Cyanotoxins and Their Risk to Human Health

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Executive Summary:

In recent years, there have been increasing incidences of algae-blooms due to non-point source run-off and other types of water pollution. Climate change has played a role in this phenomenon as well, because when water temperature increases, it increases the growth of cyanobacteria in water (Vermont Department of Health, 2005). During post algae-blooms, the decomposition of algae consumes oxygen, and the water becomes oxygen-depleted, or anoxic (Australian Academy of Science, 2009). Anoxia influences other aquatic organisms, including fish, which need oxygen to survive. Furthermore, certain taxa of cyanobacteria are known to produce toxins including Anatoxin-a, Microcystin LR, B-N-Methylamino-L-Alanine (BMAA), and Nodularin, which can cause death not only in aquatic organisms, but also in domestic animals and terrestrial wildlife (Cox, 2005). These toxins have also been linked to neurological diseases in humans. It is important to understand the behavior and mechanism of cyanotoxins in the environment, which will allow scientists to find ways to prevent the toxins from further impacting organisms and the environment.

Our main research goals were to better understand how cyanobacteria becomes toxic, as well as discover how closely they are linked to various degenerative neurological diseases, such as Amyotrophic Lateral Sclerosis (ALS) and Parkinson's Disease. We also would like to determine the best method of cyanobacteria removal from drinking water, and look at different exposure pathways. Research was concentrated on human health impacts, measuring blooms, removal, spatial trends, especially in New England once the general overview was complete. Exposure levels were researched to determine whether there was a difference in an acute or chronic exposure, and how certain removal methods, such as sedimentation, or even chemical treatments, will reduce or eliminate toxicity in the system.

It appears the best solution for now is to continue to decrease phosphorus loading and stream bank erosion through stream buffers and preventing livestock from entering waterways, while treating the bacteria with a variety of methods, such as sedimentation and chemical remediation. Once even more professional research has been thoroughly conducted, cyanotoxins will hopefully be understood and a solid connection will be made between the toxins and diseases, and a solution for toxin elimination will be available.
**Problem Statement:**

Cyanobacteria, which are found worldwide, including Lake Champlain, have recently been linked to several types of neurodegenerative diseases, including amyotrophic lateral sclerosis (ALS), Parkinson's Disease, and Alzheimer’s Disease, which occur through exposure to toxins produced by cyanobacteria.

**Background:**

As cyanobacteria cells die, some produce toxins and release them into the surrounding water (Tebaldi, 2010). Toxins can then be absorbed, inhaled, or ingested, creating a variety of potential exposure pathways. Even small amounts of toxins can be lethal doses for many animals, and exposure to them is now being linked to certain neurodegenerative diseases in humans, such as ALS (Lou Gehrig's Disease), Parkinson's Disease, and various liver diseases, such as Primary Liver Cancer (Hitzfield, 2000).

In Vermont, cyanobacteria blooms occur in Lake Champlain every year and have been linked to the deaths of family pets, but luckily blooms haven't had a noticeable impact on humans yet. Problematic areas in the lake include the Missisquoi, St. Albans, and Burlington bays. This is particularly troublesome because two of these areas (Burlington and St. Albans bays) are located in high-density residential areas, meaning a toxic bloom could enter drinking water poisoning thousands of people (Phosphorus Pollution, 2007). It is important to understand how these toxins are produced, what water remediation techniques are available, and these toxins' potential to cause disease so that we may be better equipped to eliminate some to all of these toxins in the water so they no longer pose a threat to human and animal health.

**Purpose Statement:**

The purpose of this project is to study the behavior and mechanism of cyanotoxins in the environment and the human body. We will also thoroughly investigate cyanotoxin's effects on human health in the Lake Champlain Basin and determine precautionary measures to prevent the toxins from further impacting human life and the environment.

**Objectives:**

There are several objectives to this study, each building on the previous objective to gain a better overall understanding of cyanobacteria, the toxins they produce, and their effects on human health. The first objective is to examine the behavior and mechanism of cyanotoxins so we may better understand where, why, and how they form. We will then investigate how they become toxic to both humans and animals and what sort of effects they have on human health. We will also look at different methods of eliminating the toxins from water, and how effective they have been. We will determine what method(s) appears to be the best way of eliminating cyanobacteria, either partially or completely, so as not to pose any threats to human health.
Finally, we will research precautionary measures that may be taken to prevent toxins from entering the water, or at the very least reduce them so humans and animals are not exposed to them.

**Approach:**

Suzanne Levine was interviewed for background information on cyanotoxins, as she has performed research in Lake Champlain and was able to provide a local perspective on the issue. Most information was gathered via online searches using Google, Google Scholar, and the UVM Library search engines including JSTOR, Web of Science, and Science Direct. Key words that were utilized include "cyanotoxins", "cyanobacteria", "health effects", and "Lake Champlain". All research was posted for group members to access via BlackBoard or email, and individual members researched what they deemed necessary at the time to gather a complete breadth of information.

**Findings:**

**Cyanobacteria Blooms**

Cyanobacteria blooms, more commonly known as blue-green algae blooms, have been presented as an environmental risk in water resources for the past decade. Cyanobacteria are a class of ancient, unicellular, photosynthesizing organisms that occur in both freshwater and marine environments. There are about 2,000 different species of cyanobacteria, 40 of which are known to produce toxins (Hitzfeld, 2000). When conditions are favorable cyanobacteria populations can multiply rapidly and create algal blooms. A number of factors can contribute to the formation of algal blooms, including nutrient concentrations (primarily nitrogen and phosphorus), temperature, light, and the morphology of the impoundment (Yoo, 1995).

There is a wide array of cyanobacteria that produce cyanotoxins. Some of these toxins include hepatotoxins, neurotoxins, cytotoxins, irritants, gastrointestinal toxins, and others that have not been linked to particular disease (Funari and Testai, 2008). Hepatotoxins cause liver disease. Many cyanotoxins, including anatoxin-a, homoanatoxin-a, anatoxin a-(s), saxitoxin, are classified as neurotoxins (Funari and Testai, 2008), which cause damage or death to neurons or the nervous system in general. The cyanotoxins that are irritants and gastrointestinal toxins are alysiatoxin, debromoaplysiatoxin, and lyngbyatoxin, lipopolysaccharidic endotoxins (Funari and Testai, 2008). Many of the short-term effects of cyanotoxins are known, but few of the long-term effects on humans have yet to be studied (New York Department of Health, 2003).

**Cyanotoxins**

The cyanotoxin BMAA is produced by the cyanobacteria *Microcystis*, *Anabaena*, *Nostoc*, and *Planktothrix*. Microcysts are produced mainly by the following cyanobacteria; *Microcystis* spp., *Planktothrix* spp., *Anabaena*, *Nostoc*, *Synechocystis*, *Cyanobium bacillare*, *Arthrosira fusiformis*, *Limnothrix redekei*, *Phormidium formosum*, and *Hapalosiphon hibernicus*. Anatoxin-a is formed by most of *Anabaena* spp., and some of the following cyanobacteria; *Aphanizomenon*
spp., *Cylindrospermum, Microcystis, Planktothrix* spp., and *Raphidiopsis mediterranea*. Nodularins are produced by *Nodularia spumigena* (Funari and Testai, 2008).

**Cyanotoxins and Human Health**

According to Funari and Testai in 2008, Parkinson's Disease, Alzheimer's, and ALS can all be caused by neurotoxins, some of which are produced by cyanobacteria. As many as 30 species of cyanobacteria have been shown to produce the neurotoxin BMAA which can bioaccumulate both in terrestrial and marine ecosystems, as is demonstrated in Figure 1. Even low levels of BMAA can cause motor neuron disease or even death. In 2007 Banack stated that this neurotoxin has been most frequently studied in Guam as exposure to the toxin was found by a cluster of ALS and Parkinsonism Dementia Complex after World War II. Originally, BMAA was found to be from the seeds of cycads, which natives ate, but later it was found that its concentrations were much higher in the roots due to symbiotic cyanobacteria producing the BMAA (Bradley and Mash, 2009). Current research has shown that patients exhibiting neurodegenerative symptoms have accumulations of BMAA in their brain tissue (Banack, 2007).

![Figure 1. Cyanobacteria’s connection to human health, ecosystems, and organisms.](image)

Other aspects of human health that are compromised due to cyanobacteria exposure have been found by accident. In Brazil, a hospital used water for hemodialysis patients that was contaminated with microcystins. 56 of the 130 patients died, all stemming from exposure to cyanotoxins (Hitzfeld, 2000). In some countries the water used for dialysis is regulated for quality; however, many do not require a cyanobacteria limit and cyanobacteria is not looked for at all (Funari and Testai, 2008).

Exposure to cyanotoxins can occur through eating contaminated food, drinking contaminated water, swimming, or coming in contact with contaminated water. How one comes in contact with the cyanotoxins, the species they are exposed to, and how long they are in contact for can
help predict the severity and the type of disease they may experience. The bioavailability of the toxin in the human system is thought to be based on the situation as well as how one was exposed (Funari and Testai, 2008). Swimming or being in dermal contact with cyanobacteria can cause skin rashes on humans (Vermont Department of Health, 2005). Contact and inhalation from airborne water droplets can cause irritation of the eyes, nose, throat, skin, and respiratory tract (New York Department of Health, 2003).

Drinking contaminated water can cause both acute and chronic illness based on level of contamination in water. Most short-term effects are due to water not being treated, or the treatment working inefficiently, causing the lysis of the cyanobacterial cells. Cyanobacteria in drinking water has been known to cause gastroenteritis, liver and kidney damage, and even death. Chronic effects are hard to prove that they in fact are caused by cyanotoxins. Many times, geospatial analysis has shown clusters of people with the same chronic illness around areas with cyanobacteria bloom (Funari and Testai, 2008).

It is important for drinking water suppliers to monitor for cyanotoxins in their water in order to prevent human exposure. However, this can be a very difficult task for a variety of reasons. Cyanotoxins are produced inside the cyanobacteria cells, but can be released into the environment if the cell membrane is damaged. It is also difficult to predict the levels of toxins inside the cells at a given time, and toxin levels can vary widely in space and time in aquatic environments (Yoo, 1995).

**Cyanobacteria in Lake Champlain**

Algal blooms and scum are a nuisance in some of the bays of Lake Champlain, especially St. Albans Bay and Mississquoi Bay (Vermont Department of Health, 2005). This is due to many favorable conditions for bacteria growth, which include warm, shallow, stagnant water that is loaded with nutrients. Cyanobacteria cause blooms and scum, but because not all species of cyanobacteria are toxic, neither are all blooms and scums. Toxic cyanobacterial blooms have only been documented in the lake since 1999. Within the last four years, the cyanobacteria that can produce toxins have become dominant in the blooms (Watzin, 2005). One type of cyanobacteria mixes within the lake and can only be found by testing (Levine, 2010). Since Burlington and St. Albans residents get their drinking water from the lake, there is a potential for them to become exposed through ingestion or dermal contact in their own homes (Burlington Department of Public Works, 2008).

As seen in Table 1, an increase in algal blooms has caused additional concern to the stakeholders of Lake Champlain. Algal blooms seem to be increasing despite a decrease in phosphorus input into the lake at the same time (Phosphorus Pollution, 2007). Mississquoi Bay has a large amount of algal blooms due to phosphorus loading (Levine, 2010). Beaches are becoming closed for recreation due to the health hazards associated with the algal blooms (Vermont Department of Health, 2005). One factor contributing to this is the switch from grass-fed cows to grain-fed ones. The grain is being imported from outside the Lake Champlain Basin and is essentially adding more nutrients to the watershed, which eventually ends up in the lake. The natural cycling of the lake cannot handle this extra load of nutrients (Levine, 2010).

Table 1. Potentially toxin-producing cyanobacterial species in Lake Champlain by frequency of

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Table 1. Potentially toxin-producing cyanobacterial species in Lake Champlain by frequency of
occurrence (Watzin, 2005).

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Main Lake</th>
<th>South Lake</th>
<th>Missisquoi Bay</th>
<th>St Albans and other Northeastern Bays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anabaena flos-aquae</td>
<td>83</td>
<td>29</td>
<td>57</td>
<td>53</td>
</tr>
<tr>
<td>Anabaena spp.</td>
<td>51</td>
<td>50</td>
<td>43</td>
<td>58</td>
</tr>
<tr>
<td>Microcystis aeruginosa</td>
<td>47</td>
<td>43</td>
<td>94</td>
<td>56</td>
</tr>
<tr>
<td>Coelosphaerium spp.</td>
<td>34</td>
<td>29</td>
<td>4</td>
<td>44</td>
</tr>
<tr>
<td>Gloeotrichia spp.</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Aphanizomenon flos-aquae</td>
<td>73</td>
<td>43</td>
<td>22</td>
<td>49</td>
</tr>
<tr>
<td>Samples Analyzed</td>
<td>102</td>
<td>14</td>
<td>175</td>
<td>45</td>
</tr>
</tbody>
</table>

2003 Frequency of Occurrence - Percent of Samples

Cases of animal deaths have been reported; however, there have been no cases of human deaths due to exposure to cyanotoxins (Department of Health, 2005). The climate of Lake Champlain does not allow for the continual presence of blooms, so it is much more unlikely that there will be long-term human health effects from the lake (New York Department of Health, 2003).

**Water Treatment**

Several techniques for the removal of cyanobacteria and cyanotoxins from drinking water have been tested. They include coagulation, flocculation, flotation, chlorination, ozonation, UV light, and various methods of filtration; sand/biofilm, activated carbon, and membrane filtration (Chow, 1997; Grutzmacher, 2002; Chow, 1999; Hitzfeld, 2000). Each removal technique includes several variations on the theme, and certain removal techniques, such as flocculation, flotation, and coagulation, have been combined in progressive removal experiments. In water treatment, coagulation is the binding together of various water impurities onto a substrate to form colloids. This is usually facilitated by flocculation, which is the mixing or stirring of the water containing the impurities and substrates. The colloids formed may be concentrated at the water's surface -- for removal -- by bubbling air through the water. Water treatment using ozone is similar to flotation in that it utilizes bubbling, but with molecules of ozone (O₃). The ozone molecules react with organic compounds, such as cyanotoxins, breaking them down. UV light also breaks apart cyanotoxins. Both are expensive though, and not effective if the water treated contains much sediment or extraneous organic matter. Similarly, each filtration method has its strengths and weaknesses, and conditions under which effective filtration fails.

The wide range of treatment techniques, treatment variations, and different result analysis methods makes it difficult to compare studies and determine if a technique consistently produces a result of desirable effect. Grutzmacher et al. (2002) found that slow sand filtration was effective at removing greater than 95% of microcystin toxins and 85% of cyanobacteria, when ambient temperature was above four degrees centigrade. However, Hitzfeld et al. (2000) cited sources questioning the effectiveness of sand filtration, even when combined with flocculation and coagulation. Hitzfeld also stated that coagulation/flocculation, while effective at removing
cyanobacteria, was not effective at removing cyanotoxins, and caused significant lysis of cyanobacteria and release of cyanotoxins. On the other hand, Chow et al. (1999) studied a treatment procedure used in modern water-treatment plants -- a process of coagulation-flocculation-sedimentation-filtration -- and found that nearly 100% of cyanobacteria were removed by the process with 95% or greater cell survival rate, indicating a low percentage of cell lysis. Chow et al. (1999) did not measure cyanotoxin concentration at any point in their study, but they did appear to refute the idea that coagulation/flocculation/filtration should not be used due to lysis of cells and release of cyanotoxins. Hitzfeld et al. (2000) have produced an overview of the effectiveness of all potential techniques for removing cyanobacteria and cyanotoxins, but given the evidence provided by Chow (1999) and Grutzmacher (2002), the conclusions of Hitzfeld might be called into question. It is difficult to make a recommendation on implementation and BMP for the maintenance of a drinking water supply, clean of cyanotoxins, given the variation in results for the same techniques.

Studies need to be replicated, or all the techniques attempted at a location of application, before a BMP can be determined for minimizing cyanotoxin/cell concentration in drinking water. For now, minimization should be the goal, until further risk assessment can be conducted to determine No Observable Adverse Effects Level (NOAEL) concentration targets. There exist a great many possible combinations for the removal of toxins and cells, some of which are more effective than others. However, our understanding of cyanotoxin and cyanobacteria occurrence and persistence in the environment is limited, and this makes analysis of the effectiveness of treatment methods difficult. It appears, given the evidence provided by Hitzfeld, that coagulation/flocculation/filtration -- to remove cyanobacteria cells and organic material -- followed by treatment with UV light or ozone -- to remove residual cyanotoxins -- might be most effective at reaching a target for drinking water quality. This combination has not been tested, though, so much uncertainty exists.

Conclusions and Recommendations:

Our recommendation has three aspects: prevention, increased public and government awareness, and continuation of research and monitoring. For prevention, there are two elements, preventing cyanobacteria blooms, and preventing human exposure. It is important to eliminate, or at least reduce non-point source pollution and agricultural runoff, as they are the main sources of pollution in the Lake Champlain watershed, as well as cyanobacterial blooms. Some of these pollutants include heavy metals, sediment, phosphorus, nitrogen, which can create more algae and cause massive plant and animal die-offs. In addition, impaired streams and reaches that have been identified by the state and EPA should be placed as a high priority, and should be restored as fast as possible within fiscal and societal limitations.

Prevention
Past research (Annadotter, 1999) has shown that the most effective method to neutralize non-point source and agricultural runoff is to establish riparian buffers and constructed wetlands along the edges of the areas considered to be impaired. Riparian buffers can be constructed along the edges of agricultural land. The optimal riparian buffer should be constructed based on a functional scale that includes attributes such as root strength, litter fall, shading, and coarse
woody debris (Keeton, 2010). As for constructed wetlands, they should be only established in areas that are prone to cyanobacterial blooms, or areas with a high volume of industrial discharge, nutrient loading, and/or runoff, as wetland construction can be a costly endeavor.

According to our research, the technology available for current water treatment methods is unable to completely eliminate cyanotoxins from water. During a bloom, the level of cyanotoxins in each water treatment step should be closely monitored, as chemical processes might need to be adjusted in order to effectively reduce the concentration of the toxins to safe levels. Current technology does not have the ability to effectively prevent human exposure from cyanotoxins in water intake; therefore, it is important to inform the public about the health impacts that cyanotoxins might cause in drinking water. For now, minimization should be the goal, until further risk assessment can be conducted to determine NOAEL concentration targets.

It appears, given the evidence provided by Hitzfeld et al. (2000), that coagulation/flocculation/filtration -- to remove cyanobacteria cells and organic material -- followed by treatment with UV light or ozone -- to remove residual cyanotoxins -- might be most effective at reaching a target for drinking water quality. This is a supposition, and must be actually tested.

**Education**
Right now the public is largely unaware that cyanotoxins can cause degenerative diseases in humans. Consequently, there is minimum media coverage, and lack of governmental response. This information needs to be reported to the public and can be reported through different local, state, and government environmental organizations, if officials in these areas vocalize the problem at hand. Clean Water Action would be a good environmental organization to get started with, as they have been dedicated to advocating for clean drinking water since late 1960’s, and have offices in almost every state. As the public becomes increasingly informed about the impacts of cyanotoxins in drinking water, it would be helpful for them to advocate and demand actions from government officials. In time, new policies might be designed to target protecting water resources from cyanobacterial blooms, and increase funding to invest in cyanotoxin research and monitoring.

**Continued Monitoring and Research**
The last aspect of our recommendation is to continue monitoring and researching cyanobacteria and the toxins they produce. Monitoring of cyanotoxin concentrations should be required in areas with repetitive cyanobacterial blooms, and continued research would allow for a more in-depth understanding of the behaviors and mechanisms of the cyanobacteria and toxins in both water and the human body.

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**Literature Cited:**


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