and temporal accumulation of the CB population observed near the shoreline as a result of light intensity only (**Figure 4.2c**) and coupled light and wind effects (**Figure 4.2c**). However, not all of the CB cells in the water column are affected by the effects of wind. This means that the wind has strong effects on the distribution of CB in limited zones. The dimensions of these limited zones depend strongly on the wind intensity. Two zones, X and Y, marked in **Figure 4.3b** and **Figure 4.1c** highlight the influencing areas of wind effects and limitations to CB mass dispersion induced by wind factors. Consequently, the CB cells' buoyancy appears to be the dominant factor at the bottom of the water column.

Figure 4.2 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 the CB population; iii) even when there exists an accumulation of cells attaining a critical mass 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.

4.5.3 Application of the eulerian model to Missisquoi Bay and comparison to field data

The simulations in our project, performed with real wind and light intensity (photosynthetic active radiation (PAR)) data collected at Missisquoi Bay (**Figures 4.4a** and **b**), shows the presence of a thin layer of CB and their movement from the surface to the bottom of the water column (**Figure 4.4b**). In this study the initial density of CB was assumed to be approximately equal to 1030 kg/m^3 at12:30 PM.

Through the simulation with real meteorological data from Missisquoi Bay, it can be seen that light intensity penetration in the water column showed little variation from its sinusoidal curve during all days that were used for simulation (**Figure 4.4a**).

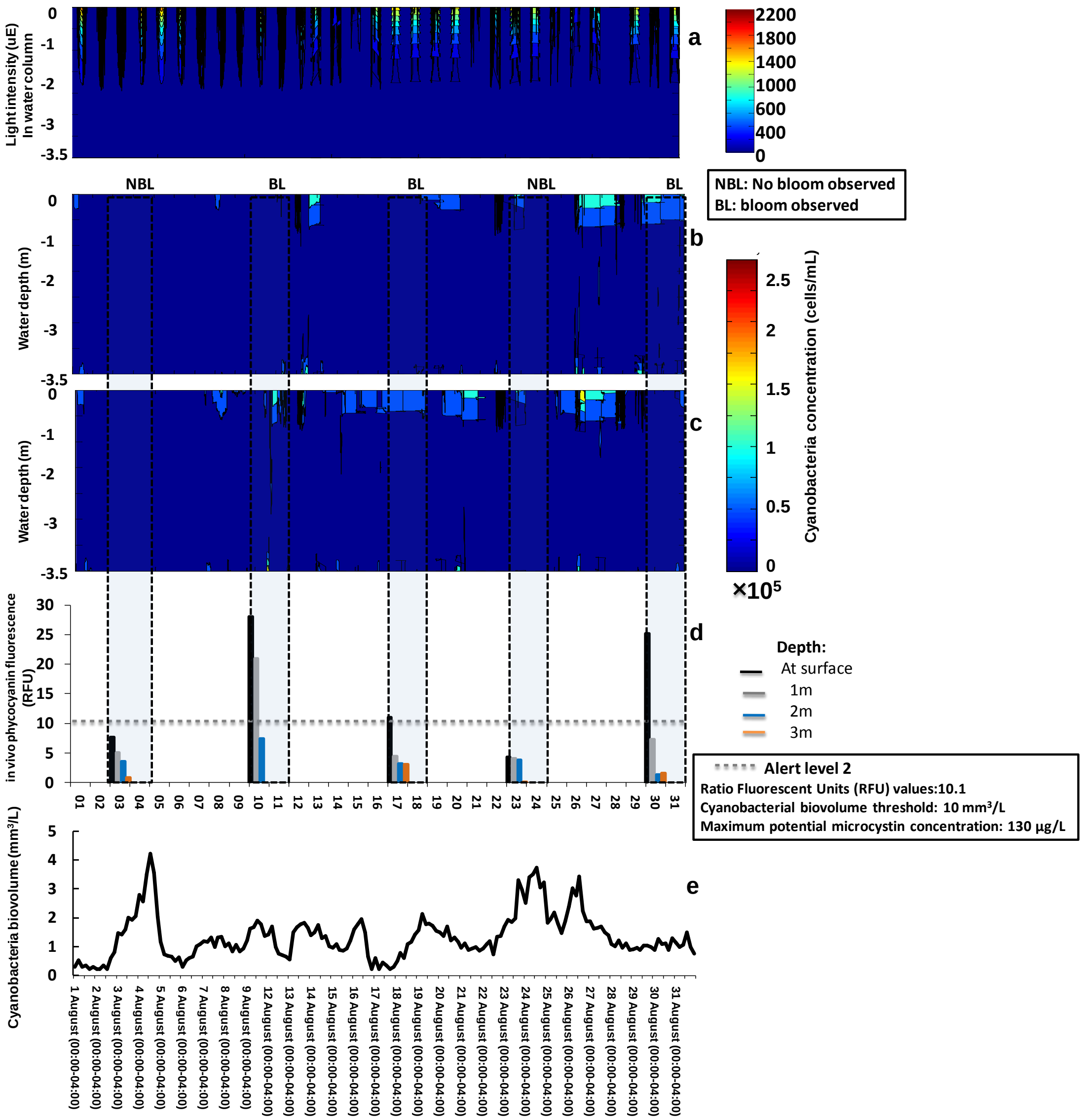

Figure 4.4: a) Light intensity Penetration in water column; b, c,) Spatio-temporal distribution of cyanobacteria obtained by running real data of wind and photosynthetic active radiation (PAR) at Missisquoi Bay during 2011: b) with time delay photoadaptation in dark d) Real data of cyanobacteria value in RFU recorded above the drinking water intake (at PE – Figure 4.8) e) Real data of cyanobacteria biovolume recorded inside water treatment plan (drinking water intake)

In our study, the photoadaption time response was taken account for two cases: first, when CB are exposed to light intensity greater than light intensity compensation (Ic) and, second is when light intensity is less important than Ic. For the first case, the time delay suggested by Wallace and Hamilton (2000)was used (4mins) when irradiance occurring in the water column (Iz) is higher than compensation irradiance (Ic). For the second case (when Iz<Ic) two different values of the time delay in the dark were tested: 1) a delay of 4 mins (**Figure 4.4b**), 2) without delay (**Figure 4.4c**), the time response delay suggested by Wallace and Hamilton (2000) had been obtained from laboratory experimental data. The time response associated with CB photoadaptation must be considered when modeling the CB distribution. Wallace and Hamilton(2000) suggested a time delay of 4 minutes (1200 seconds) when using the Visser et al.(1997) model and 20 minutes when using the Kromkamp and Walsby(1990) model. Ignoring this delay leads to unrealistically rapid CB movement.

To compare model results with field observations, a threshold of 10.1 RFU (in vivo phycocyanin fluorescence) was fixed to define abloom 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 10mm^3/L and maximum potential (theoretical) microcystin concentration of 130µg/L. For all the values of RFU above this limit value (10.1 RFU) during our sampling day (**Figure 4.4d**), CB bloom occurrences were observed in the model within a 24 hour period following the observations (when Iz>Ic: with a time delay of 4mins and Iz<Ic: without time delay) **Figure 4.4c**. A Spearman rank correlation demonstrated a weak correlation (Spearman rho = 0.13, p-value<0.08) between the model results (using mean modeled CB concentrations from the surface to the bottom of the water body at the DW intake location) and continuous physical measurements from samples from the DW intake well (obtained with the phycocyanin probe). The weak correlation is partly explained by the sampling method at the intake well that has a retention time that may exceed the CB response time and measurement concentrations biased towards bottom conditions. For the case using a time delay of 4 mins for Iz>Ic and Iz<Ic, CB blooms events were not well captured by our model.

The model results demonstrate the need for high frequency data for the entire water column in water sources affected by cyanobacteria because conditions can change rapidly in response to environmental forcings. More field investigations must be performed in order to determine a more realistic time delay of CB under the effects of phototaxis in realistic environmental conditions. No field scale data are available for the time delay response with regards to CB acclimation considering multiple varying parameters such as temperature, light intensity or nutrient availability. Without consideration of the time delay, a difference between real ecosystem data and model results occurs. It was also hypothesized that the time delay was constant throughout the water column depth. However, this hypothesis needs to be evaluated through high frequency sampling and field experimentation in order to understand CB behaviour throughout the water column. Furthermore, there is a need to study factors related to cyanobacteria accumulation at the bottom of the water column that are not related to the light and hydrodynamic effects considered in the model. In order to accurately simulate concentrations of cyanobacteria at a DW intake, their movement (or delay in movement) in relation to nutrients released from bottom sediments will need to be elucidated at the full scale of water bodies.

The real physical scale of the 200m length scale (grid size: $\Delta \boldsymbol{x}$) of our model can be applied to large water bodies such as Missisquoi Bay. Hence the buoyancy effects from phototaxis behaviour were found to play the dominant role generating upward and downward motions of CB cells. The dispersion of the critical mass of accumulated CB in blooms would be more influenced by the buoyancy force that pushes CB cells away from the bottom of the water column, than by the effect of horizontal advection which transports them away from the shoreline. The cyclic effect of light, hence the cyclic effect of buoyancy or phototactic behavior increases CB cell movement from the bottom to the top of the water column and vice-versa, following which, they are transported as a result of circulation effects induced by wind. Thus, the formation of scum and thin layers at the water's surface are strongly associated with the CB buoyancy mechanism. However, 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 induce density changes (becoming greater than water density (Kromkamp & Walsby, 1990)), leading to the downward motion of CB cells to the bottom. These upwards and downwards motions are continuous over a long duration of time and create a cyclic movement of CB. 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.

Lake recirculation induced by wind also has a large influence on the horizontal distribution of CB. CB can be advected by the currents of recirculation due to the effects of the wind (Howard, 1997; Howard, 2001; Howard et al., 1996; Kromkamp & Walsby, 1990; Porat et al., 2001; Verhagen, 1994; Visser et al., 1997; Wallace et al., 2000; Webster, 1990; Webster & Hutchinson, 1994). Webster and Hutchinson (1994) showed that phytoplankton mixing occurs when wind speed is greater than 2-3 m/s as a critical threshold value. Wind direction must also be considered because it affects CB accumulation and also prevents blooms. Verhagen's (1994) analysis of CB velocity buoyancy versus water velocity showed that in the region of downwelling water near the downwind shore, if the CB moving velocity induced by their own buoyancy is greater than the descending water velocity, CB will aggregate in the upper water layer near the downwind shore. They concluded that a wind-induced circulation pattern in the vertical plane is essential for the mechanism of CB aggregation in the upper water layer. Through the results shown in **Figure 4.2c** at times 725 minutes and 752 minutes, we can observe CB moving at the upper layer of the water column by the effect of recirculation. However, this recirculation effect can also contribute to CB movement from the top to the bottom of water surface. Thus, 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 & Hamilton, 1999).

4.5.4 Recurrent risk from cyanobacteria movement and siting of drinking water intakes

The siting of a DW intake is critical for DW treatment plants. To reduce the risk associated with CB bloom occurrence, it is indispensable to choose an appropriate position for a DW intake in a water body. From **Figures 4.2b** and**4.2c**, our results show that the movement of CB blooms can cause a significant risk for a DW intake located at the bottom of the water column. The risk associated with CB blooms would be cyclic (as observed in **Figure 4.3**) as the effects of buoyancy and the currents of recirculation in the water column are of cyclic form (Rabouille et al., 2005). George (1993) and Falconer et al. (1999) demonstrated that within a few hours, wind induced effects could cause a significant growth of phytoplankton cell density by a factor of 1000. The risk to DW intakes can be increased as well by the turbulent effects also caused by wind factors. Turbulent mixing in the bottom of water column could supply new nutrients available for promoting new CB production and entrain cells to the bottom of water column (Velo-Suárez et al., 2010). Therefore, for the long term 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 define the possible areas where CB concentration under the coupled effects of light and wind factors might be lower to reduce risks for DW intakes. 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 raised from the bottom to 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, 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. However, high frequency sampling throughout the water column are 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., 2013a). 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 and CB toxins would remain.

Light intensity and wind force are two dominant factors associated with the buoyancy effects and advection leading to CB bloom pattern formation. These factors are favourable also for the CB accumulation at the shorelines and the formation of the thin layers at the surface and bottom of the water column. The CB thin layer formation is governed by the buoyancy term via the phototaxis behaviour and their dissipation is favoured when strong winds occur.

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.

Bloom apparition patterns at a given location are largely controlled by the effects of light and wind, but other factors such as the availability of nutrients could also play a role in the distribution of CB in the water column. The effects of light and winds are important for the onset of the CB bloom and create 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 (Nguyen-Quang & Guichard, 2010).

Results demonstrated that in a water body where there are CB bloom occurrences and wind speeds are weak, the buoyancy effect is dominant and CB cells could descend to DW intakes. The risk to DW intakes would be cyclic and dependent largely on both light intensity and wind stresses. Due to the recirculation by advection, there will be the zones where the CB concentration is low, although even low concentrations would still be of concern in DW treatment without the availability of appropriate treatment processes and adequate treatment plant operation.

The model based on an eulerian framework demonstrated a good conservation of mass using our new scheme for solving the advection-diffusion equation. All mass losses during each step of simulation were registered and the results showed that mass addition or losses were negligible. This mass conservation scheme will therefore be useful when other processes such growth and mortality (reaction terms) are considered given that the forcing of the model was accurate, we expect the model will be improved by considering additional processes, however additional high frequency sampling and further testing is required. Nevertheless, the present model demonstrates that wind forcing functions coupled with a set of rather simple physical and biological process equations (CB cell transport equation) explain much of what is observed.

Future development of the model will consider other important processes such as growth, mortality and varying behaviours of different species of CB including their behaviour in relation to surface water hydrodynamics. Future efforts will also involve the quantification of the threshold for the CB bloom onset by light and wind effects using the approach of Nguyen-Quang and Guichard (2010), i.e. to combine our approach with the Boussinesq approximation. The model is a useful tool for water management and water treatment decision making with regards to the DW intake location and identifying periods of high or low risk of CB breakthrough into DW.

4.6 Associated content

The supporting information contains the system of equations and boundary conditions for hydrodynamic, transport and buoyancy equation, the methodology of transport equation resolution, the numerical validation results.

AUTHOR INFORMATION

Corresponding Author

*Current address: École Polytechnique de Montréal, Department of Civil, Geological and Mining Engineering, P.O. Box 6079, Station Centre-Ville, Montreal, Quebec, Canada, H3C 3A7Phone: 514-340-4711 extension 2983; Fax: 514-340-5918

E-mail: mouhamed.ndong@polymtl.ca

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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4.9 Supporting Information (SI)

HYDRODYNAMIC MODELING OF LIGHT INTENSITY AND WIND EFFECTS ON THE SPATIAL DISTRIBUTION OF CYANOBACTERIA

[a]Mouhamed Ndong*, [b]David Bird, [c]Tri Nguyen-Quang, [a]René Kahawita, [a]Michèle Prévost, [a]Sarah Dorner

a. Department of Civil, Geologic and Mining Engineering. École Polytechnique de Montréal, C.P. 6079, succ. Centre-ville, Montréal (Québec), Canada, H3C 3A7

b. Department of Biological Sciences, Université du Québec à Montréal, C.P. 8888, succ. Centre-ville, Montréal (Québec), Canada, H3C 3P8

c. Department of Engineering, Faculty of Agriculture, Dalhousie University, PO Box 550, Truro-Bible Hill (Nova Scotia), Canada, B2N 5E3

* Corresponding author. Current address: Department of Civil, Geological and Mining Engineering. École Polytechnique de Montréal, C.P. 6079, succ. Centre-ville, Montréal (Québec), Canada, H3C 3A7.
Tel.: (+1) 514 994 6872
E-mail address: mouhamed.ndong@polymtl.ca

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4.9.1 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 presented here is a necessary step to evaluate the relative importance of light and wind effects and to describe cyanobacterial accumulation in relation to environmental forcing.

Continuity

$$\mathbf{\nabla . V = 0} \tag{4.1}$$

Momentum equation

$$\boldsymbol{\rho_w \frac{\partial V}{\partial t} + \rho_w \nabla .(VV) = -\nabla p + \nu \nabla^2 V + \rho \vec{g}} \tag{4.2}$$

Where V is the velocity of fluid (m/s); **p** is the dynamic pressure (Pa); **ρ** is the suspension density (kg/m^3); ρ_w is the water density (kg/m^3); **g** is the gravitational acceleration (m^2/s), **ν** is water viscosity (Pa.s) and t is the time (s).

Equation (4.2) may be expressed in the vorticity and stream function form according to (Nguyen-Quang & Guichard, 2010):

$$\boldsymbol{\rho_w \frac{\partial \xi}{\partial t} + \rho_w \nabla (V\xi) = \nu\, \nabla^2 \xi + \nabla \times \overrightarrow{\rho g}} \tag{4.3}$$

$$\boldsymbol{\xi = -\, \nabla^2 \varphi} \tag{4.4}$$

The equations (4.3) and (4.4) for Vorticity **ξ** and stream function **φ** were used in our model principally to eliminate the instability caused by the pressure term in the Navier-Stokes equations during the simulation process.

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

$$\xi=\frac{\partial w}{\partial x}-\frac{\partial u}{\partial z}=\frac{\partial^2\varphi}{\partial x^2}-\frac{\partial^2\varphi}{\partial z^2} \qquad 4.5$$

If we introduce the horizontal and vertical diffusivity coefficients, respectively, equation (4.3) becomes:

$$\frac{\partial\xi}{\partial t}+\mathbf{u}\frac{\partial\xi}{\partial x}+\mathbf{w}\frac{\partial\xi}{\partial z}=\Gamma_x\frac{\partial^2\xi}{\partial x^2}+\Gamma_z\frac{\partial^2\xi}{\partial z^2} \qquad 4.6$$

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 Γ_x and $\Gamma_z$are the horizontal and vertical diffusivity coefficients (m^2/s), respectively.

Equation (4.6) does not incorporate buoyancy effects, the specific density of water was assumed to be constant. This implies that CB have a negligible effect on density.

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.

$$\frac{\partial \mathbf{C}}{\partial \mathbf{t}}+\nabla(\mathbf{VC})+\nabla(\mathbf{FC})=\mathbf{D}\nabla^2\mathbf{C} \qquad 4.7$$

Where C is the CB cell or phytoplankton concentration (cell/m^3); V is the fluid medium velocity involving on the CB cells, D is the plankton diffusivity (m^2/s) and F is the motion term of CB cells. This motion term can be understood as the taxis term (Nguyen-Quang & Guichard, 2010).

Under the effect of light, this taxis term represents the phototactic behaviour (phototaxis) of CB cells. This phototactic term has been described in other studies (Ghorai et al., 2010; Litchman & Klausmeier, 2001; Mellard et al., 2011; Visser et al., 1997).

We propose here that a simple way to introduce the phototactic behavior of CB is by using F as the sinking velocity (m/s). This sinking velocity may be obtained from equation 19 below as originally proposed by Visser et al.(1997) for the buoyancy effects.

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 (4.1), (4.5) and the transport equation (4.7).

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 (intensity and direction) and atmospheric pressure.

At the water surface the boundary conditions are expressed as:

$$\begin{cases} \boldsymbol{w} = \boldsymbol{\varphi_s} = \mathbf{0} \\ \Gamma_x \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{z}} = \frac{\tau_x^s}{\rho_w} \end{cases} \qquad 4.8$$

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

$$\boldsymbol{\xi_s} = \frac{\tau_x^s}{\Gamma_x \boldsymbol{\rho_w}} \qquad 4.9$$

Where$\tau_x^s$is the surface wind stress at the water surface (N m^{-2})

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

$$\boldsymbol{\tau_x^s = C_v \times \rho_a \times W_a^2 = C_v \times \rho_w \times u_s{}^2} \qquad 4.10$$

Where C_v is the drag coefficient; ρ_a is the air density (kg m^{-3}); W_a is the wind speed at 10 m above the water surface (m s^{-1}) and u_s is the surface water velocity (m s^{-1})

The surface water velocity will be:

$$\boldsymbol{u_s = \sqrt{\frac{\rho_a}{\rho_w}} \times W_a \approx 0.03 \times W_a} \qquad 4.11 \text{ A}$$

Wind direction change is taken into account by introducing the term cos ($\boldsymbol{\varphi}_{\mathbf{dir}}$) as suggested by Hsu(1972), so that equation 11a is modified to read:

$$\boldsymbol{u_s} = \sqrt{\frac{\rho_a}{\rho_w}} \times \boldsymbol{W_a} \approx \mathbf{0.03} \times \boldsymbol{W_a} \times \mathbf{cos}\,(\boldsymbol{\varphi}_{\mathbf{dir}}) \qquad 4.11\ \text{b}$$

Where $\boldsymbol{\varphi}_{\mathbf{dir}}$ is the wind direction.

At a closed boundary, the vorticity is null (ξ=0) and

$$\begin{cases} \dfrac{\partial^2 \varphi}{\partial x^2} = 0 & \text{at left and right boundaries} \\ \dfrac{\partial^2 \varphi}{\partial z^2} = 0 & \text{at bottom} \end{cases} \qquad 4.12$$

4.9.2 Method for resolution

a) Discretization scheme for diffusion-advection equation

One important feature of the eulerian approach for CB modeling is that we need to know the CB density variation during all simulation steps. Traditional numerical schemes proposed such as QUICK, SIMPLE, etc. (Leonard, 1979; Patankar, 1980) do not allow for convenient monitoring of the CB density variation during each iteration step. That means the conservation property of the numerical algorithm is not sufficient if using these traditional schemes. To avoid this situation when dealing with the CB spatial temporal distribution using a eulerian approach, a constant CB buoyancy has traditionally been assumed for all steps of calculations (Chen et al., 2009; Webster, 1990; Webster & Hutchinson, 1994). This assumption however, does not correspond to physical reality and different models using a Lagrangian approach have shown that CB are able to move due to their own mechanism of buoyancy (dependent on light intensity) even if the aquatic environment is at rest (quiescent medium) (Kromkamp & Mur, 1984). In order to follow the variation of CB cell density in the water column due to the light intensity for each iteration step, while respecting conservation properties, we here propose a new numerical scheme to replace traditional schemes such as QUICK and SIMPLE. We therefore considered a control volume (CV) as is shown in **Figure 4.5**.

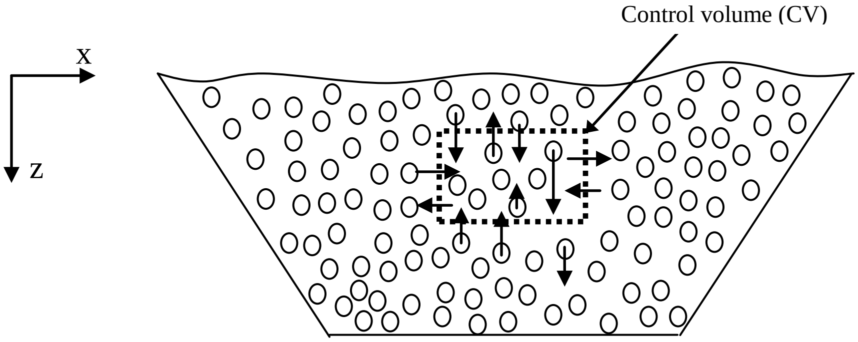

Figure 4.5: Schematic illustration of the distribution of cells and definition of the control volume (CV)

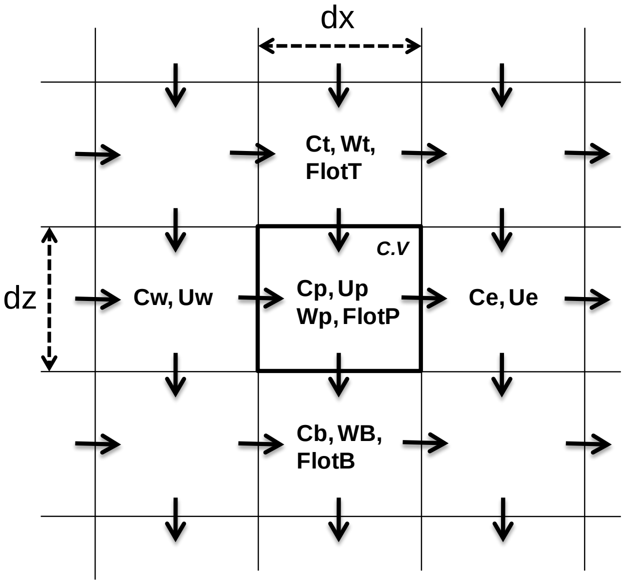

Figure 4.6: Mass flux distribution in grid meshing

The transport of CB is particular because they can move in the water column using their own mechanism of buoyancy. Unlike suspended particulate matter, the vertical velocity vector of cells may be towards the water's surface independent of the water's velocity. For the mass balance in the CV at time t, some cells may leave whereas other cells may enter according to their density and the horizontal and vertical advection. In this approach, the mechanism for the regulation of buoyancy is dependent on exposure to light and its intensity. The CV receives cells from above when the density of these cells is greater than the density of water and they will tend to accumulate in the bottom CV. When cell density is less than the density of water, cells will migrate to the control volume above. Following **Figure 4.6**, we can write:

$$\frac{\partial C}{\partial t} + \frac{\partial (uC)}{\partial x} + \frac{\partial [(w+F)C]}{\partial z} = \frac{\partial^2 (D_X C)}{\partial x^2} + \frac{\partial^2 (D_Z C)}{\partial z^2} \qquad 4.13$$

$$\frac{\partial C}{\partial t} + \frac{\partial (M_X)}{\partial x} + \frac{\partial (M_Z)}{\partial z} + \frac{\partial (M_F)}{\partial z} = \frac{\partial^2 (D_x C)}{\partial x^2} + \frac{\partial^2 (D_z C)}{\partial z^2} \qquad 4.14 \quad \text{A}$$

with

$$\frac{\partial (M_X)}{\partial x} = \frac{M_{XE} - |M_{XP}| + M_{XW}}{2\Delta x}$$

$$\frac{\partial (M_Z)}{\partial z} = \frac{M_{ZT} - |M_{ZP}| + M_{ZB}}{2\Delta z}$$

$$\frac{\partial (M_F)}{\partial z} = \frac{M_{FT} - |M_{FP}| + M_{FB}}{2\Delta z} \qquad 4.14 \quad \text{b}$$

$$\frac{\partial^2 (D_x C)}{\partial x^2} = \frac{D_{XE}C_E - 2D_{XP}C_P + D_{XW}C_W}{\Delta x^2}$$

$$\frac{\partial^2 (D_Z C)}{\partial z^2} = \frac{D_{ZT}C_T - 2D_{ZP}C_P + D_{ZB}C_B}{\Delta z^2}$$

$$\frac{\partial C}{\partial t} = \frac{C_P^{t+1} - C_P^{t-1}}{\Delta t} \qquad 4.14 \quad \text{c}$$

with

$$M_{XP} = U_P . C_P$$

$$M_{ZP} = W_P . C_P$$

$$M_{FP} = Flot_P . C_P$$

$$\mathbf{M_{XE} = \max(0, -U_E).C_E}$$
$$\mathbf{M_{XW} = \max(0, U_W).C_W}$$
$$\mathbf{M_{ZT} = \max(0, -W_T).C_T}$$
$$\mathbf{M_{ZB} = \max(0, W_B).C_B}$$
$$\mathbf{M_{FT} = \max(0, -Flot_T).C_T}$$
$$\mathbf{M_{FB} = \max(0, Flot_B).C_B}$$

$$\mathbf{\frac{C_P^{t+1} - C_P^{t-1}}{\Delta t} + \frac{M_{XE} - |M_{XP}| + M_{XW}}{2\Delta x} + \frac{M_{ZT} - |M_{ZP}| + M_{ZB}}{2\Delta z} + \frac{M_{FT} - |M_{FP}| + M_{FB}}{2\Delta z} = \frac{D_{XE}C_E - 2D_{XP}C_P + D_{XW}C_W}{\Delta x^2} + \frac{D_{ZT}C_T - 2D_{ZP}C_P + D_{ZB}C_B}{\Delta z^2}} \quad 4.15$$

$$\mathbf{(C_P^{t+1} - C_P^{t-1}) \times \frac{\Delta x \Delta z}{\Delta t} + (M_{XE} - |M_{XP}| + M_{XW})\frac{\Delta z}{2} + (M_{ZT} - |M_{ZP}| + M_{ZB})\frac{\Delta x}{2} + (M_{FT} - |M_{FP}| + M_{FB})\frac{\Delta x}{2} = \frac{\Delta z}{\Delta x}(D_{XE}C_E - 2D_{XP}C_P + D_{XW}C_W) + \frac{\Delta x}{\Delta z}(D_{ZT}C_T - 2D_{ZP}C_P + D_{ZB}C_B)} \quad 4.16\ \text{A}$$

With

$$\mathbf{V_t = \frac{\Delta t}{\Delta x \Delta z}} \quad 4.16\ \text{b}$$

$$\mathbf{M_{XE}\delta_z = m_{XE} \qquad M_{ZT}\delta_x = m_{ZT} \qquad M_{FT}\delta_x = m_{FT}}$$
$$\mathbf{|M_{XP}|\delta_z = m_{XP} \qquad |M_{ZP}|\delta_x = m_{ZP} \qquad |M_{FP}|\delta_x = m_{FP}} \quad 4.16\ \text{c}$$
$$\mathbf{M_{XW}\delta_z = m_{XW} \qquad M_{ZB}\delta_x = m_{ZB} \qquad M_{FB}\delta_x = m_{FB}}$$

With

$$\boldsymbol{\delta}_{\mathbf{x}} = \frac{\mathbf{\Delta x}}{\mathbf{2}} \textbf{ and } \boldsymbol{\delta}_{\mathbf{z}} = \frac{\mathbf{\Delta z}}{\mathbf{2}}$$

$$\frac{\mathbf{\Delta z}}{\mathbf{\Delta x}}\mathbf{D_{XE}C_E} = \mathbf{Diff_{XE}}\ \frac{\mathbf{\Delta x}}{\mathbf{\Delta z}}\mathbf{D_{ZB}C_T} = \mathbf{Diff_{ZT}}\ \frac{\mathbf{\Delta z}}{\mathbf{\Delta x}}\mathbf{D_{XP}C_P} = \mathbf{Diff_{XP}} \qquad 4.16\text{ d}$$

$$\frac{\mathbf{\Delta z}}{\mathbf{\Delta x}}\mathbf{D_{XW}C_W} = \mathbf{Diff_{XW}}\ \frac{\mathbf{\Delta x}}{\mathbf{\Delta z}}\mathbf{D_{ZB}C_B} = \mathbf{Diff_{ZB}}\quad \frac{\mathbf{\Delta x}}{\mathbf{\Delta z}}\mathbf{D_{ZP}C_P} = \mathbf{Diff_{ZP}} \qquad 4.16\text{ e}$$

$$\begin{aligned}\frac{\mathbf{C_P^{t+1}} - \mathbf{C_P^{t-1}}}{\mathbf{V_t}} &+ (\mathbf{m_{XE}} - \mathbf{m_{XP}} + \mathbf{m_{XW}}) + (\mathbf{m_{ZT}} - \mathbf{m_{ZP}} + \mathbf{m_{ZB}})\\ &+ (\mathbf{m_{FT}} - \mathbf{m_{FP}} + \mathbf{m_{FB}})\\ &= (\mathbf{Diff_{XE}} - \mathbf{2Diff_{XP}} + \mathbf{Diff_{XW}}) + (\mathbf{Diff_{ZT}} - \mathbf{2Diff_{ZP}} + \mathbf{Diff_{ZB}})\end{aligned} \qquad 4.17\ \text{A}$$

$$\begin{aligned}\mathbf{C_P^{t+1}} = \mathbf{C_P^{t-1}} - \mathbf{V_t}[&(\mathbf{m_{XE}} - \mathbf{Diff_{XE}}) + (\mathbf{m_{XW}} - \mathbf{Diff_{XW}}) + (\mathbf{m_{ZT}} + \mathbf{m_{FT}} - \mathbf{Diff_{ZT}})\\ &+ (\mathbf{m_{ZB}} + \mathbf{m_{FB}} - \mathbf{Diff_{ZB}})\\ &+ (\mathbf{m_{XP}} + \mathbf{m_{ZP}} + \mathbf{m_{FP}} + \mathbf{2Diff_{XP}} + \mathbf{2Diff_{ZP}})]\end{aligned} \qquad 4.17\ \text{b}$$

b) Numerical approach and convergence criterion

For the equations in stream function and vorticity form (equations (4.4) and (4.5)), an iterative method was implemented by using the method of Gauss-Seidel resolution (TDMA: Tridiagonal Matrix Algorithm) as described by Patankar (1980). The convergence criterion ϵ is:

$$\boldsymbol{\epsilon} = \left|\frac{\boldsymbol{\phi} - \boldsymbol{\phi}_{\mathbf{P}}^{'}}{\mathbf{max}(\boldsymbol{\phi})}\right| \leq \mathbf{10^{-5}} \qquad 4.18$$

Where ϕ is the variable calculated at the current time while $\phi_P^{'}$ is the variable calculated at the previous iteration step. The convergence obtained for had to be lower than 10^{-5}. For the transport equation or mass conservation equation above, we used an explicit iteration scheme in order to deal with CB density and buoyancy change at any time according to the light intensity (phototaxis effects) in each control volume in the studied area, because the process becomes unstable when using the implicit scheme.

4.9.3 Validation benchmarking

The accuracy and precision of the model were evaluated. Unstable and divergent situations caused by the pressure in Navier-Stokes equation for most numerical frameworks using an eulerian approach have been avoided in our model due to the form of the vorticity equation. We validated our model first by using analytical results obtained from Li and Zhang(1993). Thus, the vertical profile of the *u*-component of fluid velocity in the center of a rectangular basin with a *2000 m X 2000 m* of surface area and *10 m* of depth may be calculated from the equation below:

$$\mathbf{u=\tau_x^s\,\sigma\,(h+\eta)(3\sigma-2)/4\varepsilon_v\rho_w} \qquad 4.19$$

with

$$\mathbf{\sigma= (h+\Delta z)/(h+\eta)} \qquad 4.20$$

where **u***:* horizontal velocity in the x direction *(m s^{-1});* **h**: water depth*(m);* **η**: free surface water elevation above the water depth (m); ε_v: vertical diffusivity coefficient *(0.01 m^2/s); :* water density*(1000 kg m^{-3})*; **Δz**: vertical grid size *(m).*

Data used in our model are the wind stress of 0.75 *N m^{-2}* and mesh size **Δx**=*100m* on a total length of *2000m*. The model was simulated for two cases with the water depth of 10m: case 1 with **Δz**=*0.5m*; case 2 with **Δz**=*1m* and the time step **Δt**=*5*seconds.

Water movement patterns were validated and the results are shown in **Figure 4.7a** and **b**.

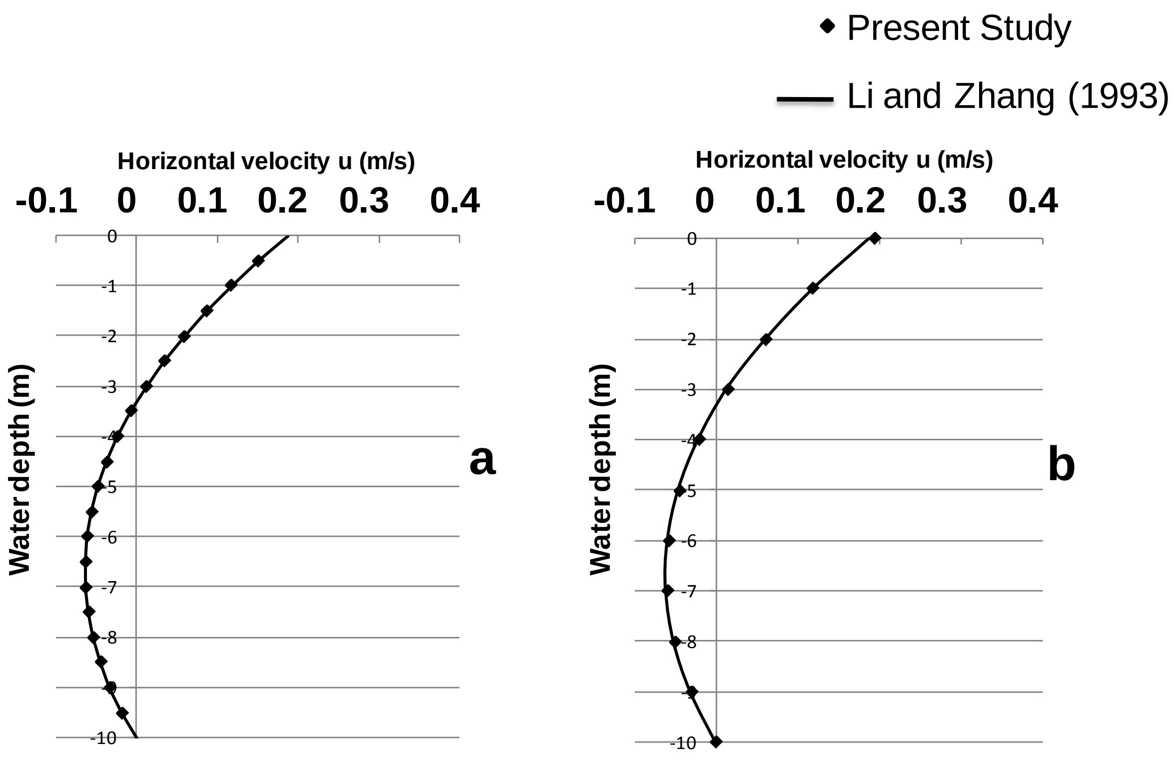

Figure 4.7: Model comparaison-horizontal velocity u (m/s) at the center of cavity a) dz=0.5 (vertical spatial step) and b) dz=1 (vertical spatial step)

By comparing the analytical solutions of Li and Zhang (1993) with our numerical results, an excellent fit was observed (**Table 4.1** and **Table 4.2**). The accuracy and precision of numerical results depends strongly on the mesh dimensions. Error ranks between our numerical simulations and analytical results by Li and Zhang (1993) are indeed much lower for a finer meshing. Results presented in **Table 4.1** and **Table 4.2** show that the refinement of the mesh tends to increase the model accuracy and precision.

Table 4.1: Model comparaison: Error value for dz=1

Depth (m)	Li and Zhan Formula	Present Study	Error
0	0.1875	0.1943	4%
-1	0.1181	0.1193	1%
-2	0.0600	0.0613	2%
-3	0.0131	0.0146	11%
-4	-0.0225	-0.0209	7%
-5	-0.0469	-0.045	4%
-6	-0.0600	-0.058	3%
-7	-0.0619	-0.0596	4%
-8	-0.0525	-0.0501	5%
-9	-0.0319	-0.0292	8%

Table 4.2: Model comparaison: Error value for dz=0.5

Depth(m)	Li and Zhan Formula	Present Study	Error
0	0.1875		
-0.5	0.1514	0.1519	0%
-1	0.1181	0.1186	0%
-1.5	0.0877	0.0881	1%
-2	0.0600	0.0605	1%
-2.5	0.0352	0.0356	1%
-3	0.0131	0.0136	4%
-3.5	-0.0061	-0.0056	8%
-4	-0.0225	-0.0220	2%
-4.5	-0.0361	-0.0356	1%
-5	-0.0469	-0.0464	1%
-5.5	-0.0548	-0.0544	1%
-6	-0.0600	-0.0595	1%
-6.5	-0.0623	-0.0619	1%
-7	-0.0619	-0.0614	1%
-7.5	-0.0586	-0.0581	1%
-8	-0.0525	-0.0520	1%
-8.5	-0.0436	-0.0431	1%
-9	-0.0319	-0.0314	1%
-9.5	-0.0173	-0.0169	3%

4.9.4 Phototaxis behavior of cyanobacteria buoyancy

The enhanced approach to calculate the velocity of CB as a function of light proposed by Visser et al.(1997) was selected for this study. Although, the Lagrangian approach is interesting for studying the movement of cells, an eulerian approach enables us to explore the temporal spatial distribution of cells in relation to specific points of interest, for example, a drinking water intake.

We used the model proposed by Visser et al.(1997). By using a sinusoidal function for light intensity and an extinction coefficient, light intensity at the surface and in the water column was calculated using the following equation:

$$\mathbf{I_{surf}=I_m\times sin[(\pi\times t)/(D_L\times 60)]} \qquad 4.21$$

Where I_{surf} is the photon irradiance on the surface at different times t (µmol photons m^{-2} s^{-1}); I_m is the maximum value of photon irradiance at noon (µmol photons $m^{-2}s^{-1}$); **t** is the time (min) and D_L is the length of the photoperiod (hour).

$$\mathbf{I_z=I_{surf}\times e^{-(\varepsilon\times z)}} \qquad 4.22$$

Where I_z is the photon irradiance at the depth of the cyanobacterial colony (µmol photons $m^{-2}s^{-}$ 1); **ε** is the extinction coefficient of the water (m-1) and **z**is the depth of the colony (m). In this study **ε** was assumed to be approximately 1.25 m^{-1}

Under laboratory conditions, Visser et al. (1997) found that the CB behaviour changes when they are exposed to light intensity above or under the compensation value defined as the value where plankton respiration is equal to primary production, and the rate of density change is given by two conditions:

$$\mathbf{If\ I_z\leq I_c\ \Delta\rho_{col}=-f_1\times(\rho_{col_1}^{-})+f_2} \qquad 4.23$$

$$\mathbf{If\ I_z>I_c\ \Delta\rho_{col}=\left(N_0/60\right)\times e^{I_z/I_0})+f_3} \qquad 4.24$$

Where I_c is the compensation photon irradiance (10.9 µmol photons $m^{-2}s^{-1}$); $I_0$is the intensity where I_z is maximum (277.5 µmol photons $m^{-2}s^{-1}$); N_0 is the normative factor (0.0945 kg m^{-3}µmol^{-1} photons m^2); I_z is the photon irradiance (µmol photons $m^{-2}s^{-1}$); $\Delta\rho_{col}$ is the rate of density change (kg m^{-3} min^{-1}) at photon irradiance I_z; $\rho_{col_1}{}^{-}$ is the initial density (kg m^{-3}); f_1 is the slope (9.49 $10^{-4}min^{-1}$); f_2 is the theoretical rate of density change with no carbohydrate storage in the cells(0.984 kg m^{-3} min^{-1}) and f_3 is the rate of density change at I_z=0 (-0.0165 kg m^3 min^{-1}).

In order to update the current density, equation (4.25) is used:

$$\boldsymbol{\rho_{col_2}{}^{-}=\rho_{col_1}{}^{-}+\Delta t\times\Delta\rho_{col}} \qquad 4.25$$

Where $\rho_{col_2}{}^{-}$ is the new density of CB (kg m^{-3});$\rho_{col_1}{}^{-}$ is the previous density of CB (kg m^{-3}) and Δt is the time step (min).

Equation (4.25) was obtained through experiments on CB without gas vesicles, thus, a correction is made in order to obtain the real density using the following equation Visser et al. (1997):

$$\boldsymbol{\rho_{col}=\rho_{col_2}{}^{-}+CorFact} \qquad 4.26$$

Where ρ_{col} is the real density of CB (kg m^{-3}) and CorFact is the factor correction (65 kg m^{-3}).

Finally, F (m s^{-1}) the sinking velocity as a function of CB buoyancy is given by Stokes' law:

$$\boldsymbol{F=\frac{2gr^2A\left(\rho_{col}-\rho_w\right)}{9\Phi\mu}} \qquad 4.27$$

g is the gravitational acceleration (9.8 m s^{-2}); **r** is the effective radius of the colony (m); A is the proportion of cell volume relative to colony volume; ρ_w is the water density (1000 kg m^{-3}); **Φ** is the form resistance and **µ** is the viscosity of the water (10^{-3} kg m^{-1} s^{-1}).

In order to ensure that the CB model is based on physical reality, the minimum and maximum densities are used as boundaries. These values are:

Minimum buoyancy density=920 kg/m^3

Maximum buoyancy density=1065 kg/m^3

By taking into account the temporal delay, Wallace and Hamilton (1999) related the rate of change of density to changing light intensity. This consideration has been introduced by incorporating the following expression:

$$\mathbf{G(t) = 1 - e^{-(t/\tau_r)}} \qquad 4.28$$

Where t is the time and τ_r is the response time.

Finally equations 4.23 and 4.24 have been written in the following forms:

$$\textbf{If } \mathbf{I_z \le I_c} \ \Delta\boldsymbol{\rho}_{\mathbf{col}} = \left[-\mathbf{f_1} \times (\boldsymbol{\rho}_{\mathbf{col_1}}{}^{-}) + \mathbf{f_2} \right] \times \mathbf{G(t)} \qquad 4.29$$

$$\textbf{If } \mathbf{I_z > I_c} \ \Delta\boldsymbol{\rho}_{\mathbf{col}} = \left[\left(\mathbf{N_0}/\mathbf{60} \right) \times \mathbf{e}^{\mathbf{I_z}/\mathbf{I_0}}) + \mathbf{f_3} \right] \times \mathbf{G(t)} \qquad 4.30$$

In their study using the Kromkamp and Walsby(1990) model, Wallace and Hamilton(1999) suggested that the time response (τ_r) is around 20 mins for $\mathbf{I_z > I_c}$and suggest a time response of 4 minutes for $\mathbf{I_z > I_c}$for the model of Visser et al.(1997).

For the case when $\mathbf{I_z \le I_c}$, the response time is not clearly defined. We conducted numerical tests for the time response when $I_z \le I_c$ in order to calibrate the model with raw water data collected at the water intake.

Missisquoi Bay is a large bay (77.5 km^2 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 (**Figure 4.8**). A detailed description of Missisquoi Bay and available phycocyanin probe monitoring data are provided by Ndong et al. (2014a). Missisquoi Bay is shallow with a mean depth of 2.8 m(Galvez & Levine, 2003), thus the wave base can be deep enough to cause mixing of bottom sediments in areas without rooted aquatic vegetation (Keleti et al., 1979).

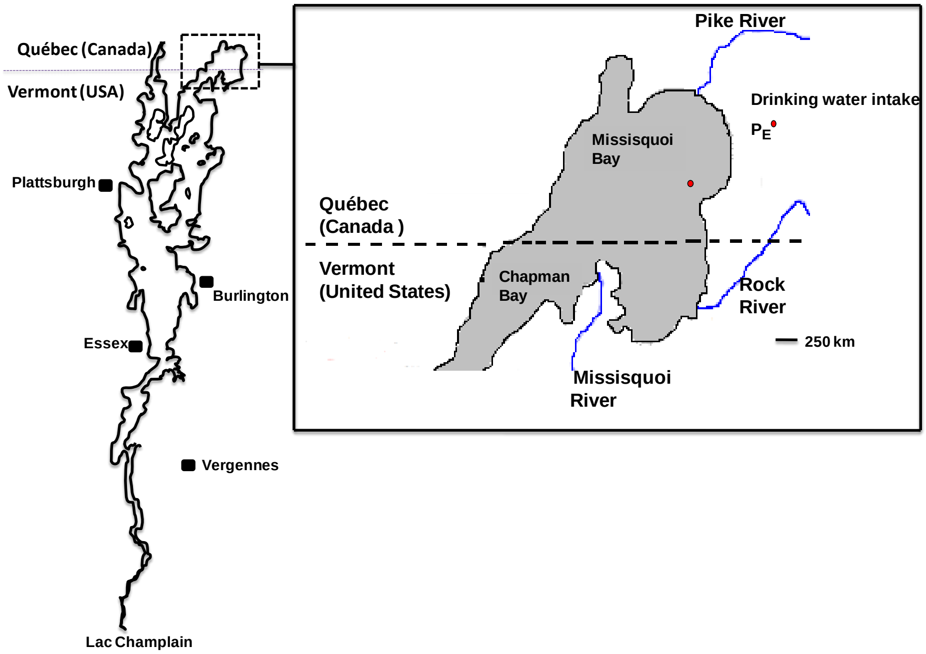

Figure 4.8: Missisquoi Bay with drinking water intake position (PE) in Lac Champlain

4.9.5 Meteorological data collection

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. (2014a).

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CHAPITRE 5 ARTICLE 3: THERMAL STRATIFICATION AND WATER COLUMN STABILITY EFFECTS ON CYANOBACTERIA DISTRIBUTION IN A DRINKING WATER SOURCE

Ce chapitre présente les résultats de la modélisation de la distribution de la température dans la colonne d'eau en utilisant des données météorologiques réelles. A travers cette étude, l'effet de la stratification thermique et de la stabilité de la colonne d'eau sur la distribution spatio-temporelle des CB est explorée. Ce chapitre est une suite du chapitre précédent visant à mieux comprendre les facteurs qui influencent le comportement des cyanobactéries dans une colonne d'eau. Ce chapitre a été soumis à *Water Research* en septembre 2014.

THERMAL STRATIFICATION AND WATER COLUMN STABILITY EFFECTS ON CYANOBACTERIA DISTRIBUTION IN A DRINKING WATER SOURCE

[a]Mouhamed Ndong, [b]David Bird, [c]Tri Nguyen-Quang, [a]Marie-Laure de Boutray, [a]René Kahawita, [a]Michèle Prévost, [a]Sarah Dorner

a. Department of Civil, Geologic and Mining Engineering. École Polytechnique de Montréal, C.P. 6079, succ. Centre-ville, Montréal (Québec), Canada, H3C 3A7

b. Department of Biological Sciences, Université du Québec à Montréal, C.P. 8888, succ. Centre-ville, Montréal (Québec), Canada, H3C 3P8

c. Department of Engineering, Faculty of Agriculture, Dalhousie University, PO Box 550, Truro-Bible Hill (Nova Scotia), Canada, B2N 5E3

5.1 Abstract

Cyanobacteria (CB) outbreaks have become more frequent as a result of nutrient enrichment and increasing global temperatures. Within a system, physical factors play a role on a shorter term, including variable solar irradiance, thermal stratification, wind speed and direction, as well as eco-physiological responses such as buoyancy regulation. The effects of thermal stratification on CB distribution and bloom formation have been well described. However, some water bodies can present weak or no thermal stratification. The ecological implications of water column stability related to wind speed intensity need to be explored. To investigate the effects of water column stability on the distribution of CB, a novel deterministic model integrating the dominant processes associated with cyanobacteria movement and transport in surface waters was developed. The model considered CB buoyancy changes in response to light history and intensity. Meteorological and CB data from Missisquoi Bay (Québec, Canada) were used to explore the effects of temperature distribution, irradiance penetration in the water column and wind leading to water column stability. Observed and simulated results demonstrated that the thermal stratification was not strong, as is typical of large, shallow water bodies. In this case, the lack of turbulence, induced by low wind speed, becomes an important process that can lead to CB blooms. A wind speed range above 3 m/s led to stable water column conditions favourable for CB dominance. Weak thermal stratification with optimal water temperatures facilitates their dominance by enabling CB to maintain the same temperature-dependent growth conditions throughout the entire water column.

Keywords: hydrodynamic modeling, cyanobacteria, temperature, thermal stratification, drinking water

* Corresponding author Phone: 514-340-4711 extension 2983; Fax: 514-340-5918

E-mail: mouhamed.ndong@polymtl.ca

* Corresponding author. Current address: École Polytechnique de Montréal, Department of Civil, Geological and Mining Engineering, P.O. Box 6079, Station Centre-ville, Montreal, Quebec, Canada, H3C 3A7

5.2 Introduction

Surface waters are increasingly threatened by cyanobacteria (CB) occurrences as a result of local-to-global disruptions of elemental cycles such as carbon, nitrogen and phosphorus (Moroney & Somanchi, 1999). CB and their toxic metabolites can pass into drinking water treatment plants (Zamyadi et al., 2012), negatively impact the health of recreational water users (Lévesque et al., 2014), or result in the death of animals directly consuming the water (Gunn et al., 1992), among other concerns. The factors that control CB blooms are nutrient availability, primarily nitrogen and phosphorus, as well as water temperature, availability of solar irradiance, wind mixing, and water body stratification. Among these factors, the surplus of nutrients (phosphorus and nitrogen) has generally been identified as the primary cause of widespread CB blooms (Bergström, 2010; Smeltzer et al., 2012; Smith, 1986; Wang et al., 2002). Through its impacts on the controlling factors, climate change is expected to increase the frequency of CB occurrence (Carey et al., 2012; Paerl & Paul, 2012a; Paerl & Huisman, 2009).

Climate change implies changing precipitation patterns and increased temperatures. In temperate regions, these factors could favour a larger phytoplankton biomass peak (De Senerpont Domis et al., 2013). Increased and intensified precipitation induces an increase of nutrient loads in the water body (King et al., 2007). These nutrient loads combined with (or originating from) climate change could contribute to CB dominance (Jones et al., 2005). Elevated temperature is considered as a primary factor for bloom occurrence. In general, CB biomass increases with temperature (Kosten et al., 2011) and growth is optimal during periods of high temperature (usually when the temperature exceeds 25^{o}C) (Coles & Jones, 2000; Rapala, 1998; Robarts & Zohary, 1987). *Microcystis* spp. lose their buoyancy in the temperature range from 12^{o}C to 18^{o}C (Reynolds, 2006). Higher temperatures favour CB blooms when they are in competition with other phytoplankton species (Jöhnk et al., 2008).

Under the influence of solar radiation and warm air, water temperature can form a gradient within the water column, leading to thermal stratification. It can be persistent (Westwood & Ganf, 2004) and permit vertical variation of phytoplankton composition (Halstvedt et al., 2007; Koreiviene & Karosiene, 2012). In particular, a stable water column permits CB species that can control their buoyancy, including *Microcystis* and *Anabaena*, to outcompete others for light (Paerl, 1988), and at the same time, to exploit the internal sources of phosphorus and nitrogen, released within the hypolimnion (Bormans et al., 1999; Sondergaard et al., 2003). In eutrophic lakes, CB proliferation is enhanced by phosphorus release from sediments during anoxia (Journey et al., 2013; Nürnberg, 1996). Thermal stratification is under the control of lake morphometry (Bilinska, 2005) and stratification is rarely observed in shallow water bodies (Rucker et al., 1997). Where thermal stratification does not occur, the ecological implications for CB distribution and bloom formation have not been explored in the literature.

Mixing prevents bloom formation and reduces the growth of bloom forming species (1983). CB scum formation at the water surface is favoured by weaker winds (<3 m/s) that do not disrupt water stability (Cao et al., 2006). Thus, in order to address the knowledge gap in the literature concerning weak thermal stratification occurrence in shallow waters, we initiated this study with the following specific objectives: 1) to identify the conditions under which weak or absent stratification can be observed in a shallow lake by modeling, 2) to validate this understanding using recorded water temperature data, 3) to discuss the ecological implications of the presence or absence of thermal stratification for CB bloom occurrence, 4) to investigate CB behaviour and distribution and compare our model to full-scale field data recorded in the water column for different bloom conditions, and 5) to identify critical monitoring parameters needed for future studies.

5.3 Methodology

Theoretical calculations

Water motion and CB buoyancy control the distribution of CB through their effects on advection and vertical velocity induced by changes in specific density (Kromkamp & Walsby, 1990; Reynolds et al., 1987; Thomas & Walsby, 1985; Visser et al., 1997). Two equations govern the hydrodynamic effects:

Continuity

$$\boldsymbol{\nabla . \mathrm{V} = 0} \qquad 5.1$$

Momentum

$$\rho_w \frac{\partial V}{\partial t} + \rho_w \nabla.(VV) = -\nabla p + \nu \nabla^2 V + \rho \vec{g} \qquad 5.2$$

Where V is the velocity of fluid (m/s); ***p*** is the dynamic pressure (Pa); **ρ** is the suspension density (kg/m^3); ρ_w is the water density (kg/m^3); ***g*** is the gravitational acceleration (m^3/s), **ν** is water viscosity and t is the time (s). Numerical validation for the fundamental hydrodynamic model is available in (Ndong et al., 2014b).

The buoyancy effect is taken into account in the CB transport equation as presented in the following equation:

$$\frac{\partial C}{\partial t} + \frac{\partial(uC)}{\partial x} + \frac{\partial[(w+F)C]}{\partial z} = \frac{\partial^2(D_X C)}{\partial x^2} + \frac{\partial^2(D_Z C)}{\partial z^2} \qquad 5.3$$

Where C is the concentration of CB cells or phytoplankton (cell/m^3), *u*, *w* correspond respectively to the two components of water velocity (m/s) in the horizontal (x) and vertical (z) directions, F is CB cells buoyancy (m/s) and D_x and D_z are the horizontal and vertical diffusivity coefficients (m^2/s), respectively.The CB transport equation treatment with CB buoyancy are described in detail in Ndong et al. (2014b) which is the first model to consider at a full scalethe effects of buoyancy in relation to phototaxis. The upward movement is related to the cells' buoyancy as a function of light rather than as a process related to resuspension due to critical shear stress.

Equations 1 through 3 are mainly related by the water velocity. Many other relationships exist among variables but were not considered in this study. Examples of relationships among other variables include density change induced by temperature and cyanobacteria concentration (Nguyen-Quang & Guichard, 2010), temperature and cyanobacteria effects on water viscosity, and the effects of viscosity on cyanobacteria velocity. However, to our knowledge, there have been no studies examining or quantifying the relationships among these factors.

Water temperature: Conceptual approach and assumptions

CB behaviour in a water body is affected by the hydrodynamics of water movement and their own properties of buoyancy from changes to their density, according to their exposure to or exclusion from light. Water movement and buoyancy changes are both influenced by temperature through water density and viscosity. From the Navier-Stokes equation, it can be deduced that a large vertical gradient of water density changes in a water column can affect surface water hydrodynamics. The influence of viscosity on CB is observed in the CB buoyancy model (Kromkamp & Walsby, 1990; Visser et al., 1997; Wallace et al., 2000) where CB moving velocity is calculated assuming the validity of Stokes' law.

Water temperature is affected by the net heat flux from solar radiation (Shanahan, 1985). It is modelled by using the transport equation and taking account solar radiation as the source of energy as shown in equation 4. The form of the transport equation for temperature including heat balance is described as follows:

$$\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} + \boldsymbol{\nabla}(\boldsymbol{VT}) = \boldsymbol{D}\boldsymbol{\nabla}^{2}\boldsymbol{T} + \frac{\mathbf{1}}{\boldsymbol{\rho C_p}} \times \frac{\partial \boldsymbol{Qz}}{\partial \boldsymbol{z}} \qquad 5.4$$

Where T is the water temperature (^{o}C); V is the fluid medium velocity, **ρ**is the water density, Cp is the specific heat of water (J/kg.K), D is the coefficient of diffusion de la temperature (m^{2}/s) and Qz is the solar radiation penetrating into water (W/m^{2}).

The penetration of solar radiation (**Qz**)into the water column is obtained by using the Beer-Lambert law (Lap & Mori, 2007):

$$\boldsymbol{Qz} = \boldsymbol{Qs} \times \boldsymbol{e}^{-\boldsymbol{\varepsilon}\times\Delta \boldsymbol{z}} \qquad 5.5$$

Where**ε**is the extinction coefficient per m of the water column. In this study **ε**was assumed to be approximately1.25 m^{-1}.

Short wave solar radiation from 300 to 3000 nm(**Qsw)** and net atmospheric long wave radiation from 3 to 10 µm (**Qatm)** will penetrate the water column, such that **Qs=Qsw+Qatm**

Long and short wave radiation can be calculated through the following equations:

Short wave radiation(Lap & Mori, 2007):

$$\boldsymbol{Qsw} = (\mathbf{1} - \boldsymbol{Fa}) \times \left(\boldsymbol{PAR} \times \frac{\boldsymbol{\alpha}}{\boldsymbol{\beta}}\right) \qquad 5.6$$

Fa (surface albedo) is the fraction of the solar shortwave radiation that is reflected immediately at the surface (0.65)

α is the coefficient to convert PAR in µmol/m^{2}s into W/m^2 (0.219) **β** is the coefficient to convert PAR (W/m^2) into short wave radiation which was assumed to be around 50% to 65% (0.50 value in this study).

Net atmospheric long wave radiation:

$$\boldsymbol{Qatm} = \boldsymbol{Ce} \times (\mathbf{1} - \boldsymbol{RL}) \times (\mathbf{1} - \mathbf{0.17} \times \boldsymbol{CL}^{\mathbf{2}}) \times \boldsymbol{\sigma} \times (\boldsymbol{Ta} + \mathbf{273.16})^{\mathbf{4}} \qquad 5.7$$

Where Ce is a constant value (9.37.10^{-6}), RL is the reflectivity of water (0.03); CL is the fraction of sky covered by clouds, $\boldsymbol{\sigma}$ is the Stefan-Boltzmann constant (5.6697·10^{-8} W /m^2.K^4), Ta represents air temperature above the water's surface (^{o}C).

For calculated cloud cover fraction, the following formula proposed by Ek and Mahrt (1991)was used:

$$\boldsymbol{CL} = \begin{cases} \left(\dfrac{\mathbf{RH_{850}} - \boldsymbol{RHc}}{\mathbf{1} - \boldsymbol{RHc}}\right)^{xp} & \boldsymbol{if} \quad \dfrac{\mathbf{RH_{850}} - \boldsymbol{RHc}}{\mathbf{1} - \boldsymbol{RHc}} > 0 \\ \mathbf{0} & \boldsymbol{if} \quad \dfrac{\mathbf{RH_{850}} - \boldsymbol{RHc}}{\mathbf{1} - \boldsymbol{RHc}} \leq \mathbf{0} \end{cases} \qquad 5.8$$

Where RHc is a critical relative humidity at which cloud assumed to form and xp is a constant parameter. Their values are: RHcrit= 0.85 and xp = 2 (Grabowska & Mazur-Marzec, 2014).

The equation (5.8) is a formulation of cloud cover which is based on the fractional relative humidity ($\mathbf{RH_{850}}$) near the top of the boundary layer. It has been establish at layer 850 mb (altitude 1500 m). In order to use it, we apply a correction by calculated the relative humidity at this layer (**$\mathbf{RH_{850}}$)** by using air temperature and relative humidity recorded by our meteorological station. The following equations are used to calculate **$\mathbf{RH_{850}}$:**

$$\boldsymbol{Es = 6.1121 \times e^{\frac{Ta \times \frac{18.678 - Ta}{234.5}}{254.14 + Ta}}} \qquad 5.9$$

$$\boldsymbol{Ea = \frac{Es \times RH}{100}} \qquad 5.10$$

$$\boldsymbol{q = \frac{0.622 \times Ea}{P - 0.378 \times Ea}} \qquad 5.11$$

Where q is the specific humidity, Ea is the air vapor pressure (hPa) and Es is the saturation vapor pressure of air at the temperature of the surface water (hPa).The air temperature at 850 mb (altitude h=1500m) is calculated by using the equation:

$$\mathbf{Ta_h = Ta - 6.5 \frac{h}{1000}} \qquad 5.12$$

Where Ta_h is the air temperature at altitude (h) and Ta is the air temperature at ground level (measured with our meteorological station).

The equation (5.9) is used to calculated the air vapor pressure at saturation at an altitude of 1500m (850mb) and equation (5.11) gives the specific humidity at saturation at this layer ($q_{s_{850}}$) by changing Ea by Es. Finally, the relative humidity is:

$$\mathbf{RH_{850} = \frac{q}{q_{s_{850}}}} \qquad 5.13$$

Boundary conditions:

- *Hydrodynamic boundary conditions:*

These hydrodynamic conditions are the same mentioned in Ndong et al. (2014b). Vorticity(ξ) and stream ($\boldsymbol{\varphi}$) functions are used and at the water surface the boundary conditions are expressed as:

$$\begin{cases} \boldsymbol{\varphi_s = 0} \\ \boldsymbol{\xi_s} = \dfrac{\boldsymbol{\tau_x^s}}{\boldsymbol{\Gamma_x \rho_w}} \end{cases} \tag{5.14}$$

Where $\boldsymbol{\varphi_s}$is the surface stream, $\boldsymbol{\xi_s}$ is the surface vorticity, τ_x^s is the surface wind stress (N m^{-2}), Γ_x is the horizontal diffusivity coefficient (m^2/s) and $\rho_w$is the water density (kg/m^3).

- *At a closed boundary, the vorticity is null (ξ=0) and the stream is expressed by:*

$$\begin{cases} \dfrac{\partial^2 \varphi}{\partial x^2} = 0 & \textbf{at left and right boundaries} \\ \dfrac{\partial^2 \varphi}{\partial z^2} = 0 & \textbf{at bottom} \end{cases} \tag{5.15}$$

Where x, z are respectively the horizontal and vertical Cartesian coordinates

- *boundary conditions for heat flux*

At the water surface, the heat loss flux must be taken into account. Surface water **Qs** is a function of short wave radiation (**Qsw)**, net atmospheric long wave radiation (**Qatm)**, long wave back radiation (**Qb)**, sensible heat flux from the water **(Lv)**, latent heat flux from the water **(Qlat)** as follows (Shanahan, 1985):

$$\boldsymbol{Qs = Qsw + Qatm - Qb - Lv - Qlat} \tag{5.16}$$

Long wave back radiation

$$\boldsymbol{Qb} = \in \times \boldsymbol{\sigma} \times (\boldsymbol{Tw + 273.16})^{\boldsymbol{4}} \tag{5.17}$$

Where ∈ is the emissivity (0.975) and Tw is the water surface temperature (^{o}C).

Sensible heat flux from the water

$$\boldsymbol{Lv = Cs \times Cp \times Uz \times \rho_a \times (Tw - Ta)} \tag{5.18}$$

Where Cs is a constant value ($1.45 \cdot 10^{-3}$), Uz is wind speed (m/s), ρa is the air density [kg/m^3] calculated with the equations:

$$\boldsymbol{\rho a} = \frac{\boldsymbol{P \times 100}}{\boldsymbol{Rd \times Tv}} \tag{5.19}$$

$$\boldsymbol{Tv = (Ta + 273) \times (1 \, + \, 0.61 \times q)} \tag{5.20}$$

$\boldsymbol{Rd}$ is the specific gas constant for dry air (287.05 J/kg/K) and $\boldsymbol{Tv}$ is a virtual temperature(°C) that represents the temperature of a quantity of dry air in the same condition of pressure and density as the same quantity of wet air, q is the specific humidity, Ea (air vapor pressure) and Es(saturation vapor pressure of air at the temperature of the surface water) are calculated through equation (5.9), (5.10) and (5.11) by changing $\boldsymbol{Ta}$ by $\boldsymbol{Tw}$

Latent heat flux from the water

Latent heat flux follows the relation:

$$\mathbf{Qlat = \rho a \times Lel \times Cel \times Uz \times (q \, - \, q_s)} \tag{5.21}$$

Where *Lel*= latent heat of vaporisation (as constant, Lel=2.5 10^6 J/kg), *Cel*= drag coefficient (as constant, Cel=1.2 10^{-3} J/kg), $\boldsymbol{q_s}$ is the specific humidity (kg water/kg air) for saturated air over water at surface temperature at Ta. It is calculated by using formula (5.9), (5.10) and (5.11).

Adiabatic conditions were applied in closed boundaries conditions in order to consider only the heat budget at the upper surface in the water column.

- *Boundary conditions for cyanobacteria*

The initial CB cell concentration was assumed to be 10 000 cells/mL that is the alert level 1 for CB occurrence at drinking water intake, representative of conditions in Missisquoi Bay (McQuaid et al., 2011). No other sources of cyanobacteria were considered. At closed boundaries conditions, it was expressed as a zero flux.

Study site: Missisquoi Bay, Québec, Canada

Missisquoi Bay is a shallow water body of Lake Champlain, a transboundary lake situated in Canada (Québec) and the United States of America (Vermont and New York). It is a large Bay (77.5 km^2 at the latitude and longitude coordinates of 45°01’37.63’’ North and -73°07’34.84’’ West) with a mean depth of 2.8 m.The bay’s morphological characteristics are described in detail in Ndong et al. (2014a). Missisquoi Bay is the source of drinking water for a population of approximately 4500 residents (Organisme de bassin versant de la baie Missisquoi, 2011). As with many surface water bodies, climate change, particularly rising temperatures, is affecting Missisquoi Bay. Jensen and Andersen(1992) suggested that in a shallow water body like Missisquoi Bay, higher temperatures at the sediment-water interface also leads to greater phosphorus release during the summer. Summer air temperatures increased at an annual average rate of 0.037^{o}C from 1976 to 2005 in Lake Champlain (Stager & Thill, 2010). A rising trend of water surface temperature during the month of August was noted from 1964 to 2009 in the same lake (Smeltzer et al., 2012).

Water density and viscosity variation as a result of temperature fluctuations were assumed to be small given that the model was applied to the summer and early fall season exclusively and were therefore not considered in the hydrodynamic and mass transport equations.

Sampling procedures and meteorological data collection

A multi-probe system from YSI (YSI, Yellow Springs, Ohio) as described by McQuaid et al. (2011) was installed inside the drinking water treatment plant intake in Missisquoi Bay to record temperature, conductivity, turbidity, pH, dissolved oxygen, chlorophyll fluorescence and phycocyanin fluorescence.

For phycocyanin analyses, water samples were collected once per week in the lake at the site of the drinking water intake. On each sampling date, water samples were collected in duplicate every meter in clean 500 mL plastic bottles for chemical analysis and biological extractions. The bottles were rinsed three times with sampled water before they were filled completely and tightly closed. All the samples were preserved on ice in coolers for transport and processed or prepared for storage (pigments) within 24 hours. Phycocyanin and chlorophyll analyses were performed with a Turner Designs 10AU™ Field Fluorometer (Turner Designs, Sunnyvale, CA, USA) using EPA Method 445.0 (Arar & Colling, 1997).

In 2011, a HOBO weather station (Onset Computer Corporation, Bourne, MA, USA) was installed directly at the drinking water treatment plant on the eastern shore of Missisquoi Bay to collect temperature, humidity, wind speed and direction, and photosynthetic active radiation (PAR) data. HOBO TempPro Loggers (0.2^{o}C accuracy) were installed to collect additional temperature data above the drinking water intake.

In order to investigate water temperature, light penetration and CB distribution in the water column, simulations were performed for the summer of 2011; three representative sampling days with different meteorological conditions are described in **Table 5.1**.

Table 5.1: Three representative sampling days at Missisquoi Bay, August 2011

	03 August 2011	***17 August 2011***	***23 August 2011***
Meteorological conditions	Little wind and partially cloudy	No cloud cover, ambient temperature around 28^{o}C, no wind, no rain	Windy, sunny, almost no cloud cover
Observations on the presence of CB at the drinking water treatment plant intake	No CB blooms were observed visually (Maximum phycocyanin: 2.9µg/L-PC; alert level was: Caution)*	A severe CB bloom occurred on this day (visual observation made) (Maximum phycocyanin: 40µg/L-PC; alert level was: Warning)*	No CB blooms were observe visually (Maximum phycocyanin:8.3µg/L-PC; alert level was: Caution)*

*The alert level to define a bloom was based on cyanobacteria monitoring with phycocyanin concentrations (µg/L) as proposed by Ahn et al. (2007) (No bloom : <0.1µg/L-PC; Caution: between 0.1µg/L and 30µg/L-PC; Warning: between 30 ug/L and 700ug/L-PC; Outbreak:> 700µg/L-PC).

These dates were selected based on the availability of data throughout the water column, as full water column data were available on a weekly basis from mid-July to the end of August in 2011.Water column profiles and samples were taken during the day at times ranging from 10:30 am to 12:00pm using the YSI multi-probe, or as described above. Weekly data were available for the entire season from the drinking water intake, which rests on the lake bottom; these were presented in Ndong et al. (2014a).

5.4 Results

5.4.1 Temperature modeling

A good temperature model is important when considering temperature dependent processes such as CB growth, water density and viscosity changes. In this study, these coupled processes were not considered and the temperature was modelled as a critical first step in the development of a complete coupled hydrodynamic CB transport model. In addition, the model provides detailed results of thermal stratification for periods without measured temperature data and provides a description of fundamental processes governing the movement of CB in surface waters. As such, the model provides a physically realistic prediction of the vertical temperature profile throughout the critical bloom period. The results in **Figure 5.1b** and **c** show that water temperature modeling at the drinking water intake at Missisquoi Bay was in good agreement with measured data. Relative errors were less than 10% (**Figure 5.1c**) recorded just once during the entire simulation (20 days) with a time step of 5seconds). We can observe thermal stratification during some days when water temperature recorded at the surface are high (4th-5th August and 8 th-9th August 2011) (**Figure5.1a**), but there were more days with a weak (or no) thermal stratification.

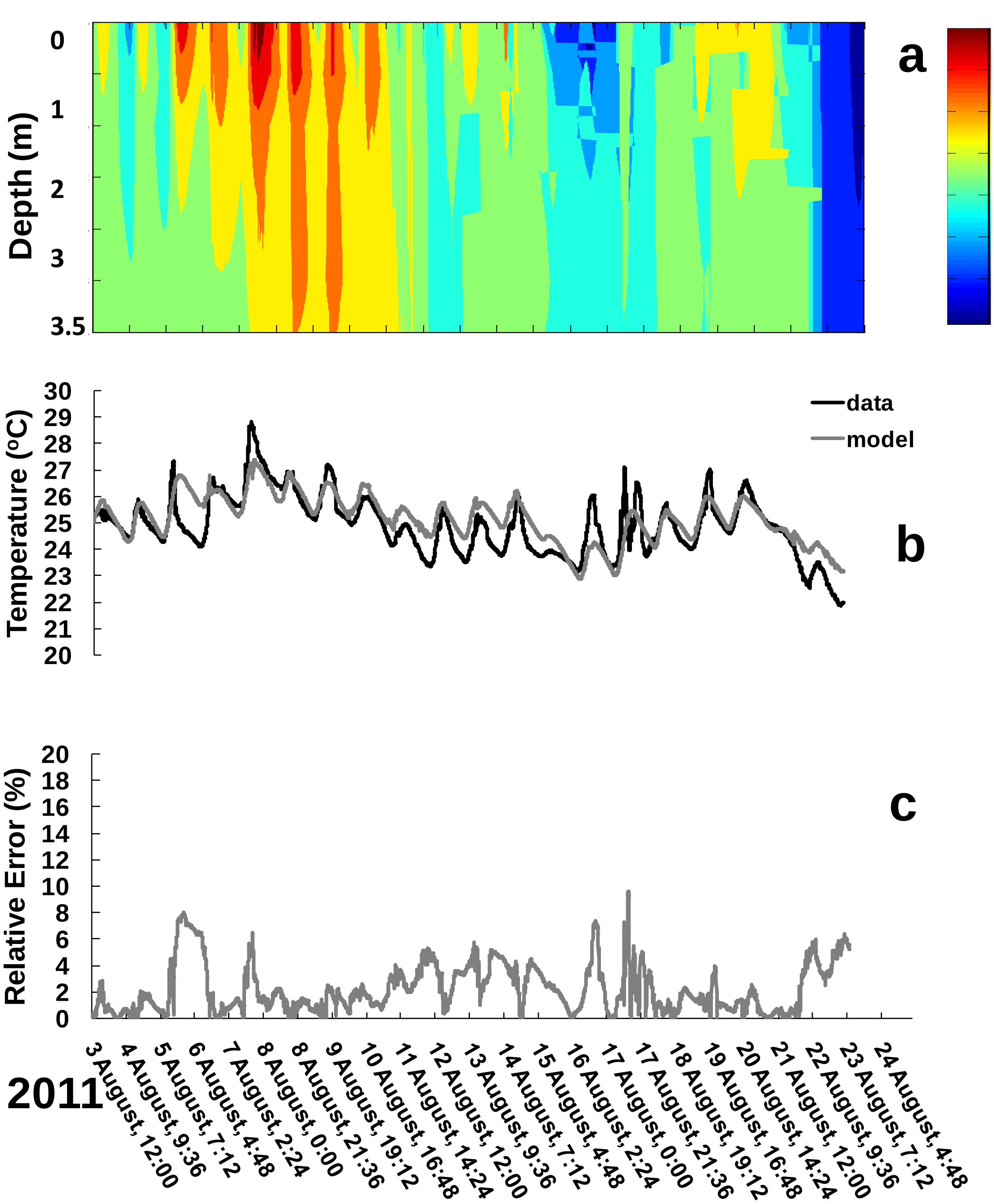

Figure 5.1: Time series: a) Simulated profile of temperature in water column; b) measured temperature (data) and simulated temperature (model) at the surface water above the drinking water intake c) Relative error between measured data and model results

Vertical temperature profile presents weak to no stratification for the days of August 3rd 2011, August 17th 2011 and August 23rd 2011 (**Figure 5.2**). The differences between model results and measured data were less than 1.5°C. A weak (or no) thermal stratification and similar range of temperature were observed during these three days with adequate temperatures for CB growth. It was observed that during these days (**Figure 5.2a, b** and **c**), water temperature was around 22°C to 25°C. However, only the 17thof August 2011 had a visible CB bloom at the surface (**Table 5.1**). Furthermore, the physiological behaviour of CB affected by light intensity should be the same during all the three sampling days because there were no significant differences in light penetration throughout the water column among the three sampling days (**Figure 5.2**).

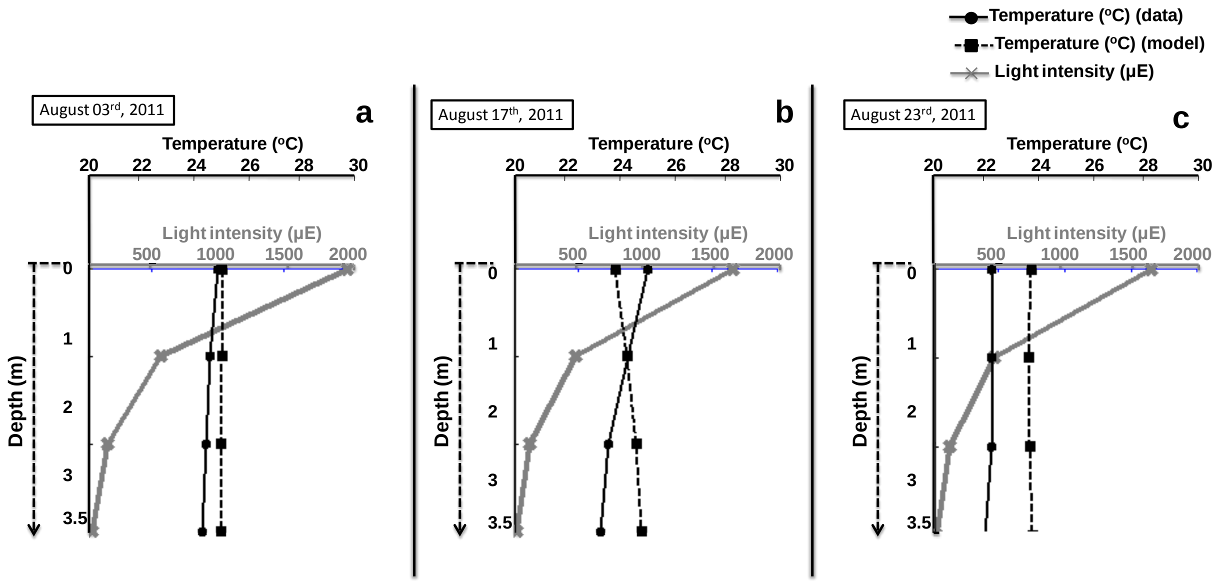

Figure 5.2: Light penetration in water column and temperature (model result vs collected data) during three sampling days: a) August 03rd, 2011, b) August 17th, 2011 and c) August 23rd, 2011

5.4.2 Wind effects

Although simulations were performed for the entire season, results are presented for three different days, the 3rd, 17th and 23rdof August 2011, representing three contrasting wind conditions at Missisquoi Bay (**Figure5.3**).

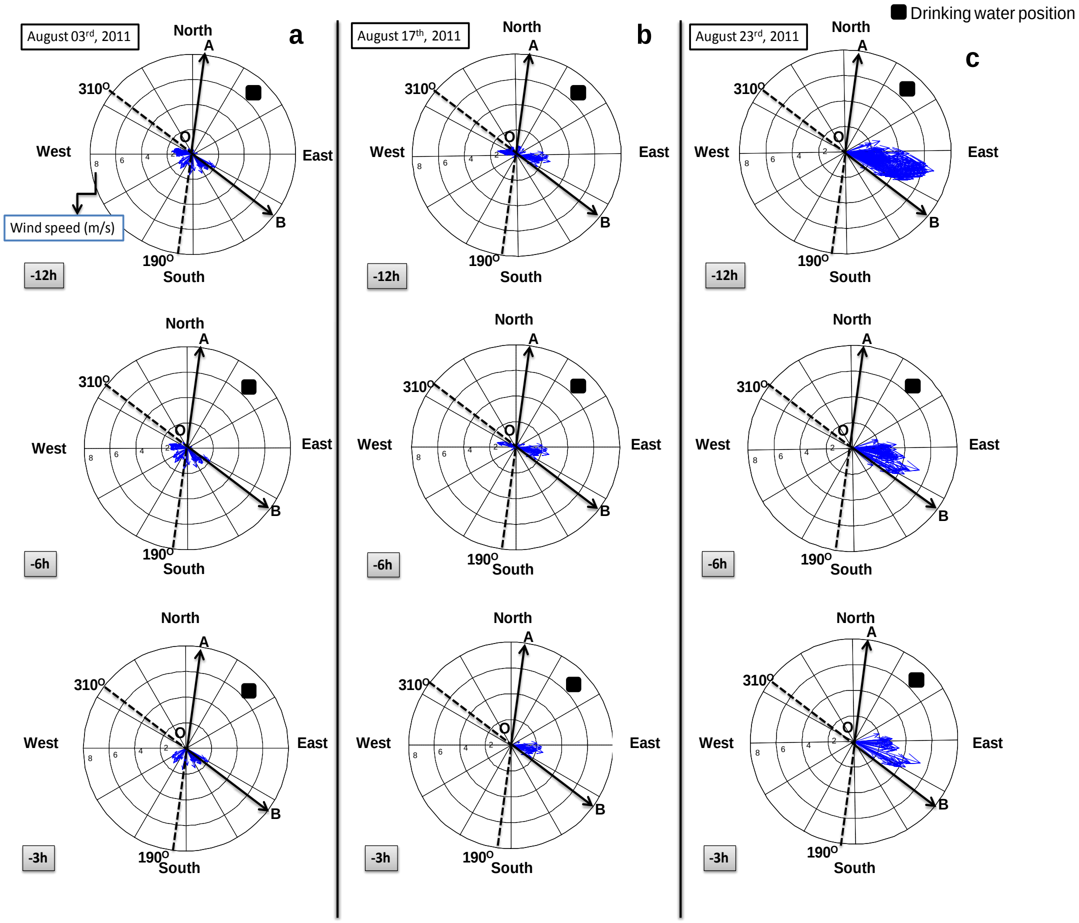

Figure 5.3: Wind occurence (speed and direction) 12hours, 6hours and 3hours before sampling: during the day: a) 03 August 2011, b)17 August 2011 and c) 23 August 2011 with wind direction angle (AOC) that exposed drinking water intake to CB occurence

When mixing induced by wind speed over than 6-8m/s occurred, as was observed on the 3rd and 23rd of August, the accumulated CB at the water's surface were quickly dispersed (Kanoshina et al., 2003). The drinking water intake is located on the North-East side of the Bay (**Figure 5.3**), exposing it to cyanobacteria accumulations from winds coming from 190°to 310°, with an optimal value of 200° (Ndong et al., 2014a). Wind direction was not favourable for bloom accumulation on August 3, 2011 (**Figure5.3**). In contrast, the wind was favourable on Aug. 17, 2011 (**Figure5.3**) with a modest speed (mean 1.5m/s). On August 23rd, 2011 (**Figure5.3**), the wind direction could favour CB blooms at the drinking water intake based upon its position within the water body (i.e., wind was blowing towards the intake) but the associated speed was very high (mean 5m/s) leading to turbulent conditions.

5.4.3 Cyanobacteria distribution

CB distribution and water temperature were modelled and compared with data collected for three different sampling days (**Table 5.1**) in order to investigate water temperature, light penetration and CB distribution in the water column. CB distribution in the water column represented by phycocyanin concentration (**Figure5.4**) was compared with our results from our numerical model run with meteorological data.

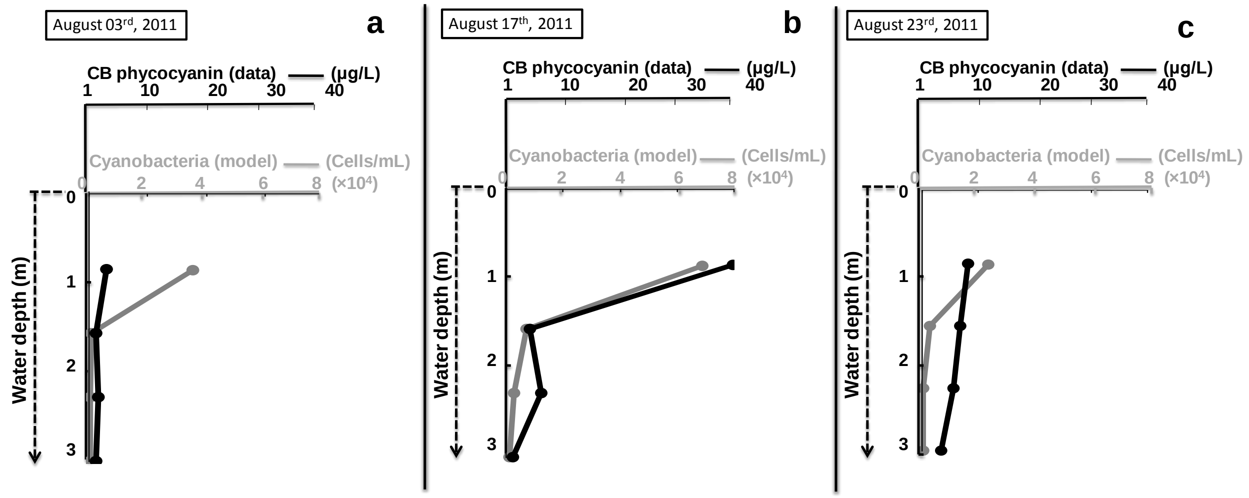

Figure 5.4: Comparison of Cyanobacteria (CB) trend distribution in the water column (model result vs collected data) during three sampling days: a) 03 August 2011, b)17 August 2011 and c) 23 August 2011

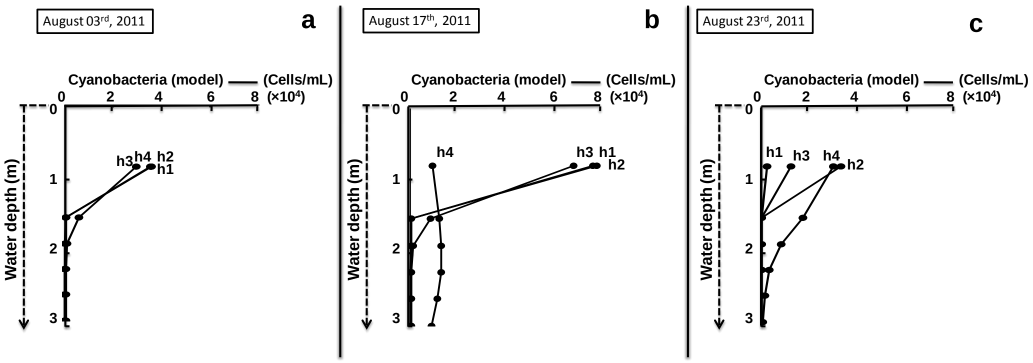

Figure 5.5: Variance of Cyanobacteria (CB) distribution in the water column during three sampling days: 03 August 2011, b) 17 August 2011 and c) 23 August 2011. Model result data at different time (h1:10:30; h2:11:00; h3:11:30 and h4:12:00)

The general trends were well captured by the model during the day of August 17th 2011, though less well on August 03rd 2011 and August 23th 2011. However, during the three sampling days, it is interesting to note the total number of CB cells recorded in the water column above the drinking water intake. It appears that CB accumulation occurs when wind speed is modest or low and its direction is in the range or zone previously mentioned as being close to optimal (190°-310°) (**Figure 5.3b**). In contrast, August 23rd 2011 had a favourable wind direction but was intense (**Figure 5.3c**), causing a high density of CB that were well dispersed throughout the water column (**Figure 5.3c**) as water column turbulence was also more intense.

5.5 Discussion

5.5.1 Ecological implications of the absence of stratification

It was suspected that eutrophic shallow water bodies are vulnerable to CB blooms because favourable thermal conditions occur throughout and blooms are generally limited by the stability of the water column, as was also observed in the model. For testing this hypothesis, results from sampling dates were analyzed in order to demonstrate the role of the water column stability in the case of weak stratification as is frequently observed at Missisquoi Bay. Water column stratification has been reported to be a key parameter that intensifies CB accumulation, whereby adequate water temperature conditions enable the initiation of a bloom and stratified conditions favour CB dominance (Kanoshina et al., 2003). Fast migration of buoyant CB is facilitated by increasing stratification (Carey et al., 2012). Stratified conditions can be exploited by many CB species (Walsby, 1975; Walsby, 1997) and stratification has been shown to govern the vertical distribution of algal biomass (Albay & Akçaalan, 2003).

Warming temperatures as a result of global climate change are expected to intensify thermal stratification of surface waters and lengthen the period of seasonal thermal stratification, thereby enhancing conditions for CB (Li & Han, 2012). Stratification favours buoyant CB to the detriment of others algal species (Huisman et al., 2004). There is strong evidence that persistent stratification leads to the formation of CB blooms (Westwood & Ganf, 2004) and that potentially toxic CB occurrences can be promoted by long stratification periods (George & Harris, 1985). All these findings do not explain CB distribution and bloom formation at Missisquoi Bay during our study period. Based on these results, we suspect that the lack of stratification has led to uniform, high velocity movement for cyanobacteria in the water column. When high temperatures occur, buoyant CB surface bloom formation will be enhanced and their vertical movement as a function of light availability and nutrient status will be more rapid (Paerl & Huisman, 2009). This is due almost entirely to the decrease in water viscosity with rising water temperatures (Hutchinson, 1957), because the effect on the radius and thus the density of cyanobacteria cells is relatively weak. The decreased viscosity leads to a faster movement of CB, both in ascent and descent, because the CB moving velocity is inversely proportional to water viscosity based on Stokes' law (Reynolds, 2006).

In Missisquoi Bay and other shallow water bodies where CB dominate such as Lake Winnipeg (Kling et al., 2011) Lake Erie (Stumpf et al., 2012) and an embayment of Lake Ontario (Hotto et al., 2007), strong thermal stratification does not explain the dominance of CB. For the case where stratification is weak, other physical processes must be considered, knowing that nutrients are sufficient to support CB growth. It is recognized that wind speed is inversely related to CB bloom occurrence by affecting water column stability (Bormans et al., 2004).The mixing of buoyant phytoplankton cells has been observed when wind speed was greater than 2-3 m/s (Webster & Hutchinson, 1994). According to Cao et al. (2006), *Microcystis* scums float to the water's surface when the wind speed is below 3.1 m/s. The spatial distribution of CB has been more linked to wind forced advection than possible transport of nutrients (Kanoshina et al., 2003); however, the presence of nutrients has not been well quantified with regards to cyanobacteria movement and its inclusion in models may improve predictions (Ndong et al., 2014a).

Albay and Akçaalan (2003) observed that surface water with weak thermal stratification can experience severe CB blooms with CB dominance. The shallow layer permits CB to have greater access to light quickly during the day and to maintain their nocturnal dominance (Carey et al., 2012). Based on their buoyant properties, CB will tend to float in stable layers (Marcé et al., 2007). In Missisquoi Bay, conditions throughout the water column are favourable for CB and CB can easily move through the water column. Thus, it is not necessary to have stratification to enable CB dominance, but rather favourable thermal conditions to facilitate CB growth and movement through a reduction of the water's viscosity in the water column. CB are considered to be very strong competitors for light because of their accessory pigments and structural organisation of their light harvesting antennae (e.g (Osborne & Raven, 1986)). Light availability was sufficient for CB on all three days and is therefore not a discriminating factor to explain differences in CB concentrations at the drinking water intake.

In this way, this analysis shows that water column stability induced by modest wind speed is very important in shallow water where CB occurrences are observed and that longer and stronger periods of water column stability lead to favourable conditions for CB such as *Microcystis*, which are often dominant in Missisquoi Bay (McQuaid et al., 2011; Ndong et al., 2014a). Finally, the wind was likely the determining factor to explain differences among the three days.

In order to simulate exact concentrations of CB above the intake, it would be necessary to include all processes that affect absolute numbers of CB in the water body. For example, processes such as flushing events (including flows from rivers and streams draining to Missisquoi Bay), CB growth, CB mortality, the dynamics of nutrients and nutrient loads to the Bay, photo-inhibition, would further improve the numerical model for CB and compare with real concentrations rather than general trends.

It is important to note the importance of the sampling frequency when developing CB models and comparing with field data. Although hydrodynamic models have been used for modeling CB transport and comparing with satellite imagery, these are not sufficient to determine whether or not a drinking water treatment plant is at risk. Satellite images provide CB information at the surface of a water body, whereas drinking water intakes are generally located near the bottom of the water column. Thus, models describing the movement through the water column are needed to understand the risk of CB breakthrough into drinking water treatment plants.

5.5.2 Critical findings for cyanobacteria modeling

Hydrodynamic simulations demonstrated that CB blooms occur when a combination and necessary factors such as wind speed, wind direction and water temperatures are favourable. These results support results found in a previous study on the development of an index for evaluating the risk associated with CB blooms occurrence at a drinking water intake using water temperature, wind speed and wind direction. It was shown that water temperature, wind speed and wind direction as factors in eutrophic waters such as Missisquoi Bay could explain up to 68% of the probability that CB blooms occurs at a given location within the water body (Ndong et al., 2014a). This study provides the detailed mechanistic description of the processes involved that explain why these three factors are dominant in a shallow water body such as Missisquoi Bay.

Our finding demonstrated the vulnerability of an intake location according to modest changes in winds patterns. Because of this variability, it may be challenging to predict the most critical periods of CB accumulation at the water intake. Nevertheless, the model proposed appears highly useful in the setting the boundary concentrations that may be found at the water intake.

The short term variability of the model shows that CB cells distribution can change quickly between 10:30 (h1) to 12:00 (h4) (Figure 5.5a,b and c). The rapid changes can be explained by the rapid buoyancy changes probably caused by the time response delay of 4 minutes (Wallace and Hamilton, 2000) for the Visser and al. (1997) model used in this study. The time delay needs more investigation for field scale (as opposed to lab-scale) environmental conditions. We suspect that the time delay response is of longer duration for Missisquoi Bay than previously reported elsewhere (Ndong et al., 2014b). Meteorological data such as wind, solar irradiance, humidity, have high hourly variability and this variability is critical for the risk to a drinking water treatment plant when the density of CB reach a threshold that will allow them to accumulate in high numbers. Thus, high frequency sampling of CB should be considered (for example, through the use of phycocyanin probes) and the collection of meteorological data describing changing conditions would provide the most relevant information for the development and use of hydrodynamic CB models and operational decisions at drinking water treatment plants.

5.6 Conclusions

Through this study, water temperature at Missisquoi Bay was well modelled. Thermal stratification which is not often observed in shallow lakes such as Missisquoi Bay is not the main process that favours CB blooms occurrence. Water column stability appears to be the key factor that leads to CB bloom occurrence in the case of Missisquoi Bay where nutrients are generally not limiting. The effects of these factors lead to water column hydrodynamic stability resulting from wind speed intensity that represent adequate conditions that permit CB to exploit their physiological characteristics, including specifically their own capacity to move in the water column. Wind speed below 3m/s was found to be favourable for CB occurrence as was also observed by (Webster & Hutchinson, 1994). This study highlights the importance of the primary physical factors used when developing an index for evaluate CB risk occurrence (Ndong et al., 2014a) and illustrates the details of the primary physical processes involved. To estimate actual CB concentrations in the water column, other important processes such as flushing events, growth, mortality, the dynamics of nutrients should be considered. It is important to note the many physical and biological processes that influence CB occurrences. The model results demonstrate that the greatest data needs are for high frequency sampling throughout the water column and that these data are needed for fully understanding CB occurrence and behaviours, and ultimately the risk to users of the water resource.

5.7 Acknowledgment

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CHAPITRE 6 : DISCUSSION GÉNÉRALE

6.1 Évaluation des objectifs et hypothèses de travail par rapport aux résultats obtenus

La forte prolifération de cyanobactéries dans les eaux de surface servant de sources d'approvisionnement en eau potable est un problème complexe du fait de l'ensemble des processus physiques, biochimiques et biologiques impliqués. Elle nécessite une pluridisciplinarité afin de pouvoir bien la comprendre, la prévenir et mettre en place des techniques permettant d'y remédier et qui ne sont pas nuisibles à la population aquatique. C'est dans ce contexte que beaucoup d'études ont été menées afin de déterminer les principales causes d'une forte prolifération de cyanobactéries dans les plans d'eau. Cependant, jusqu'ici il n'y a que les études faites avec des images satellites qui essaient de développer une méthodologie de quantification du risque selon la position d'une prise d'eau (Wheeler et al., 2012). Un système d'alerte est nécessaire afin de réagir aux conditions et d'ajuster l'opération des usines d'eau potable. Dans le cadre de cette thèse, l'évaluation de ce risque d'occurrence des cyanobactéries est faite avec une approche statistique qui ne décrit pas les mécanismes qui contrôlent la distribution spatio-temporelle des cyanobactéries. C'est ce qui a motivé le développement d'un modèle déterministe avec une approche eulérienne qui décrit l'effet d'advection et de flottabilité des cyanobactéries. Ces deux défis majeurs ont été les centres d'intérêt de cette thèse avec les objectifs suivants : 1) Quantifier le risque associé à l'effet du vent et de la température de l'eau ; 2) Développer un modèle avec une approche eulérienne en intégrant les données météorologiques réelles permettant de suivre la distribution spatio-temporelle des cyanobactéries ; 3) Étudier leur comportement face à une éventuelle stratification thermique et valider le comportement avec les données de terrain et les résultats du modèle.

Nos travaux dans le chapitre 3 (article 1) constituent une avancée conséquente dans le domaine de la quantification du risque compte tenu de la position de la prise d'eau. Ils ont permis d'évaluer quantitativement pour la première fois le risque d'occurrence des cyanobactéries à une prise d'eau tenant en compte sa position. Cependant, la température de l'eau et les paramètres météorologiques que sont le vent (vitesse et direction) ont été les seuls facteurs pris en compte vu que cela nécessite des données de haute fréquence.

Il faut noter que la non-linéarité des variables impliquées rend complexe le traitement des données recueillies. Néanmoins, l’hypothèse sur le rôle dominant joué par les facteurs exogènes a été confirmée avec un risque d’occurrence des cyanobactéries de 68 % associé à ces facteurs (température de l’eau, vitesse et direction du vent). Cependant l’indice proposé pourrait être amélioré vu qu’il y a une probabilité de 26 % associé à des faux négatifs. Effet, il serait fort intéressant d’inclure les nutriments en disposant de données de haute fréquence telle qu’il a été le cas pour les facteurs inclus dans le calcul de l’indice météorologique proposé dans le chapitre 3 (article 1). Cette prise en compte des nutriments se justifie par le rôle des nutriments dans le processus de croissance des CB et l’importance du rapport DIN/TP proposé par certains auteurs (Bergström, 2010; Ptacnik et al., 2010) comme indicateur de condition favorable pour une forte prolifération de cyanobactéries et confirmée à travers nos études comme étant une condition nécessaire, mais pas suffisante pour prévenir l’occurrence des CB à un endroit précis d’un plan d’eau.

L’indice proposé est conçu pour évaluer le risque d’occurrence et non la disparition ou la fin d’un épisode de « fleurs d’eau » qui inclurait des processus tels que le « flushing » qui conduit au renouvellement de la masse d’eau, la croissance, la mortalité. Une éventuelle combinaison entre un système de suivi de la phycocyanine et l’évaluation de l’indice proposé pourrait constituer un important outil pour les gestionnaires de plan d’eau et les opérateurs des usines de traitement d’eau potable.

Les résultats obtenus dans notre premier axe de recherche montrent également qu’une analyse séparée des variables impliquées ne permet pas de comprendre les épisodes de « fleurs d’eau ». Seule une approche globale incluant l’ensemble des facteurs impliqués serait mieux adaptée. Néanmoins, l’approche proposée se caractérise par sa nouveauté, sa robustesse et son applicabilité sur d’autres sites. Cependant, il faudra noter que cette approche est purement statistique et ne permet pas d’expliquer l’importance des processus reliés à la distribution des cyanobactéries dans un plan d’eau. C’est ce qui explique l’approche déterministe adoptée par la suite dans le chapitre 4 (article 2). Cette approche déterministe présente aussi une réflexion très avancée afin d’éviter la simplification faite dans presque tous les logiciels commerciaux de modélisation hydrodynamique couplée à la qualité de l’eau (**Tableau 1.4**). En effet, les cyanobactéries sont la plupart du temps considérées comme de simples particules avec une vitesse moyenne de sédimentation. Cette simplification fausse complètement le vrai problème et les éventuelles explications qui pourraient en découler pour élucider la distribution des cyanobactéries dans une colonne d'eau.

Il n'y a que CAEDYM (logiciel commercial) qui tente de tenir en compte l'aspect de flottaison selon l'intensité lumineuse (Hipsey et al., 2006). Cependant, dans ce logiciel, l'effet phototaxis est utilisé pour évaluer la vitesse de sédimentation des cellules. Par contre, pour leur remontée et remise en suspension, ce logiciel considère l'effet d'advection comme le principal facteur. Cette simplification permet de contourner l'approche lagrangienne, mais elle ne s'accorde pas avec le fait que le comportement lié à la flottaison (sédimentation et remise en suspension) pourrait dépendre uniquement sur l'effet phototactique (Kromkamp & Walsby, 1990; Reynolds & Irish, 1997; Visser et al., 1997). En effet, le changement de densité des cyanobactéries selon l'intensité lumineuse fait que leur mouvement change dans l'espace et le temps. Jusqu'ici seule une approche Lagrangienne permettait de faire ce suivi spatio-temporel pour une seule cellule rendant presque trop lourd en calcul le suivi de toute une population de cyanobactéries dans un plan d'eau. Il faut retenir que seule l'approche eulérienne permet d'avoir une vue d'ensemble de la distribution des cyanobactéries dans le plan d'eau.

C'est ainsi que nous avons proposé une nouvelle méthodologie avec l'approche eulérienne permettant de faire un suivi de l'ensemble des cyanobactéries. A travers celle-ci, il a été mis en évidence le rôle joué par l'effet phototaxis dans le processus d'accumulation des CB à la surface d'un plan d'eau. Il a été observé un comportement cyclique du risque d'occurrence des CB à la prise d'eau lorsque la flottabilité est dominante et que les intensités de vents enregistrées sont faibles (chapitre 5: article 2), ce qui est observé dans des conditions de faibles intensités de vents (effet advection négligeable) et qui permet de confirmer notre hypothèse selon laquelle dans un milieu naturel, selon certaines conditions hydrodynamiques (présence ou absence de stabilité de la colonne d'eau), la distribution spatio-temporelle des cyanobactéries, leur forte accumulation en surface (présence d'écume) et au fond de la colonne d'eau seraient dépendantes de leur aptitude à la mobilité (présence ou absence de vésicules de gaz).

Dans notre démarche, les processus biologiques n'ont pas été inclus pour le moment (croissance-mortalité). En effet, s'il existe des modèles de croissance jusqu'ici assez acceptables, les différents processus de la phase de décroissance ne sont pas encore bien maitrisés (manque de nutriments, mortalité due à la forte exposition à la lumière ou à la prédation, «flushing»). En fait, la non-maîtrise de cette phase empêche toute validation quantitative de la distribution des cyanobactéries dans un plan d'eau. C'est ainsi que pour une première étape, dans le but de perspective future, nous jugions primordial d'assurer un bilan de masse strictement sans pertes durant la simulation, c'est ce qui nous a motivé à tester beaucoup d'algorithmes proposés pour le modèle de transport. Il s'avère qu'une perte de masse pouvait être minime et acceptable pour un temps de simulation court, ce qui n'était pas le cas pour des temps de simulation assez long de l'ordre de quelques jours à des mois.

L'accumulation des pertes constituait une importante source d'erreur qui rendrait une validation quantitative biaisée. C'est aussi l'une des raisons pour lesquelles nous avons travaillé aussi sur le développement d'algorithmes tenant en compte aussi le mouvement des cyanobactéries selon les disponibilités de la lumière. Notons que la mise en place d'une contrainte qui limite le nombre de cellules que peut contenir un volume donné est nécessaire afin d'éviter une surestimation des concentrations de cellules. En effet, la non prise en compte de cette contrainte, pourrait biaiser une validation en terme quantitative lorsqu'il y a une forte accumulation de CB durant une simulation. L'autre aspect qui mérite une réflexion est la prise en compte de l'hétérogénéité du diamètre des cellules et des colonies de cellules dans l'approche eulérienne. En effet, lors d'un bloom de CB, le diamètre des cellules de CB n'est pas parfaitement homogène. Cet aspect pourrait avoir un grand effet sur la distribution spatio-temporelle des CB au cas où une forte hétérogénéité existe entre les cellules présentes dans l'écosystème. La prise en compte future dans le modèle serait limitée par un temps de calcul qui pourrait s'avérer très important et nécessiterait une grande capacité de stockage de l'outil utilisé pour le traitement numérique.

Il existe aussi un manque d'information concernant le temps de réponse des cyanobactéries en milieu naturel lorsqu'elles changent de densité. En effet, pour modéliser cet aspect, une fonction retard est introduite (Wallace & Hamilton, 2000). Ces auteurs préconisent un temps de réponse de 4 minutes quand l'intensité lumineuse est plus élevée que l'intensité de compensation pour le modèle de Visser et al. (1997). La question à se poser est la suivante : ce temps de réponse est-il constant ou dépendant de leur position dans la colonne d'eau ?

L'ajustement du modèle par rapport au délai de réponse quand les CB sont exposés ou non à l'intensité lumineuse est un important facteur à prendre en compte afin de se rapprocher d'un modèle plus réaliste. Compte tenu des tests faits sur le temps de réajustement phototactique ou délai de réponse phototactique, le modèle hydrodynamique couplé avec le transport des CB présente une corrélation significative telle que rapportée dans le chapitre 4 (article 2).

Cependant la corrélation trouvée n'est pas très forte même si elle est significative; ce qui nous pousse à suspecter que le délai de réponse pourrait être fonction de la position des CB dans la colonne d'eau comme c'est le cas du coefficient d'extinction (Kirk, 1983). Ce délai de réponse pourrait aussi être fonction de la température dans la mesure où cette dernière a un impact sur le comportement physiologique des CB (Carey et al., 2012). Ce qui rend plus complexe la problématique des cyanobactéries dans les plans d'eau et le besoin jusqu'ici de continuer les investigations afin de disposer enfin d'un modèle pouvant refléter d'une façon encore plus réaliste la distribution spatio-temporelle des cyanobactéries. Pour cela, il sera absolument nécessaire de faire un suivi à haute fréquence de la distribution des cyanobactéries afin d'avoir des résultats permettant de faire une validation tant quantitative que qualitative (distribution dans la colonne d'eau).

6.2 Rôle des processus physiques et biologiques dans la distribution spatio-temporelle des cyanobactéries

Les processus qui régissent la distribution spatio-temporelle des cyanobactéries sont d'ordre physique et biologique. Il s'agit respectivement de l'advection et de la flottabilité induite par le changement de densité des CB. Ces derniers sont contrôlés par des facteurs exogènes liés aux conditions météorologiques. Il s'agit du vent (vitesse et direction) et de la radiation photosynthétique active (PAR). Il faut retenir que jusqu'ici, l'effet de la PAR sur la flottabilité a été bien modélisé et validé expérimentalement (Kromkamp & Walsby, 1990; Visser et al., 1997). Ce qui n'empêche pas de suspecter un éventuel effet de la disponibilité des nutriments sur la flottabilité tels que rapportés par certains auteurs (Brookes et al., 1999; Chu et al., 2007; Klemer, 1991). La dominance entre la flottabilité des CB et l'advection est dépendante de l'intensité du vent. En effet, quand l'intensité du vent est très importante, l'advection horizontale entraine les CB dans le mouvement de recirculation de l'eau. Dans le cas d'une contrainte de vent constante, combinée avec le comportement sinusoïdal et journalier de l'intensité lumineuse, un risque cyclique de présence des CB pourrait être observé à la prise d'eau.

Pendant une période d'occurrence de CB avec une faible intensité de vent, la flottabilité des CB serait dominante comparée à l'advection. La formation d'écumes à la surface d'un plan d'eau serait un mécanisme fortement dépendant de la flottabilité des CB. Une comparaison quantitative des données du modèle ne peut être faite qu'en tenant en compte d'un ensemble d'autres processus impliqués tels que la croissance, la mortalité, la dynamique des nutriments et l'effet « flushing ». La fréquence d'échantillonnage devrait être revuepour une assimilation entre les données mesurées et celles obtenues à partir du modèle. L'effet de la turbulence, en plus de favoriser la dispersion des CB, aurait pour conséquence de remettre en suspension les nutriments qui étaient dans les sédiments.

L'absence d'une forte stratification thermique ne nous permet pas de tirer des conclusions sur une éventuelle influence sur la distribution des cyanobactéries dans la colonne d'eau. De ce fait, notre hypothèse, selon laquelle la stratification thermique influence fortement la distribution spatio-temporelle des cyanobactéries dans une colonne d'eau, ne peut pas être confirmée ou infirmée. Sa vérification nécessite de faire l'étude dans un lac assez profond avec un suivi à haute fréquence.

Cependant, nous suspectons que l'absence d'un fort gradient de température dans les lacs peu profonds comme la baie Missisquoi aurait aussi pour conséquence de favoriser une croissance quasi uniforme dans toute la colonne d'eau. Au vu des résultats présentés dans le chapitre 5 (article 3), pour le cas d'un lac peu profond et eutrophe, la stabilité de la colonne d'eau pourrait être le principal facteur qui favoriserait l'occurrence des CB dès que celle-ci est stable et que les températures optimales de croissance des CB sont atteintes.

6.3 Emplacement des prises d’eau et risque d’occurrence des cyanobactéries

L’emplacement des prises d’eau des stations de traitement d’eau potable n’inclut pas jusqu’ici les effets d’une éventuelle prolifération d’algues bleu-verts. Il existe un grand vide en termes de conception pour l’emplacement le plus adapté pour une prise d’eau. Il apparait selon les résultats publiés dans le chapitre 3 (article 1) que la direction des vents joue un grand rôle dans la probabilité d’occurrence des cyanobactéries à la prise d’eau. La conception des prises d’eau devrait tenir compte d’un éventuel risque de prolifération et de transport par advection des CB. En d’autres termes, il faudrait faire une étude d’occurrence du facteur f(p) proposé dans l’article 1. La méthodologie d’évaluation quantitative du risque d’occurrence des cyanobactéries à un endroit donné d’un plan d’eau à partir des paramètres météorologiques et de la température de l’eau devrait permettre de caractériser les emplacements possibles pour une prise d’eau.

Selon le guide de conception du MDDEP (Ministère du Développement durable de l’Environnement et des Parcs, 2002), la localisation d’une prise d’eau tient compte des facteurs suivants :

- la sécurité d’approvisionnement ;
- la qualité de l’eau brute ainsi que l’impact sur l’environnement et le milieu aquatique.

Plus précisément, il est mentionné dans ce guide la disposition suivante :

« la prise d’eau doit être située à l’endroit où la qualité de l’eau est la meilleure et la moins vulnérable à la pollution tout en posant moins de dommage à la faune aquatique »,

Cette disposition ne peut être prise en compte qu’en intégrant une étude de vulnérabilité basée sur une approche purement déterministe et non sur une évaluation du nombre d’événements (présence de cyanobactéries, déversement de produits chimique) survenu durant les 5 ou 10 dernières années précédant l’étude tel que cela est défini dans le nouveau règlement sur le prélèvement des eaux et leur protection (Gouvernement du Québec, 2014).

A travers notre étude de modélisation, nous remarquons que les processus physiques (advection) peuvent entrainer les cyanobactéries dans différentes zones d’un plan d’eau. De ce fait, l’installation des prises d’eau trop près des berges augmente le risque que les CB entrent dans l’usine de traitement, et leur localisation au fond de la colonne d’eau ne garantit pas un risque moindre.

L’approche que nous suggérons à l’issue de cette étude est l’option de prise d’eau à entrées multiples permettant de capter les eaux de meilleure qualité selon des mesures in situ en continue.

6.4 Les apports de cette thèse par rapport à la problématique des cyanobactéries dans les plans d’eau

À travers les résultats trouvés, cette thèse a permis :

- de poser les fondements d‘une nouvelle approche pour quantifier le risque associé à certaines variables jusqu’ici citées dans la littérature comme ayant une influence sur l’occurrence des cyanobactéries;
- d’aborder la distribution des cyanobactéries selon une approche eulérienne en tenant compte des effets de flottabilité de ces dernières selon la disponibilité de la lumière. Ceci a permis d’étudier les implications écologiques d’une faible stratification thermique sur la distribution spatio-temporelle des cyanobactéries.

En intégrant les données météorologiques, les gestionnaires de plan d’eau pourraient disposer d’un outil intéressant leur permettant d’être avertis du moment propice à l’entrée des cyanobactéries dans l’usine de traitement d’eau potable à partir de la prise d’eau au fond du plan d’eau. Cependant, les processus de « flushing », de croissance et de mortalité devront être inclus en plus de l’intégration des données météorologiques en temps réels permettant de disposer d’un outil de suivi et de surveillance de la prise d’eau.

CONCLUSIONS ET RECOMMANDATIONS

L’occurrence des blooms de cyanobactéries menace les ressources en eau de surface. La complexité des différents processus impliqués rend difficile la gestion des plans d'eau déjà affectés. En général, ce phénomène affecte un endroit donné d’un plan d’eau. Son apparition dans la zone où est installée une prise d’eau est redoutée dans la mesure où les toxines qu’elles produisent peuvent franchir toute la filière de traitement conventionnel et se retrouver dans l’eau destinée à la consommation. De ce fait, il est opportun d’évaluer le risque d’occurrence des cyanobactéries au niveau des prises d’eau. C’est dans ce contexte qu’une nouvelle méthodologie a été développée afin de répondre à cet objectif. À l’issue de ces travaux, dans le cas de la Baie Missisquoi, il a été démontré que :

- des conditions favorables de température de l’eau, de vitesse et direction du vent auraient une probabilité quantifiable jusqu’à 68 % sur l’occurrence des cyanobactéries,
- les facteurs impliqués dans l’occurrence des cyanobactéries ne devraient pas être analysés séparément si nous voulons évaluer le risque d’occurrence à la prise d’eau,
- la prise en compte des facteurs météorologiques dans les systèmes d’alertes actuels doit se faire dans la mesure où ils jouent un rôle important dans l’occurrence des cyanobactéries à la prise d’eau,
- les variables météorologiques doivent être prises en compte dans les systèmes d’alerte existants (principalement basés sur les comptes taxonomiques ou les concentrations en toxines ou tout autre facteur propre aux cyanobactéries),
- Le rapport DIN/TP concernant la disponibilité des nutriments est un bon indicateur, cependant il ne tient pas compte de la position de la prise d’eau.

Rappelons que la méthodologie proposée utilise une approche statistique et peut s’appliquer à d’autres sites. Elle pourrait être améliorée en tenant compte des nutriments et de la radiation photosynthétique active (PAR). Cependant, cette approche statistique proposée ne nous permet pas de comprendre la distribution spatio-temporelle des cyanobactéries. C’est ainsi qu’une approche déterministe de type eulérienne a été développée. Il s’agit d’un modèle 2D. Elle implique les équations de continuité, de quantité de mouvement, de transport et de flottabilité des cyanobactéries suite aux effets phototactiques. Elle a permis de montrer que :

- la formation de couche de cyanobactéries à la surface de l’eau et leur accumulation à la berge sont liées à la flottabilité des cyanobactéries due à leur changement de densité combiné à l’advection induite par le mouvement de la masse d’eau,
- le processus d’accumulation des cyanobactéries à la surface d’un plan d’eau est le résultat de l’effet phototactique et leur dispersion serait favorisée par des vents forts (>3 m/s),
- le risque qu’une prise d’eau soit affectée pourrait être cyclique dans la mesure où le mouvement des cyanobactéries vers la prise d’eau serait dominé par les mécanismes de flottabilité des cyanobactéries, en particulier à cause de leur changement de densité si elles sont exposées ou non à la lumière durant les conditions de faible intensité de vent (<3 m/s),
- l’effet recirculation crée des zones où les concentrations de cyanobactéries sont faibles durant les périodes durant lesquelles une fleur d’eau est constatée,
- l’effet phototactique serait un élément clé dans le processus d’accumulation des cyanobactéries à la surface d’un plan d’eau tandis que des vents forts (>3 m) contribueraient à la dispersion des cyanobactéries dans la colonne d’eau,
- il est apparu à travers les études de modélisation que le risque d’occurrence des cyanobactéries à la prise d’eau de l’usine pourrait être cyclique durant les périodes de faible intensité de vent (<3 m/s). En effet, dans ces conditions, la flottabilité des cyanobactéries due à leur changement de densité serait dominante,
- la flottabilité des cyanobactéries due à leur changement de densité combiné à l’advection induit par le mouvement de la masse d’eau contribue fortement à la formation de couche de cyanobactéries à la surface de l’eau et à leur accumulation à la berge,
- à cause des effets de recirculation induits par le vent, il existerait des zones où les concentrations de cyanobactéries seraient faibles.

Il faut noter que les processus de croissance, mortalité, « flushing » ainsi que les processus biochimiques n’ont pas été inclus. Néanmoins, la distribution des cyanobactéries suivant les températures enregistrées dans la Baie a été étudiée. À la suite de celle-ci, il apparait que

- la stratification thermique n’est pas forte dans le cas de la Baie Missisquoi, qui est un lac peu profond et eutrophe,

- dans des conditions de stratification thermique peu significative, pour un plan d'eau eutrophe, la stabilité de la colonne d'eau apparait comme une des conditions qui pourraient favoriser l'occurrence des CB,
- dans le cas d'un plan d'eau eutrophe et faiblement stratifié, la croissance et la mortalité pourraient être uniforme dans toute la colonne d'eau car elles seraient uniquement dépendantes de la température, ce qui favoriserait une dominance des cyanobactéries dès que des températures optimales de croissance sont atteintes.

A l'issue de ces travaux, les principales recommandations seraient :

- de prendre en compte le facteur f(p) dans le choix de l'emplacement d'une prise d'eau afin de minimiser le risque d'occurrence de cyanobactéries à l'endroit où elle est installée,
- de continuer les études afin d'améliorer l'indice proposé en tenant compte du rapport DIN/TP et de l'intensité lumineuse en plus de la concentration en phycocyanine,
- de modéliser le processus de décroissance après blooms, en investiguant sur les facteurs responsables,
- d'introduire les processus de croissance et mortalité dans le modèle déterministe développé
- de mener une compagne d'échantillonnage à haute fréquence (variabilité horaire ou journalière) afin de bien assimiler les résultats du modèle avec les données issues de la modélisation. En effet, l'échantillonnage hebdomadaire ne permet pas d'affiner les conclusions et rend difficile l'analyse des données.

Les objectifs visés à travers cette thèse ont été atteints. La poursuite de ces études permettraient de disposer de deux outils importants: 1) d'évaluation de risque d'occurrence à la prise d'eau et 2) de compréhension de l'occurrence des cyanobactéries et de la distribution spatio-temporelle des cyanobactéries dans un plan d'eau.

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