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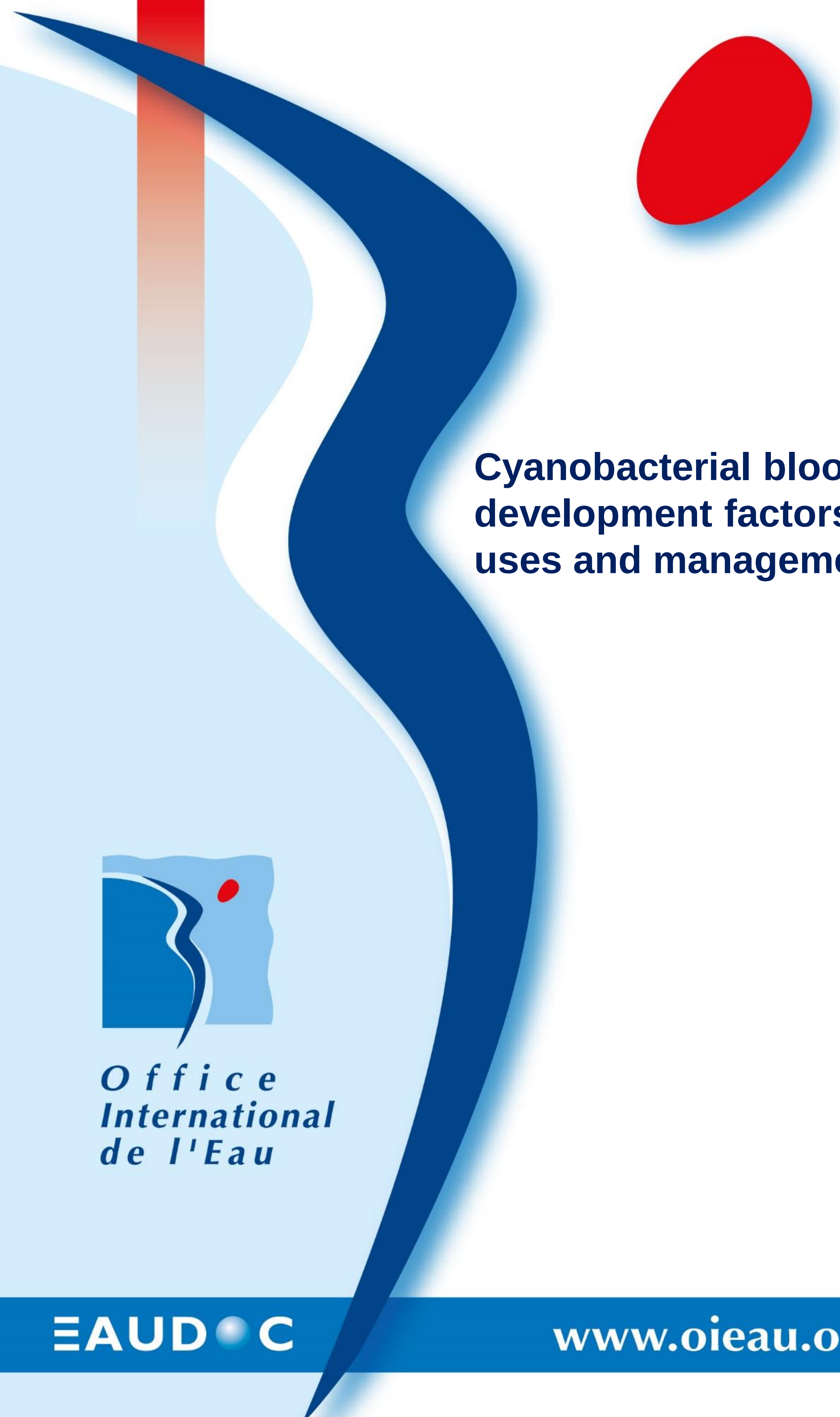

Cyanobacterial blooms : development factors, impacts on the uses and management measures

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SYNTHESIS

Cyanobacterial blooms: development factors, impacts on the uses and management measures

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ABSTRACT

The development of Cyanobacteria in freshwater is widespread worldwide. Proliferation of these microorganisms has taken place in specifics environmental and physio-chemical conditions: high temperatures, standing water and places where there is high availability of nutrients (such as phosphorous and nitrogen). Phosphorus is seen as the limiting factor of cyanobacteria proliferation as this element is naturally rare in water. Nitrogen is also an important nutrient but not limiting as some cyanobacteria's species can fix atmospheric nitrogen. Phosphorus input control is an important checkpoint to reduce cyanobacteria proliferation. In agricultural and urban environments phosphorus can come from agricultural input and wastewater released into natural water. Water bodies also contain an internal charge of phosphorus stocked in the sediment. Cyanobacteria proliferation in water for recreational use or drinking water supply is a major problem due to the health risks associated with the potential production of cyanotoxins. In the event of water contamination, preventive measures are introduced in order to limit population exposure.

Keywords : Cyanobacteria, proliferation, freshwater, nitrogen, phosphorus, preventive measures.

RESUME

Le développement des cyanobactéries dans les plans d'eau est un phénomène mondial. La prolifération de ces micro-organismes se déroule dans des conditions environnementales et physico-chimiques spécifiques : température élevée, eau stagnante et disponibilité en éléments nutritifs (azote et phosphore) importante. Le phosphore est considéré comme le facteur limitant à la prolifération des cyanobactéries car cet élément est naturellement rare dans l'eau. L'azote n'est pas un facteur limitant à leur développement car certaines espèces de cyanobactéries peuvent fixer l'azote atmosphérique dissous dans l'eau. La maîtrise des apports de phosphore est donc un point de contrôle déterminant. Dans les milieux agricoles et urbanisés le phosphore peut provenir de sources externes telles que les rejets d'assainissement des eaux usées et les intrants agricoles. Les plans d'eau disposent également d'une charge interne de phosphore contenue dans les sédiments. Le relargage du phosphore se déroule lorsque l'interface eau-sédiments se trouve en condition anoxique. Les plans d'eau sont particulièrement sujets aux dépôts de sédiments en raison des faibles courants. La prolifération de cyanobactéries dans un plan d'eau à usage récréatif ou alimentation en eau potable constitue un problème majeur en raison des risques sanitaires liés à la production potentielle de cyanotoxines. En cas de contamination des plans d'eau, des mesures préventives sur les usages de l'eau sont instaurées afin de limiter l'exposition des populations.

Mots clés : Cyanobactérie, prolifération, plans d'eau, azote, phosphore, mesures préventives.

ACRONYMS

ADI : Acceptable Daily Intake

CSHPF : Higher Council of Public Hygiene of France (HCPHF)

IRSTEA : National Science and Technology Research Institute for Environment and Agriculture

NRA : National Research Agency

nm : nanometers

WHO : World Health Organization

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INTRODUCTION

Cyanobacteria are ubiquitous microorganisms found in marine, freshwater and watercourses. According to the International Botanical Nomenclature Code, about 150 genera and nearly 2 000 species are registered in the Cyanophy family (Hoek et al., 1995). Growing requirements differ among species. Under certain environmental conditions cyanobacteria can have a rapid growth of their population, it is referred to as bloom. Cyanobacteria represent a potential threat for human health because some species are capable to produce intracellular toxins that may be released into the environment (Bartram et al., 1999). The World Health Organization (WHO) classifies this phenomenon as a potential health risk. Moreover, a cyanobacterial bloom causes many environmental impacts: reduction of phytoplankton biodiversity, desoxygenation of the environment, water transparency reduction and aquatic fauna mortality by poisoning in the case of toxin production. These episodes also have negative impacts on water uses with economic losses associated with water-use restriction (tourism industry impacted) and increased treatment costs. However, when they are present in small quantities in the environment, cyanobacteria do not represent a major health risk.

In a worldwide context of increasing bloom episodes within freshwater reserves, the issue emerging in the long term, is to preserve resource uses. In France, about 50% of blooms have toxic effects (Laplace-Treyture, 2016).

Cyanobacterial bloom control represents major ecological, health and economical stakes. A deep understanding of the role of the various biotic and physico-chemical factors in the appearance of the phenomenon is fundamental for its management and control. All these parameters present complex interactions, making bloom prediction difficult (Bernard, 2014) and its management complex.

What conditions favor cyanobacterial blooms in freshwater? What is the regulatory framework in France for cyanobacteria monitoring? What are the management levers? The objective of this synthesis is to carry out an inventary of the current understanding of cyanobacteria best growing conditions, preventive measures and management, in order to implement effective long-term management strategies.

ENVIRONMENTALS CONDITIONS ENHANCING CYNOBACTERIAL BLOOMS INCONTINENTAL AREAs

CYANOBACTERIAL ADAPTATIONS STRATEGIES

Cyanobacterial life cycle

Cyanobacteria are naturally occurring bacteria in aquatic environments, either in the water column, dispersed or in colonies (phytoplankton), or infected by sediment (phytobenthos). They are located within the first link in the ecosystem food trophic chain, the phytoplankton, composed of diversified photosynthetic microorganisms. The upper links of the trophic chain (zooplankton, herbivorous and carnivorous fish) feeds by predation and grazing. A cyanobacterial bloom results from a breakdown from the whole aquatic community balance.

Cyanobacteria have seasonal development cycles. Below a temperature threshold, cyanobacteria enter in a benthic phase, a vegetative form that allows them to resist when environmental conditions are unfavorable for their development. Cyanobacteria produce resistance cells (hormogonia and akinetes). These cells contain reserves that allow them to survive in sediments in the absence of light as well as at low temperatures. The recruitment of this innoculum takes place when environmental conditions become favorable for their growth. There are different recruitment processes:

- Passive: water mixing due to the wind stirs up the cells in the column of water.
- Active: increase in light intensity (Anabaena case) and nutrients availability (*Aphanizomenon* case) at the water-sediment surface leads to a recovery of the cells metabolic activity (Jourdain, 2010).

Phosphorus availability: limiting factor

Phosphorus is considered as the common limiting factor for all phytoplankton species proliferation because this element is naturally rare in water. Sedimentation of the decaying organic matter, rock alteration and soil erosion contribute to increasing phosphorus concentration in the water body (Barroin, 1999). Beyond a total phosphorus concentration of 0.01 µg / L, cyanobacteria can proliferate in the environment if the other conditions necessary for their development are present (Chorus et al., 1999). However, studies about hundreds of European lakes have shown that cyanobacteria are rarely dominant in the environment below a total phosphorus concentration of 20 µg / L (Fastner et al., 2015).

Adaptation to low light intensity

Cyanobacteria are photosynthetic organisms. In presence of light, they synthesize organic matter from atmospheric CO_2 and nutrients. The photosynthetic apparatus of cyanobacteria comprises chlorophyll-a, a pigment which absorbs strongly at 430 nm and 660 nm, and phycocyanin, a pigment which absorbs wavelengths between 610 and 655 nm. Moreover, some species possess additional pigments such as phycoerythrin (absorption between 490 and 570 nm) and carotenoids (absorption at 450 nm). Through these different pigments, cyanobacteria can absorb a broad spectrum of light waves. This is a huge competitive advantage with regard to other photosynthetic organisms. Within a turbid environment, rich in phycocyanin cyanobacteria tend to dominate the planktonic biomass in the intermediate lake zone (the metalimnion). For example, in peri-Alpin lakes such as Le Bourget, *Planktothrix rubescens* is found in the intermediate zone. Conversely, *Microcystis* grows at the surface where light intensity is high and nutrient concentration is low.

Adaptation to lack of nitrogen

Nitrogen is an essential compound for growth of living beings. Some cyanobacteria species possess the enzyme „nitrogenase“ which allows the conversion of atmospheric nitrogen to ammonium. This enzyme is specific to cyanobacteria. The lack of nitrogen favors the proliferation of atmospheric nitrogen-fixing cyanobacteria in front of other phytoplankton species. Genera owning this specific enzyme include *Anabaena*, *Aphanizomenon*, *Cylindrospermopsis* and *Nodularia*. According to Smith (1983), cyanobacteria dominate when the stoichiometric ratio of nitrogen to phosphorus (N / P ratio) is under 29.

Movment within the water column

Most planktonic cyanobacteria have intracellular gaseous vacuoles allowing them to adjust their vertical position within the water column to position themselves at the level where conditions are most favorable (Hayes et al., 1986 ; Mur et al., 1999). The nutrients necessary for the development of cyanobacteria (nitrogen and phosphorus) are abundant near the sediments where the mineralization of organic matter takes place, while light intensity is greater near the surface. Species owning this competitive advantage are generally found in water bodies with depths greater than 3 meters. The species concerned include *Microcystis*, *Anabaena* and *Aphanizomenon*.

THE IMPACT OF HYDROMORPHOLOGICAL PARAMETERS

The hydromorphology of a water body includes the morphological aspects (surface area, variation of depth) and the hydrological regime (flows in and out, which determine the residence time of water). These parameters affect the stability of the water column, the thermal stratification regime as well as the exchanges between the water column and the sediments. The development of cyanobacteria is controlled by the hydromorphological functioning of the water body.

In low-circulation water bodies the water turnover is low. When the air temperature is stable and the depth is high, a thermal stratification regime occurs. In temperate regions, the thermal stratification of a water body follows a seasonal cycle. During the summer period, three layers are formed on a gradient of temperature and luminous intensity: epilimnion, metalimnion and hypolimnion. Differences in temperature cause a difference in density between the layers. During this period, the fine particles have enough time to sediment, resulting in the accumulation of phosphorus within the sediments. Under anoxic conditions, the phosphorus and nitrogen contained in the sediments are released. This phenomenon occurs in summer, following oxygen depletion. The products coming from the mineralization contribute to the nutrient enrichment of the water column and sediments. In deep lakes, a complete mix of water, called the winter brewing, takes place in late winter promoting nutrient diffusion throughout the water column.

Shallow water bodies do not have a seasonal thermal stratification regime; the temperature is relatively uniform throughout the water body. A shallow depth favors the regular mixing of water, in particular through the wind action, which facilitates exchanges between water and sediments.

Thus, when the internal nutrient loading is released into the water column (as a result of physicochemical processes) it creates conditions conducive to the phytoplankton development. An efflorescence that appears after an episode of water mixing suggests that the nutrient supply comes from the sediments rather than from an external contribution from the watershed.

The increase in water requirements (drinking water supply, irrigation, hydroelectricity) has led to the development of numerous hydraulic structures on watercourses. These structures have accelerated the eutrophication of water bodies by reducing their self-purifying capacities. Artificial reservoirs contributed to the increase of the residence time and the water temperature. Thus, the development of rivers has amplified the phenomenon of cyanobacterial blooms.

Thus, cyanobacterias show diversified development strategies enabling them to proliferate within a large ecological niche. The combination of the different environmental and hydromorphological factors can explain in part the phenomenon of cyanobacterial proliferation. Among the favorable parameters to their development, some can not be controlled: light intensity, water temperature and winter brewing. On the other hand, the phosphorus content and the water regime are factors on which managers can control in order to limit the risks of proliferation, as we will see later.

MANAGEMENT MEASURES OF CYANOBACTERIAL BLOOMS

THE REGULATORY FRAMEWORK

Cyanobacterial blooms are often accompanied by the production of toxins harmful to human and animal health. These toxins are classified according to their health effects. They can affect the liver (hepatoxins), the nervous system (neurotoxins) or cause irritation in cases of skin contact (dermatoxins). Same cyanobactria specie may have toxic and non-toxic strains (Chorus et al., 1999). Since the 2000s, French and European regulations have focused on the health problems associated with the presence of these toxins in water for human consumption and recreational sites.

Drinking water

Cyanobacteria synthesize different toxins including microcystins, anatoxins and saxitoxins. Microcystins are the most commonly cyanotoxins produced, with about 70 different variants identified, the most common being microcystin-LR (Ho et al., 2012). In the drinking water sector, recommendations published by the WHO are based on the concentration of microcystin-LR only, as it is the only toxin whose toxicity data for the Acceptable Daily Intake (ADI) are known. The maximum guideline recommended by the WHO is one microgram per liter of microcystin-LR equivalent[1]. In France, the Decree No. 2001-1220 of 20th December 2001 was based on the maximum value published by the WHO to define the quality threshold for water intended for human consumption. The Order of 11th January 2007 extended the limit value of one microgram per liter to the total microcystin assay.

Bathing water and recreational activities

In France the first recommendations concerning the monitoring of cyanobacteria in bathing waters were set up in 2003 by the Higher Council of Public Hygiene of France. The circular DGS/SD 7 A n° 2003-270 recommends that water managers conduct a visual surveillance of their bathing sites and follow the decision-making plan presented below. The decision-making plan has three levels of intervention. However, this circular is not intended to propose "validated and standardized methods for the counting and / or detection of cyanobacteria or their toxins".

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[1] Analyzes' results do not make it possible to distinguish the different variants of microcystins.

The decision-making plan is based on alert thresholds measured in cyanobacteria cells per milliliter (see Appendix 1), the thresholds had been revised in 2006. Three levels of alert are set up :

- **Alert level 1** is triggered from 20,000 to 100,000 cells per milliliter. The activities can be maintained. Information to the public must be provided.
- **Alert level 2** is triggered when the concentration is greater than 100,000 cells per milliliter. Information to the public must be provided, the restriction of bathing if the concentration of microcystin-LR is below 25 micrograms per liter or the prohibition of bathing otherwise.
- **Alert level 3** is triggered when foam of cyanobacteria is formed on the surface of the water body. The measures to be applied are the prohibition of all uses, information to the public and the monitoring of the movement of the scum.

The European Directive 2006/7/EC has supplemented the regulation concerning the management of bathing water quality. Article 8 incorporates the control of photosynthetic organisms in the monitoring of the water bodies quality, which was not taken into account before. This article also establishes the obligation to carry out a "profile" of the bathing waters. The objective is to identify the potential sources of pollution and to define management measures to prevent the pollution risks. However, there is no control of the recommendations application resulting from these bathing profiles. The observation made in some places is that the implementation of these measures depends on the motivation and resources devoted by the managers (Commission Locale de l’Eau du SAGE Isle Dronne, 2016).

Directive 2006/7/EC imposes to managers of bathing waters to carry out a visual surveillance of their site: measure of the water transparency, detection of the presence of foam. The warning signal is based on the observation of a coloring of the water or reduction of the water transparency. However, the visual surveillance has many limitations:

- The production of cyanotoxins can precede the appearance of visible efflorescence (Brient 2004, Sinang et al., 2013). Moreover, some species proliferate without forming visible efflorescence (*Planktothrix agardhii*) whereas the concentration of microcystins can reach up to 200-400 µg / L (Chorus et al., 1999).
- The efflorescence may be visible only at a certain time of the day[2], in the morning when the photosynthetic activity of the cyanobacteria is maximum.
- The lack of experience or training of some observers.

In addition to the monitoring carried out by the bathing water authorities, the Regional Health Agencies (RHA) carry out sanitary inspections during the bathing season. The minimum frequency of sampling is once a month. Their samples concern the search for pathogenic microbial germs. On the other hand, there is no systematic monitoring of cyanobacteria. RHAs only monitor cyanobacteria in case of suspected efflorescence. The monitoring protocol is not homogeneous between the departments.

Beyond the surveillance recommendations published by the General Direction of Health, no sampling protocol is recommended (Briand, 2008). Generally, as part of a follow-up protocol, a single sampling point, at the most frequented location or at the place where efflorescence is formed, is carried out. However, a single point can not be sufficient because it is not representative of the total biomass present in the water body, especially when the area is large (Briand, 2008). Beforehand, it is recommended to define the sensitive areas of the water body

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[2] Some species are able to regulate their position within the water column.

to determine the sampling points. However, the financial constraints affect the number of samples and their frequency. The costs of these analyzes are burdensome for the municipalities that are responsible for bathing. On large water bodies, the cost of studying hydrological and hydrobiological operations is between 40,000 and 70,000 euros (Coulon, 2016).

Other uses

Irrigation is an important use of water resources. Studies on the transfer of toxins to crops via irrigation are still few. Only one case of culture contamination has been identified in the literature. It was the contamination of a lettuce crop in England in 1998 after sprinkling the plants with contaminated water containing toxins of *Mycrosystis aeruginosa* (Codd et al., 1999, Metcalf et al., 2014). This contamination was detected on lettuce leaves. There were removed from marketing as a precautionary measure.

The persistence of cyanotoxins in the environment is a fundamental issue regarding the management of the restriction of uses. In the laboratory, these toxins can withstand high temperatures and extreme pH levels from 1 to 12. In the environment, cyanotoxins are subjected to UV photolysis of the sun. The half-life of cyanotoxins is from days to weeks (Metcalf et al., 2014). Microcystins are stable molecules (half-life estimated between 90 and 120 days for microcystins-LR), whereas anatoxins-a are much more unstable.

CURATIVES MANAGEMENT MEASURES

These measures can temporarily restore the use of a water body. Nevertheless, these measures are likely to cause damage to the fauna and flora. The choice of the measures is to be evaluated according to the cost-benefit analysis, available human resources, technical feasibility and environmental-socio-economic impacts (Anderson et al., 2007). Curative measures are emergency measures that are not intended to be used as long-term management methods.

Chemical action against proliferation

Chemical methods are adopted in a short-term perspective to control the proliferation of cyanobacteria, but these methods are controversial. The economic impacts caused by restrictions of activities during a bloom may encourage managers to use chemical methods. In France the use of these chemical compounds is discouraged by the May 2003 opinion published by the Higher Council of Public Hygiene of France. However they can be applied by derogation. Copper sulphate is the most commonly algaecide used. This algaecide has an inhibitory action on photosynthesis, cell multiplication and nitrogen fixation (Barroin, 1999). Copper is toxic to cyanobacteria from 0.06 to 0.25 mg / L (Agriculture and Agri-Food Canada, 2002). Copper treatment has many health and environmental impacts. First of all its application causes the lysis of the cells and the release of the cyanotoxins within the environment. Moreover, its action is non-specific: it also acts on zooplankton and fish (Shao et al., 2013). Finally, copper does not degrade: it precipitates and accumulates in the sediment. Therefore, this management measure is not adapted to toxic efflorescence in closed water bodies.

Researchers are currently investigating the use of hydrogen peroxide (H_2O_2) to control cyanobacterial blooms. Based on laboratory results, hydrogen peroxide would act in a targeted and efficient manner at low concentrations (Matthijs et al., 2011). Hydrogen peroxide is an inhibitor of photosynthesis. Cyanobacterias decline twice as fast as the populations of other photosynthetic eukaryotic species. Laboratory studies have shown effective results on the cyanobacteria specie *Planktothrix rubescens* from a concentration of 1.75 mg / L of hydrogen peroxide (Matthijs et al., 2011). In terms of impact on the environment, oxygenated water degrades rapidly in water, ranging from a few hours to a few days, leaving no trace in the environment (Matthijs et al, 2011). In presence of iron or manganese, the exposure of hydrogen peroxide to light can produce a toxic chemical reagent (hydroxyl radical), causing a deterioration of the aquatic species cells . To date, only one experiment in real conditions[3] has been carried out in the Koetshuis Lake in Netherlands. The maximum depth of Koetshuis Lake is two meters and its surface area is 0.12 km^2. The experiment involved a concentration of 2 mg / L H_2O_2 throughout the lake. Despite encouraging results, many questions need to be elucidated before this reagent can be used routinely to fight cyanobacterial blooms. First of all, how to dose the product according to the composition of the aquatic population of the lake, the frequency of application and the effectiveness of the treatment after several applications, regarding the development of the resistance of cyanobacteria to this treatment in particular.

Sediment reduction actions for internal nutrient loading

In a water body, phosphorus is present in various forms: in the form of phosphates within the water column (form directly available for cyanobacteria) and in sediments (internal stock). Different control methods exist to reduce the availability of directly assimilable nutrients and internal stock stored in sediments.

Short-term methods are based on the use of chemical reagents such as aluminum compounds (aluminum sulfate, aluminum chloride) to reduce the phosphates concentration in the water column. These reagents cause the precipitation of phosphorus and its accumulation in the sediments. Nevertheless, the environmental impacts are not negligible. To avoid the toxicity of aluminum, the pH of the water should be maintained between 6 and 8 (Jorgensen et al., 2005). There are temporary measures because some conditions such as pH change and water anoxia cause the dissolution of the precipitates stored in the sediments

Long-term measures focus on the problem of releasing phosphorus from sediments. Phoslock is a new process developed in Australia that ensures sediment recovery by a waterproofing clay layer of bentonite and clay (Phoslock Water Solutions Ltd., 2017). Sediment removal is another curative approach to significantly reduce the internal nutrient load of a reservoir. The sediment extraction has several disadvantages to consider. First of all, dredging is an expensive method which often involves to empty the water body. In addition, the self-purifying microorganisms present on the sediment surface are evacuated. Finally, sediments are sometimes considered as waste, which raises the question of their becoming after extraction. Curative treatments must be accompanied by preventive measures to control the external phosphorus inputs coming from the entire catchment area.

Actions ont the hydrological regime

Hydraulic management of the reservoir by renewal of the water

This method consists of limiting water residence time in the reservoir by increasing the inlet and outlet flow rates. Water renewal attenuates the period of sedimentation of organic matter and thus reduces the establishment of anoxic conditions on the sediments surface, leading to the release of nutrients. However, the increase of the current velocity, due to water flows increase, can result in the resuspension of the unconsolidated surficial sediments. It also increases the reservoir's and the river water downstream's turbidity. High turbidity limits swimming and nautical activities. In economic terms, this process creates direct costs for the workforce needed to manipulate the structures, and indirect costs due to the early organ wear and maintenance's costs. The extreme case is the complete emptying of the reservoir to chase the cyanobacteria and sediments suspended in the water column. This action is subject to declaration or authorization depending on the volume of the reservoir.

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[3] On Koetshuis Lake in the Netherlands affected by *Planktothrix agardhii* blooms.

Artificial mixing of reservoir water

This method aims at oxygenante the water. The indirect effect of this process is the resuspension of the nutrients found on the surface of the sediments. In order for the bubbling to be effective against cyanobacteria, several conditions are necessary: the bubbling devices must be distributed homogeneously throughout the horizontal surface of the lake and the depth of the mixing must be sufficient to bring the cyanobacteria into the euphotic zone (Visser et al., 2015). This method was used on Lake Grangent.

THE REDUCTION OF NUTRIENT FLOWS TO ECOSYSTEMS

The use of preventive measures aims to reduce the capacity of the natural environment to favor the development of cyanobacteria in the long term. These measures focus on reducing external nutrient inputs into the environment and are an integrated approach at the watershed scale.

Policies against eutrophication

The Council Directive 91/676/EEC of 12th December 1991, called the 'nitrates' Directive, aims to reduce water pollution by nitrates of agricultural origin. In France, the application of this directive has resulted in a classification of vulnerable zones. These areas are constrained to the implementation of specific agricultural practices.

The European Urban Wastewater Directive of 21st May 1991 encouraged the reduction of phosphorus flow through the development of wastewater treatment plants throughout the country and the improvement of wastewater treatment with the introduction of tertiary treatment. The total phosphorus discharge limits allowed by the European Union are 1 to 2 mg / L[4]. Finally, the Grenelle Environment has definitively banned the use of phosphates in detergents since the end of 2014 with Decree No. 2014-1671 of December 30, 2014.

The limitations of these actions: example of Bourget Lake

The nutrient reduction policy efficiency is limited as illustrated by the case of Bourget Lake. Following a decrease in phosphorus concentrations initiated in the 1990s, summer growth of many phytoplankton species has been reduced in the lake. From 1996 these conditions allowed the recurrent development of new specie, the toxic cyanobacteria *Planktothrix rubescens*, a filamentous specie, in the metalimnion (Humbert et al., 2007). It is a typical species of deep and mesotrophic lakes[5] (Reynolds et al., 2002). The final report about the Bourget Lake in the years 2004 and 2005 emphasizes that the proliferation of *P. rubescens* "also translate, paradoxically, an overall improvement in lake water quality since the development of this specie has been made possible by a lower production of the phytoplankton compartment within the epilimnion, in relation to the decrease in phosphorus concentrations in this stratum" (Humbert et al., 2007). In fact, the decrease in surface phytoplankton production has led to an increase in transparency within the lower layers. It has favored the development of the species present in these lower layers. In addition, despite the efforts carried out to reduce incoming flows, the internal stock in the sediments remained an important source of phosphorus. Appendix 2 summarizes the effects of the measures carried out on the Bourget Lake. The objective announced in this report was to achieve a phosphate concentration under

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[4] Differs by station size.

[5] Medium-rich nutrients lake. The phosphate concentration of a mesotrophic lake is between 0.01 and 0.035 mg / L.

15-20 µg / L to limit the development of *P. rubescens*. From 2009 the species *P. rubescens* declined while the species *Microcyst*is made its appearance in 2014.

The adaptation of different species to a wide variety of environments makes cyanobacterial bloom management complex. On the one hand, ecosystems always contain inocula of cyanobacteria which can proliferate as soon as phosphorus concentration increases again. On the other hand, sediments can represent an internal stock of nutrients long after the drop in external inputs.

EMERGING TECHNIQUES TO INCREASE THE REACTIVITY OF MANAGERS

In France, the count of cyanobacteria and their toxins must imperatively be carried out by an accredited laboratory. In March 2017, 143 laboratories have national accreditation for phytoplankton sampling and analysis (Ministère des affaires sociales et de la santé, 2017). Analyses are based on the identification of the species and the counting of the cells by microscopy. One of the main constraints mentioned by managers is the waiting period for receiving the results of a toxicity analysis (Pickhahn et al., 2016). Delays often exceed several weeks. The waiting period is far too high compared to a manager's decision time that must be extremely fast.

In this context, research is directed towards the development of instantaneous detection methods for quantifying the abundance of cyanobacteria in the environment and their toxins, allowing a real-time reaction. Moreover, limits encountered by visual surveillance also lead to the setting up of automatic monitoring devices for water bodies.

QUANTIFICATION OF THE ABUNDANCE OF CYANOBACTERIA AND THEIR TOXINS

In order to quantify in situ the abundance of cyanobacteria in the environment, new tools based on the measurement of in vivo fluorescence of cyanobacteria are developed. These methods of quantification do not make it possible to determine the species and the genera involved. In France, the National Institute for Research in Science and Technology for Environment and Agriculture (IRSTEA) is developping a fluorimeter. It measures the concentration of total chlorophyll-a and the concentration of chlorophyll-a associated with cyanobacteria. The measurement of chlorophyll-a concentration is used as an indicator of phytoplankton biomass. IRSTEA has developed the first version of its fluorimeter on the lakes of Born in Lozère (France). The challenge now is to implement a routinely protocol (Pickhahn et al., 2016). Ultimately, the goal is to introduce new alert thresholds based on the concentration of chlorophyll-a associated with cyanobacteria[6]. However, the limits from the fluorescence methods are the presence of other algae in the environment possessing the same pigments as the cyanobacteria.

In order to quantify in situ the concentration of toxins, it is possible to use enzymatic immunoassays[7]. These tests are based on the specific recognition between antigens (toxins) and antibodies leading to the staining of assay when antigen-antibody couplings occur. These tests work even at low concentrations. This visual detection through the coloring of the test allows rapid reactivity from the manager. However, some limits have to be taken into account:

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[6] Currently, alert thresholds are based on the concentration of cyanobacterial cells per mL measured in the laboratory.

[7] The ELISA test (Enzyme Linked ImmunoSorbent Assay) is the most commonly used.

false-negative results can be obtained (Lehman, 2007) and underestimation of toxins concentration (Msagati et al., 2006).

DEVELOPEMENT OF WARNING SYSTEMS

Warning systems are based on continuous measurements of different meteorological parameters (temperature, wind speed, wind direction) and water quality (water temperature, depth, pH, dissolved oxygen) to prevent bloom episodes. The National Research Agency (NRA) designed buoys containing multi-parameter probes (PROLIPHYC project). The limits encountered by this project are high equipment costs as well as the lack of available satellites (Agence Nationale de la Recherche, 2013). The OSS-CYANO project has succeeded the PROLYPHYC project with the objective of developing a low-cost air sensor able of detecting the presence of cyanobacteria in an ecosystem (Agence Nationale de la Recherche, 2016). Currently, efflorescence teledetection is effective only at high algal concentrations. It does not detect early signs of bloom. The issue of the differentiation of cyanobacteria from other algal species must also be resolved in order to set up efficient warning systems.

CONCLUSION

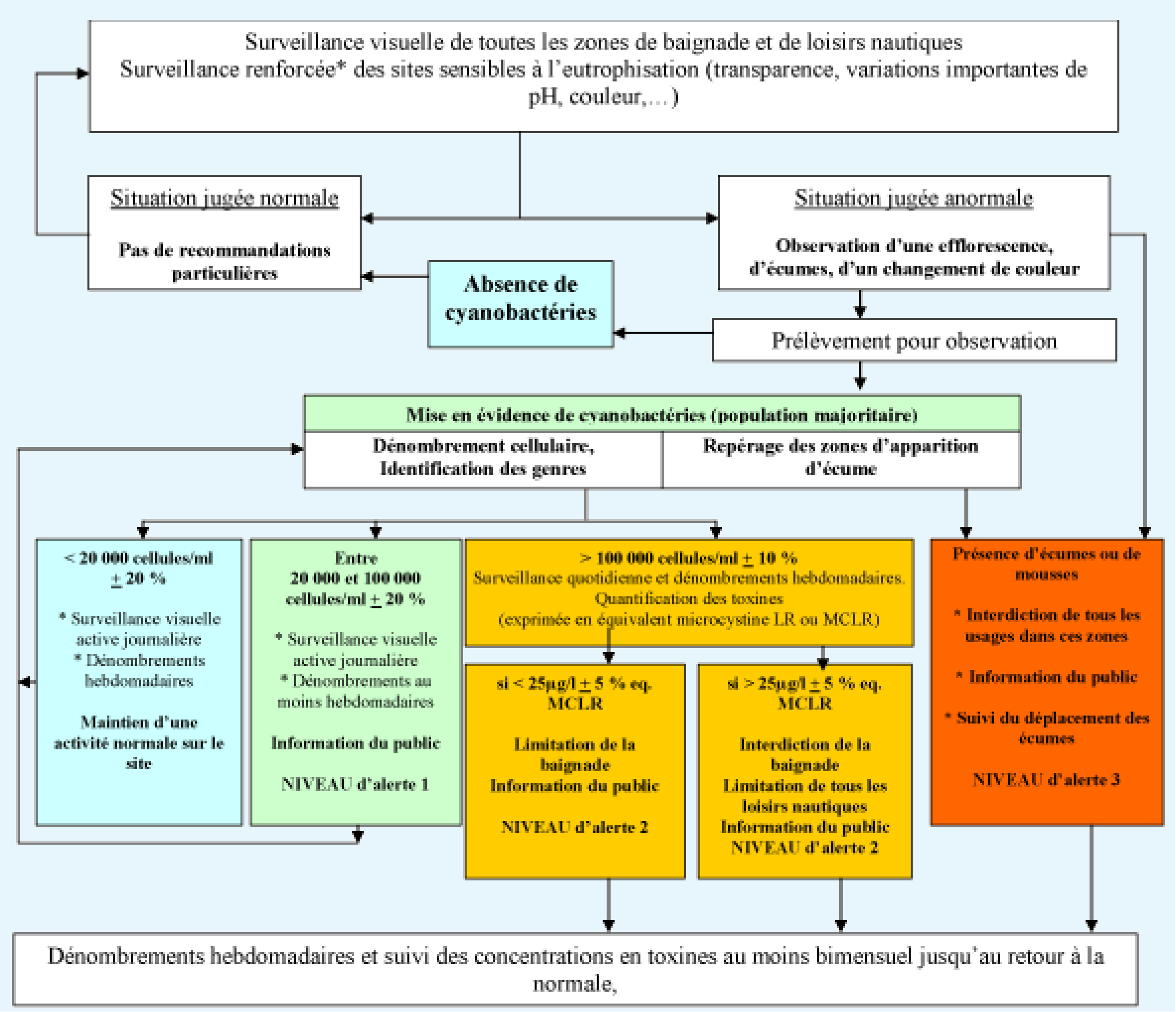
This synthesis focuses on cyanobacteria that are harmful to health, since toxin production is the main concern of health authorities and managers. It leads to the establishment of management measures to reduce the risks of proliferation and human exposure. Nevertheless, it is interesting to note that some species are used for therapeutic and energy purposes.

In France, management is still relatively unstructured. On the one hand, monitoring protocols are not harmonized between the different departments. On the other hand, management measures often focus mainly on the functioning of the reservoir due to lack of knowledge of the watershed. Collaborative management is tending to become widespread in watersheds sensitive to eutrophication. However the issues of monitoring responsibility, administrative and financial obstacles are slowing down the progress of projects.

Many mechanisms still need to be elucidated in order to increase the responsiveness of managers to bloom: blooming prediction and the determinants of toxin production. The choice of management measures must be based on a thorough analysis of the environment, because poor knowledge of the surrounding environment and the functioning of the water body can lead to costly and inefficient actions (Anderson and Al., 2007). The success of the restoration measures depends on various factors: the level of reduction of external phosphorus inputs and the renewal of water to evacuate the phosphorus released by the sediments (Fastner et al., 2015). Nevertheless, despite the development of management measures, bloom episodes can not be totally or permanently eliminated (Fastner et al., 2015) because cyanobacteria are ubiquitous species capable of adapting to many conditions.

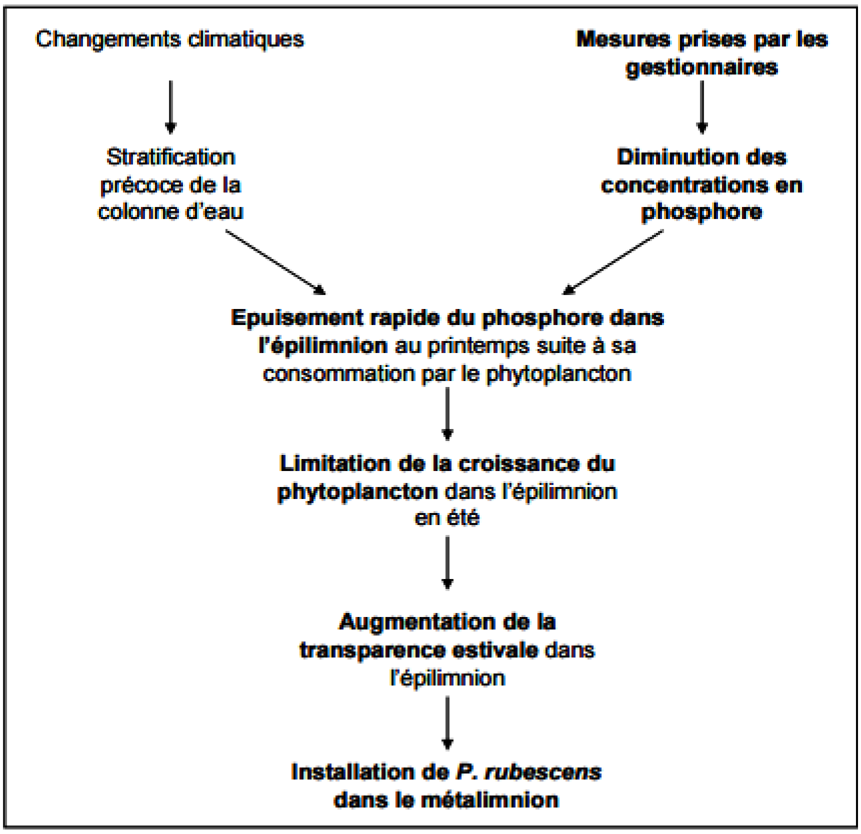
Research is very active in the field of monitoring and quantification with the development of new technologies. Currently, visual observation is the trigger for toxicity testing. This method of monitoring is criticized and therefore warning systems are being developed. These systems rely on real-time detection of the concentration of cyanobacteria. Finally, the quantification of toxins in situ is also a promising technology for better reactivity.

Appendix 1 : Alert thresholds and health risk management



Source : Ministère des affaires sociales et de la santé (publié le 25 mai 2012)

Appendix 2 : Effects of management measures on the Bourget Lake



Source : Humbert et al., 2007

Bibliography

Scientific literature

Anderson C., Lafontaine N., Meunier P., Turgeon S., 2007. *Prendre son lac en main : Guide synthèse: élaboration d’un plan directeur de bassin versant de lac et adoption de bonnes pratiques*. Québec, Gouvernement du Québec, 25 p.

Barroin G., 1999. *Limnologie appliquée au traitement des lacs et d’eau*. Thonon-Les-Bain, Agences de l’eau, 215 p. Les études des Agences de l’Eau, Etude n°62.

Bernard C., 2014. Les cyanobactéries et leurs toxines. *Revue francophone des laboratoires* (460), pp. 53-68.

Briand E., 2008. *Contribution à la compréhension du déterminisme de la mise en place des proliférations de cyanobactéries et de leur production de toxines*. Thèse pour l’obtention du doctorat en Ecologie Microbienne, Muséum National d’Histoire Naturelle, Paris, 270 p.

Brient L., Legeas M., Leitao M., Peigner P., 2004. *Etude interrégionale Grand Ouest sur les cyanobactéries en eau douce : caractérisation de sites à usage d'eau potable et de loisirs vis-à-vis de la prolifération de cyanobactéries. Examen des causes de développement des algues et proposition d’un suivi sanitaire.* Rennes, DDAS, DGS, 82 p.

Chorus I., Bartram J., 1999. Algae and cyanobacteria in fresh water. Ch. 8. In: Chorus I., Bartram J., *Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring and management.* Londres, E & F Spoon, OMS, 416 p.

Codd G.A., Metcalf J.S., Beattie K.A., 1999. Retention of Microcystis aeruginosa and microcystin by salad lettuce (Lactua sativa) after spray irrigation with water containing cyanobacteria. *Toxicon*, 37(8), pp. 1181-1185.

Coulon O., 2016. *Les Cyanobactéries dans le bassin Loire-Bretagne : retour expérience large échelle*. Biscarrosse, IRSTEA Bordeaux, 16 p. [Diffusé le 09/03/2016].

Corkal D., 2002. *Le traitement au cuivre des étangs réservoirs*. Otawa, Gouvernement du Canada, Service Agriculture et Agroalimentaire Canada, 6 p.

Fastner J., Abella S., Litt A., Mor bito G., Vörös L., Pálffy K., Straile D., Kümmerlin R., Matthews D., Phillips M.G., Chorus I., 2015. Combating cyanobacterial proliferation by avoiding or treating inflows with high P load – experiences from eight case studies. *Aquatic Ecology*, 50 (3), pp. 367-383.

Ho L., Sawade E., Newcombe G., 2012. Biological treatment options for cyanobacteria metabolite removal - A review. *Water research*, 46, pp.1536-1548

Hoek C., Mann D. G., Jahns H. M., 1995. *Algae: An Introduction to Phycology*. Cambridge, Cambridge University Press, 623 p.

Hayes P. K., Walsby A., 1986. The inverse correlation between width and strength of gas vesicles in cyanobacteria, Bristol. *British Phycological Journal*, 21(2), pp. 191-197.

Humbert J. F., Jacquet S., Anneville O.,2007. Rapport final sur l'étude lourde du lac du Bourget (2004-2005), Thonon, UMR CARRTEL, 195 p.

Jourdain M., 2010. *Les effets des variables environnementales sur le recrutement des cyanobactéries et des akinètes*. Maîtrise en Biologie, Université du Québec à Montréal, Montréal, 112 p.

Jorgensen S. E., Loffler H., Rast W., Straskraba M., 2005. *Lake and Reservoir Management*. 1ère éd., Amsterdam, Elsevier, 512 p. Developments in Water Science, vol.54.

Laplace-Treyture C., 2016. *Les cyanobactéries d'eau douce, une nuisance ?.* Biscarrosse, IRSTEA Bordeaux, 12 p. [Diffusé le 09/03/2016].

Lehman, E.M., 2007. Seasonal occurrence and toxicity of Microcystis in impoundments of the Huron River, Michigan, USA. *Water Research*, 41(4) pp. 795-802.

Matthijs H. C. P., Visser P. M., Reeze B., Meeuse J., Slot P. C., Wijn G., Talens R., Huisman J., 2011. Selective suppression of harmful cyanobacteria in an entire lake with hydrogen peroxide. *Water Research*, 46 (5), pp. 1460-1472.

Metcalf J. S., Codd G. A., 2014. *Cyanobacterial Toxins (Cyanotoxins) in Water*. A Review of Current Knowledge, Marlow, Foundation for Water Research, pp. 45.

Msagati, T.A.M., Siame, B.A., Shushu, D.D., 2006. Evaluation of methods for the isolation, detection and quantification of cyanobacterial hepatotoxins. *Aquatic Toxicology*, 78(4), pp. 382-397.

Mur L.R., Skulberg O.M., Utkilen H., 1999, Cyanobacteria in the environment. Ch. 2. In : Chorus I., Bartram J., *Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring and management*. Londres, OMS, E & F Spoon, 416 p.

OCDE, 1982. *Eutrophisation des eaux Méthodes de surveillance, d'évaluation et de lutte*. Paris, OCDE, 164 p.

Pickhahn L., Moreira S., Gogin S., Laplace-Treyture C, 2016. *Le dispositif CYANALERT : un système de surveillance et d'alerte opérationnel des proliférations de cyanobactéries*. Biscarrosse, IRSTEA Bordeaux, 16 p. [Diffusé le 09/03/2016].

Reynolds C. S., Huszar V.,Kruk C., Naselli-Flores L., Melo S., 2002. Towards a functional classification of the freshwater phytoplankton, *Journal of plankton research*, 24 (5), pp. 417-428.

Sinang S.C, Reichwaldt E.S. et Ghadouani A., 2013. Spatial and temporal variability in the relationship between cyanobacterial biomass and microcystins. *Environmental Monitoring and Assessment*, 185(8), pp. 6379-6395.

Shao J., Li R., Lepo J.E., Gu J.-D., 2013. Potential for control of harmful cyanobacterial blooms using biologically derived substances: Problems and prospects. *Journal of Environmental Management*, 125, pp. 149-155.

Smith V. H., 1983. Low Nitrogen to Phosphorus Ratios Favor Dominance by Blue-Green Algae in Lake Phytoplankton. *Science,* 221(4611), pp. 669-671

Visser P. M., Ibelings B. W., Bormans M., Huisman J., 2015. Artificial mixing to control cyanobacterial blooms: a review. *Aquatic Ecology*, 50 (3), pp. 423-44.

Other useful references

Brient L., Raoult C., Le Rouzic B., Bertru G., 2001. Conditions d'utilisation du CuSO4 pour limiter les proliférations de cyanobactéries et réduire ses effets sur l'environnement. *TSM*, (9), pp. 66-73.

Commission Locale de l'Eau du SAGE Isle Dronne, 2016. Schéma d'Aménagement et de Gestion des Eaux – Etat des lieux. Castelnaud-la-Chapelle, EPIDOR, 77 p.

Jancula D., Marsalek B., 2011. Critical review of actually available chemical compounds for prevention and management of cyanobacterial blooms. *Chemosphere*, 85 (9), pp. 1415-1422.

Sivonen K., Jones G., 1999, Cyanobacterial toxins. Ch. 3. In : Chorus I., Bartram J., *Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring and management.* Londres, OMS, E & F Spoon, 416 p.

Websites

Agence Nationale de la Recherche, 2006. Système opérationnel pour la surveillance et l'alerte en temps réel des proliférations phytoplanctoniques - application aux cyanobactéries. Disponible sur Internet : URL, http://www.agence-nationale-recherche.fr/?Projet=ANR-06-ECOT-0017 [Consulté le 17/02/2017].

Agence Nationale de la Recherche, 2013. Développement d'un capteur optique et d'un système drone pour la surveillance spatiale des cyanobactéries dans les écosystèmes aquatiques continentaux. Disponible sur Internet : URL, http://www.agence-nationale-recherche.fr/?Projet=ANR-13-ECOT-0001 [Consulté le 17/02/2017].

INRA, 2015. Quels impacts des cyanotoxines présentes dans les eaux d'irrigation des cultures ? Disponible sur Internet : URL, http://www.versailles-grignon.inra.fr/Toutes-les-actualites/201504-Cyanobacteries-cultures-maraicheres [Consulté le 01/12/2016].

Ministère des affaires sociales et de la santé, 2012. Pourquoi et comment est contrôlée la qualité des eaux de baignades ? Disponible sur Internet : URL, http://baignades.sante.gouv.fr/baignades/editorial/fr/controle/critere_s.html [Consulté le 05/10/2016].

Ministère des affaires sociales et de la santé, 2017. Laboratoires agréés pour le contrôle sanitaire des eaux. Disponible sur Internet : URL, http://social-sante.gouv.fr/sante-et-environnement/eaux/article/laboratoires-agrees-pour-le-controle-sanitaire-des-eaux. [Consulté le 14/03/2017].

Phoslock Water Solutions Ltd., 2017. The Phoslock Solution : Scientific Information. Disponible sur Internet : URL, http://www.phoslock.com.au/irm/content/scientific-information1.aspx?RID=222. [Consulté le 10/02/2017].

Interviews

Bardin N., 2017. Ex-chargée de mission qualité des eaux (Etablissement Public Territorial du Bassin Versant de la Dordogne). Interview le 16/01/2017.

Boesch P. Y., 2016. Délégué Concessions Eau Environnement & Territoire Aude Ariège (EDF – Division Production et Ingénierie Hydraulique). Interview le 14/12/2016.

Louveton F., 2017. Agent des Voies Navigables de France (Direction Territoriale Sud-Ouest, Arrondissement de l'entretien et de l'exploitation). Interview le 16/01/2017.

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