Executive summary:

A rise in annual mean global temperature will create a shift towards an increase in precipitation in the Northeastern United States. This increase in precipitation will cause an increase in runoff and higher flood pulse frequency to lakes in this region, resulting in a higher nutrient load to lakes. Lake Champlain already experiences excessive nutrient loading, specifically phosphorous loading, from agriculture and urban runoff sources which causes toxic cyanobacteria blooms in the shallower regions of the lake. These cyanobacteria blooms can have hazardous health issues to humans and other terrestrial mammals. Changes in lake stratification, as a result of changes in lake ice regimes, will cause an increase of phosphorous released from lake sediments. The sediment phosphorus release coupled with excessive phosphorous loading from runoff will cause an increase in the presence of cyanobacteria blooms in Lake Champlain, impacting fish species in the lake, water quality and recreation on the lake. Recommendations for remediation of these conditions include constructed wetlands and riparian buffers along rivers and the lake, as well as nitrification of lake water to limit sediment phosphorus release.
Problem Statement:

Environmental stressors, such as changes in temperature, runoff intensity, and alterations in lake freeze-over regimes, induced by climate change will alter internal phosphorus loading in Lake Champlain and therefore affect the species composition of algae.

Background:

The goal of the Clean Water Act (CWA) is to restore and maintain the physical, chemical, and biological integrity of the nation's waters and to make them swimmable, fishable and drinkable. This has not been achieved in Lake Champlain due to the presence of cyanobacteria and toxic algal blooms, which is of increasing concern. Algal blooms are the product of mass reproduction of cyanobacteria caused from an increase of phosphorus in the water. They pose numerous health threats by releasing a variety of neurotoxins, which can be dangerous and even deadly to humans and other species inhabiting the lake. Numerous beaches and swimmable areas are closed annually due to the excessive growth of cyanobacteria. Excessive phosphorous (P) loading due to increased runoff along with changes in the internal phosphorous loading regime and other impacts due to climate change can lead to an increase in the amounts of cyanobacteria present in the lake. An understanding of climate change’s impacts on cyanobacteria growth and accompanying blooms in the future is needed in order to assess and hopefully mitigate this comprehensive issue in Lake Champlain.

Regional climate change predictions for New England show that there will be an increase in precipitation and an increase in average temperatures. These predictions can have significant affects on lake systems and their internal functions. Increases in precipitation, and an increase in the intensity of storm events, will lead to more runoff and therefore more nutrient loading, which can increase the presence and abundance of cyanobacteria. Increases in average temperatures may lead to less Lake freeze-over events and shorter duration of freeze-over periods, which effect lake stratification, turnover and other lake dynamics. Changes in these lake structure dynamics can potentially increase the rate of internal phosphorous loading. This increase in internal phosphorous loading coupled with phosphorous loading from runoff will have great impacts on the abundance of cyanobacteria and accompanying algal blooms.

A change in species composition of algal blooms may alter primary productivity, nutrient cycling, and higher trophic levels. Increases in primary productivity could lead to decreases in dissolved oxygen in the lake system. Dissolved oxygen is a vital component to the health and survival of fish species in Lake Champlain, which are vital for recreational fishing on Lake Champlain.

Goal/Purpose Statement:

- Determine the effects of decreased lake freezing on vertical mixing via wind in the lake and how this will affect P loading.
• Determine how spring flooding and snowmelt is predicted to change due to climatic projections on precipitation and flooding. Make hypotheses on how this may alter P loading and the growing season/species composition of microbial primary producers in the lake.
• Make predictions on how climate change will affect the duration and depth extent of lake stratification during the summer season. Determine if this will change where and how long labile P is available and cyanobacteria / phytoplankton species composition (or diatoms).
• Predict the species composition of algal blooms based increases in liable P forms in the epilimnetic (surface water layer) suspended sediments.

Objectives:

• To assess the ecological risks associated with algae blooms, with particular focus on their changing frequency, magnitude, composition, toxicity, and persistence as a result of climate change.
• To identify the factors that influence algae blooms, with respect to the properties mentioned above.
• Using current climate data and model projections for climate change in the North East, determine how the Lake Champlain Basin may be affected by climatic alterations.
• Bridge information gathered on algal blooms in eutrophic lake systems and climate change in the Northeast to make predictions on how algal blooms in Lake Champlain may change due to climate change.
• To use such information in formulating some general recommendations to avoid and/or manage the negative effects of changing primary production regimes within Lake Champlain and the surrounding area.

Approach:

The need to identify changing characteristics of algae populations in Lake Champlain is of increasing concern when considering the impacts of Climate Change on the Lake. To address these principles, our primary investigation began with the processes of phosphorus cycling in eutrophic lakes and the dynamics of algae growth. We primarily consulted the source, Web of Science, for its ability to narrow search fields and linking of citations. We also consulted the journal search engines Water Resources, EBSCO Host, Science Direct, and Google Scholar. Mary Watzin, Professor of Aquatic Ecology, Pollution Studies, and Marine Sciences at the University of Vermont was also consulted on background information on climate change in the Lake Champlain Basin, lake freeze over regimes and its effects of nutrient loading to lakes. Key words used in the search engines included: phosphorus, nutrient cycling, algae, agriculture, lake sediments, lake stratification, phosphorus dynamics, eutrophication, cyanobacteria, climate change, flood regimes, eutrophic lakes, among others. The results were then often narrowed by the ability to highlight certain general topics we were interested in such as Freshwater Ecology, Environmental Science, Ecology, etc. Articles were then read and key points were addressed for their relevancy and scientific merit and finally highlighted in the following Findings section.
Findings:

1. Phosphorus Sources

One of the primary concerns regarding the incidence of algae blooms in Lake Champlain is the potential threat to human health posed by toxic cyanobacteria. Cyanobacteria make up a significant portion of the phytoplankton in the Lake, and in Missisquoi Bay in particular. In 1999 and 2000, three dogs died as a result of drinking lake water contaminated with cyanobacteria. Subsequent tests have found anatoxin and microcystin, two lethal neurotoxins associated with the genera *Anabaena*, *Aphanizmenon*, and *Microcystis*. These toxins and the associated algae were found in varying regions of Lake Champlain every year since 2000. Cyanobacteria have been detected in Burlington Bay, and trace amounts of toxins have been detected in both municipal water intakes for the city. (Watzin et al. 2006) Although toxic cyanobacteria are a potential hazard throughout the lake, populations of those species thought to pose a risk to terrestrial animal life have only ever reached “alert level” in Missisquoi Bay and St. Albans Bay.

Agricultural runoff is a major source of phosphorus responsible for the eutrophication of Lake Champlain. Dairy Farms populate the Vermont countryside including many areas in the Lake Champlain Basin. Franklin County (the county in which Missisquoi Bay Watershed is located) and Addison County are the two most populated dairy farming counties in the State of Vermont as evident in Figure 1 (Vermont Dairy 2008; Lake Champlain Basin Program 2007). Although Figure 1 illustrates a breakdown of estimated phosphorus loading by region, it is difficult to assess the exact sources of phosphorus. The difficulty in monitoring this pollution allows for the information to be grouped into a category known as non-point pollution. Taranu (2008) states that agriculture and its land-use create a large impact on the health of aquatic systems and the nutrients available within those systems. Many of these direct impacts are illustrated by algae growth, especially cyanobacteria blooms in Lake Champlain.

![Phosphorus Loading by Land Use](image-url)
Urban and suburban sources of phosphorus are also important to recognize as sources of non-point pollution. Chittenden County is an excellent example of development in the Lake Champlain Basin. It has been prone to urbanization in recent decades with the development of suburban homes on roads such as Dorset and Spear Street. This development, which is not isolated to Chittenden County and is becoming an increasing issue in the state of Vermont, creates more impervious surface and opportunities for pollution from cars, lawns mowers, etc. The impervious surfaces of developed land include parking lots, roads and roof tops. Phosphorus, as well as other pollutants and sediments, may enter water ways from developed areas via storm drains or surface waters and eventually discharging into the Lake. It is important to remember that there is typically more phosphorus on an urban acre than an agricultural acre (Lake Champlain Basin Program 2006).

2. Climate Change and its Effect on Lake Systems in the Northeast

Climate change has had significant effects globally, with specific impacts in the Northeast United States. According to the Northeast Climate Impacts Assessment (2007) the rise in annual mean global temperature will cause a shift towards an increase in precipitation. Historically, there had been an increase in summer annual precipitation, but that trend has now shifted towards more winter precipitation (Figure 4). Since 1900, annual precipitation has increased about 5-10% in the Northeast, mainly within the winter season. In addition, this precipitation consists of heavier,
denser snow, and more rain than snow. As temperatures continue to rise, these rain and snow events will be less predictable and irregular compared to historical trends, and irregularity will occur at a higher frequency.

The Northeast is already experiencing a significant decrease in snowfall, with a decline in snow cover days during the winter. Since 1970, annual temperatures have risen more than 1.5°F with winters warming the fastest at 1.3°F per decade (Northeast Climate Impacts Assessment 2007). This results in shifting seasons, with more late winter storms. Many of these storms are moving from the south and would not be able to move as far north as they currently do and are predicted in the future if not for this change in temperature.

Due to late winter storms as well as irregular storms at high frequency and warmer temperatures, there will be heavy snowmelt pulses in late winter and early spring. In a study of flood pulses, Wantzen et al. (2008) adapted the Flood Pulse Concept (FPC) of streams to four varying lakes that represent extremes of climate and morphology. This wide variation of lake systems included in the study made the FPC of lakes applicable to most lakes. The flood pulses studied ranged in time from hours to multiple years, and were on a magnitude of centimeters to meters in height. The flood pulse waters contained nutrients and organic matter from runoff and during the rise period these waters flooded the aquatic terrestrial transition zone and rewetted previously deposited sediments, which were consequently resuspended in the lake waters. During a drawback period, sediment and organic matter were deposited in the flood zone, which exposed them to natural weathering processes. Frost and wind were most effective at eroding these sediments, which made the nutrients more accessible during the following pulse. Wantzen et al. (2008) also concluded that the contribution of organic matter turnover in the littoral and flood zones was disproportionately high compared to the central regions of the lakes. The extreme fluctuations of the pulses also had the capability of causing a dieback of floodplain vegetation that have adapted to the current flood regime.

Hayhoe et al. (2007) used the Special Report on Emission Scenarios (SRES) to construct a model determining various changes in emission levels and the effects. Using historical data and the SRES model, it was predicted the short term droughts will double in their frequency within a 30 year period. The frequency of medium and long term droughts are also predicted to increase, as well and the duration in months of maximum droughts. The FPC (Wantzen et al. 2008) is applicable to droughts as well as normal lake level conditions. Lake Chad experienced a maximum level drought that lasted four years. During the drought and rewetting period, aquatic species biomass increased yet biodiversity decreased. Aquatic species composition decreased from 35 to about 5-8, with most of the biomass consisting of cyanobacteria (Wantzen et al. 2008).
With climate changes causing an increase in mean annual temperatures, lake water temperatures are increasing along with atmospheric temperature increases, leading to a decrease in the amount and duration of lake freeze-over in winter (Hayhoe et al. 2007). Hayhoe et al. (2007) stated that records of spring ice-out on lakes in the New England have indicated an advancement of 9 days for lakes in northern and mountain regions and 16 days for lakes in more southerly regions between 1850 and 2000. Most of Hayhoe et al. (2007) observations in changes of ice cover occurred between 1970 and 2000, when New England winters were warming at a rate of approximately 0.7°C/decade (Hayhoe et al. 2007; Jensen et al. 2007). During this period, Vermonters in the Lake Champlain area began to notice a decrease in the amount of lake ice during the winter (Lake Champlain Committee). It must be considered that Lake Champlain is a stratified lake system in a seasonally variable area.

3. Lake Stratification and Internal Phosphorus Loading

Changes in the duration of lake ice have effects on the stratification and turnover of lakes, and therefore have effects on internal phosphorous loading in the lake. Austin and Colman (2007) found that declining winter ice is causing the onset of spring turnover to occur earlier at a rate of approximately a half-day per year, or two weeks earlier than 27 years ago. Lakes undergo a process known as stratification or turnover where denser water sinks to the bottom and warmer, less dense water rises to the top of the lake. This separation of densities breaks the temperature layers in what is known as the water column. Stratification divides a lake into three zones: the epilimnion which is the warm surface layer (top), the thermocline or metalimnion acting as the transition zone between warm and cold waters (middle), and the hypolimnion or cold waters (bottom) (Figure 6). The mixing of the waters has great impacts on fish, algae populations, and water supply quality.

In the case of Lake Champlain, the ice melts in early spring, allowing the temperature and density of the lake water throughout the column to become the same; this uniform density allows the lake water to mix completely, know as spring turnover. The spring turnover recharges the water in the hypolimnion with oxygen and brings nutrients from the bottom up to the surface. As the water at the surface warms in spring, it looses density and stays near the surface of the lake. Wind and wave action can circulate the warmer surface waters only about 20 or 30 feet deep, so deeper waters do not mix. However, shallow lakes of less than 20 feet may stay completely mixed all summer. As lake water cools in the fall and even out in temperature, fall turnover occurs, bringing oxygen to the hypolimnion and nutrients to the
epilimnion. Stratification is stable during the winter due to ice cover blocking wind action and preventing mixing. However, photosynthetic activity is hindered in the winter months due to ice cover, cold temperatures and less sunlight. As the ice melts, spring turnover repeats in this annual process.

The stratification process traps nutrients released from sediments in the hypolimnion. The turnover processes in both spring and fall, while oxygenating the hypolimnion, also allows for the release and mixture of nutrients that had been suspended in sediments in the stratified seasons. Phosphorus is a nutrient that is often released in this process. In the fall, an algal bloom may appear when the nutrients are mixed and rise to the surface. However, this process is retarded with the onset of winter as ice cover prevents winds from mixing the water and because the water is the same relative temperature throughout the water column.

The semi-annual mixing and stratification distributes oxygen throughout the water column, oxygenating the hypolimnion. However, this oxygen is used up throughout the stratified months. During these anoxic times (oxygen poor), phosphorus becomes more soluble and is released from sediments on the bottom of the lake into the hypolimnion. In deep, non-stratified lakes, low levels of oxygen may persist in the hypolimnion. During the summer, the metalimnion acts as a barrier between the epilimnion and the hypolimnion, essentially cutting off from the exchange of oxygen between the epilimnion and hypolimnion. This anoxic environment coupled with a depth limiting sunlight, creates an environment often too dark for plants and algae to grow and produce oxygen through photosynthesis. In a eutrophic lake, the hypolimnion can become anoxic throughout the summer as bacteria and other benthic organisms consume the oxygen.

Phosphorus (P) is released into lake water from sediments by microbial processes, dissolution, and desorption of P from lake sediment. Sediment P concentrations, redox potential, pH and mineralization rates all affect amount released into waters via diffusion (Gonsiorczyk, 1997). Mineralization is the transformation of organic P, bound to organic matter in sediments, and inorganic phosphorus, a labile form. Mineralization is a microbial catalytic process, which consumes oxygen, an aerobic process. There are also the competing processes of adsorption, precipitation, and consumption of P. The availability of P is dependent on the contact between the sediments and the hypolimnetic or epilimnetic waters (Kleeberg 1997). The forms of P within the suspended sediments, particulate mixed with water, is also an important character when accessing its bioavailability. There are various forms of P based on their extractability. Soluble reactive phosphorus (SRP) or liable phosphorus is of particular interest due to its low molecular weight and easy extractability, increasing its bioavailability for cyanobacteria than other forms of P (Kleeberg 1997). For the purposes of determining how P loading affects cyanobacteria in Lake Champlain, we will focus on the summer stratification season and early autumn.

Inner bay regions within Lake Champlain have higher P concentrations than deeper lake waters. However the process of internal loading, the recycling of phosphorus sediments into overlying waters, can allow for phosphorus to be vertically distributed throughout the lake (Smeltzer 2003). In inner bay regions, such as St. Albans Bay in Lake Champlain, P released from sediments is free to disperse vertically through the water column due to a lack of stratification and fairly shallow waters with uniform temperatures. According to the St. Albans Bay report in 2003, the major controlling factors for P release in this area are temperature and re-suspension through wind currents. Although winds are relatively low
in the summer, when they do occur they have a significant impact on the distribution of suspended sediments (Smeltzer 2003). Temperature is an important factor that accounts for the seasonal variation in internal loading (Jensen & Andersen 1992). As the temperature increases during the summer, mineralization due to microbial growth and reproduction is accelerated. This increases the amount of total P in pore water of sediments directly by decomposition of organic matter fractions of lake sediments, due to heterotrophic microbial use of carbon. Accelerated mineralization indirectly contributes to P release through the consumption of oxygen. As dissolved oxygen is used and acidic byproducts are released through metabolism, the oxidation-reduction potential (redox potential) decreases, especially near the sediment and interstitial water interface. This facilitates the release of reducant soluble P (Kleeberg 1997). Reductant soluble P is a form of inorganic P bound to Fe oxide surfaces in the mineral component of the lake sediments. The oxidation of ferrous Fe immobilized orthophosphate to form Fe-phosphate. Upon the reduction of ferric Fe to ferrous Fe, inorganic P is released (Gonsiorczyk, 1997). During the summer season the shallow waters in inner bay regions can become anoxic due to oxygen consumption and high water temperatures, which hold less oxygen. In addition to these factors, nitrate levels also impact P release in shallow lake, inner bay systems. High nitrate levels are thought to increase orthophosphate sorption to sediments by keeping Fe in its oxidized state. This would be a good prediction considering nitrate is an oxidizing agent (Jensen & Andersen 1992). In St. Albans Bay, spurts of anoxia and high P levels were most likely attributed to these processes.

In the stratified portions of the lake, the release of P in the summer months and at the end of the summer is primarily governed by processes in the hypolimnion. During the summer stratification season, changes in the chemical nature of the hypolimnion cause spatial and temporal changes lake concentrations of dissolved substances. As these waters get warmer, mineralization rate and biological activity increase (Kleeberg 1997). The increase in SRP diffusion coincides with a decrease in pH in the hypolimnion and at the sediment surface (Gonsiorczyk, 1997). At the end of summer the chemically induced P release due to lower redox has higher influence on P release than in early summer. Additionally, a sudden release event of P can be due to anoxic conditions that can occur in the summer months, hence the importance of turbulence (Kleeberg 1997). Therefore, high acidity and low dissolved oxygen, lower redox potential, at the hypolimnion and sediment interface increases the solubility and release of dissolved P (Gonsiorczyk, 1997). Therefore P release from sediments is controlled by the amount of degradable organic substances as well as mineralization rates. At the end of the summer, the breaking of the thermocline allows for the rapid release of P that is highly concentrated in the hypolimnion.

![Vertical changes in total P content of suspended matter](image_url)
The vertical distribution of total P is seasonally variable, especially in a stratified lake system. Pettersson 2001 found that the highest P content was found in the epilimnetic suspended matter with a maximum mean concentration in the summer (Figure 7). This means that the P content within the epilimnetic suspended sediments was higher than that found in hypolimnian suspended matter within the summer months.

The amount of available P in the sediment found in surficial waters is important when determining P bioavailability for cyanobacteria. The P content in suspended sediments in epilimnetic waters is a direct result of quality of the lake sediments. Lake Erken, Germany, is characterized by high total P concentration in lake sediments (> 2.1 mg/g dw). Lake Erken is a dimictic lake system similar to Lake Champlain. Petterson 2001 found that labile, P (NH₄Cl-RP extracted P) had the highest concentration in surficial suspended sediments (3m) and had fewer proportions of more tightly bound forms of P (e.g., Organic P (NaOH-nRP), Fe and Al-bound (NaOH-RP) and Ca bound (0.5M HCl)) (Figure 8). This affirmed that suspended sediments were composed of high liable P concentrations in the stratified lake system. Resuspension is critical for the transport from sediment particulate in the water. Together they are the driving factors of internal P loading in the lake system. As seen in Figure 9, both the summer and autumn experienced more available forms of P in suspended sediments in the summer and autumn which corresponds with seasonal changes in internal loading previously discussed.
Predicting how P loading will change during the summer season depends on if summer stratification will be altered due to warmer temperatures. Some model projections for changes in internal P levels due to climate change assume that the epilimnetic and hypolimnetic waters will increase in temperature by the same order of magnitude. This lends to a doubling in diffusion rates as the model output (Malmaeus et al 2006). Although in this review there was a predicted increase in stratification, it was not seen in the model inputs. Other models incorporate the possible movement of the thermocline due to epilimnetic waters increasing in temperature at a high order of magnitude then hypolimnetic waters. This may cause an increase in the thickness of the anoxic layer (Figure 10) (Komatsu et al 2007).

4. Algal Blooms

Algae respond to a wide variety of environmental factors, which can be divided into three broad categories: nutrient loading, climate, and physical conditions within the water column. The interrelations of these three categories are numerous: increased rainfall due to climate change can increase nutrient loading; alterations to the water column change the rate of nutrient deposition and outflow; wind patterns influence stratification of lake waters; etc. Climate change is likely to alter many of the conditions that regulate populations of lacustrine phytoplankton. In particular, two factors seem likely to increase the incidence of harmful cyanobacterial blooms: increased stratification/decreased mixing, and increased temperature.

Joehnk et al. (2008) examined the effect of stratification on cyanobacteria populations as affected by increased temperature. During a period of higher temperatures, stratification increases, due to both a higher density-gradient between upper and lower layers and a decrease in disturbance by wind. The genus under study was *Microcystis*, one of the primary culprits in toxicity events in Lake Champlain. When stratification of the water column increases, *Microcystis* enjoys an advantage over its competitors, which in this case are diatoms and green algae. This is largely due to the buoyancy of cyanobacteria, which are able to float on the surface of the lake and exploit a greater share of the incident radiation. The competitor genera do not show any significant increase in population when mixing is minimal, but *Microcystis* shows a strong tendency to bloom under these conditions. Experiments were conducted on a shallow eutrophic lake during the exceptionally hot summer of 2003, when cyanobacteria populations were disproportionately high. By using an aeration system to disturb the water column and thoroughly mix the epilimnion, it was possible to induce a crash in the *Microcystis* population; when the aeration system
failed, the population shot back up to where it had been previously. Diatoms and green algae were unaffected. It was pointed out in the study this effect was dependant on two preconditions: first that phosphate was abundant, and second that temperatures were very high.

Huisman et al. (1999) modeled populations in a general sense in much the same way as Joehnk et al. (2008) and came up with similar findings. It was found that when the photic zone of a lake changes from oligotrophic to eutrophic, the pattern of competition between algae species changes as well. In oligotrophic systems, nutrients are limiting and species composition is primarily regulated by which are most able to use these nutrients efficiently. However, once nutrients are no longer limiting light becomes the limiting factor, and the biodiversity in the epilimnion is regulated by the degree of mixing in the water column as well as background turbidity. In well-mixed waters, turbidity determines which species dominate: those that have the least light requirement are able to achieve relatively higher populations because all species are competing for the same amount of light. In poorly mixed waters (as might be realized by climate change), those species will dominate which can control the top of the water column and thus the greatest share of incident radiation. Cyanobacteria, being buoyant, gain a sudden advantage. Once again, *Microcystis* is presented as being exemplary in this regard. Despite this however, overall biodiversity of algae also increases, since stratification creates niches for species that have a slight advantage in shaded layers of the epilimnion.

The other primary factor favoring cyanobacteria in climate change scenarios is increased temperature, both in terms of maximum yearly and earlier onset of growing seasons. De Senerpont Domis et al. (2007) conducted both experiments and models to observe how different classes of algae respond to warmer springtime conditions. There is a distinct yearly cycle of succession: in the spring, diatom populations peak and then decrease; in the early summer, green algae populations peak and then decrease; and in late summer, cyanobacteria populations peak and then decrease. Samples of lake water containing viable starting populations of all three classes were collected early springtime and hosted in controlled laboratory environments modeling three different temperature regimes: a control, a slightly warmer spring period, and a much warmer spring period. Light inputs were constant and held close to the native solar flux. It was observed, in both experiments and models that the sequence and timing of algae succession was unchanged across different warming scenarios. Diatom populations, being limited by silica still crashed in the same manner in the warm-spring environments as in the control. Green algae likewise showed only a slightly increased maximum population in the warmer scenarios. Cyanobacteria however, displayed a marked increase in maximum population in the warm-spring experiments. This indicated a strong tendency for cyanobacteria to bloom with greater intensity in warmer years. This indicates that warming brought about by climate change is likely to increase the incidence of cyanobacterial blooms, regardless of how else climate change may manifest itself.

Adrian et al. (2006) found a contrasting model of how warmer springtime conditions affect plankton population peaks. Analysis of data gathered between 1978 and 2003 found that spring blooms for all algae are now occurring, on average, almost one month earlier than usual. The degree of compliance with this trend varies greatly from species to species, depending most heavily on length of life cycle. Those species that reproduce most quickly show a more rapid shift in response to climate change, while the more slowly-reproducing species show less of shift in timing of peak population. This particular
report does not speak to cyanobacteria in particular, but it does offer a counter perspective to the models mentioned above.

**Conclusion:**

From our information on the environmental changes induced by climate change, we can make predictions based upon what we know about phosphorus dynamics in the Lake Champlain. One of the projected changes under high and low emissions scenarios is the increase in length of the summer season along with increases in average mean summer temperature (UOCS 2006). We can therefore infer with the persistence of weak stratification, early onset and delayed mixing of the lake waters; anoxic conditions in the hypolimnion can persist for a longer period of time. This may increase the amount of dissolved phosphorus in the hypolimnion and result in a large amount of dissolved phosphorus in epilimnetic waters when mixing does occur. Additionally, we can infer that with a longer summer stagnation period, higher proportions of bioavailable phosphorus fractions will be available for algal growth for a longer period of the year.

With the increase in mean summer average temperature we can also make predictions about mineralization of organically bound phosphorus in sediments. Temperature increases may result in an increase in thermocline depth and increases in mean water temperature. This could result in increased mineralization rates within lake sediments. As this mineralization increases, it will result in an increase in soluble and bioavailable phosphorus, promoting the growth of algae. With the increase in depth of the epilimnion, we can also assume that algae populations will have more room to grow and flourish since they are dependent on sunlight for photosynthesis.

Freeze over events in Lake Champlain are also decreasing annually. Freeze over of Lake Champlain decreases turbidity and allow for phosphorus to bind with sediments in the hypolimnetic layer of the water column during this winter period between fall and spring turnover events. If ice does not cover Lake Champlain, intense winter wind events can increase turbidity, limiting the binding of phosphorus to sediments, allowing for more available phosphorus to turn over into the epilimnetic zone during the spring. Spring turnover events are predicted to be earlier and earlier with each year, allowing for phosphorus to be available earlier annually. Understanding internal lake phosphorus processes is vital for prediction of how changes in lake dynamics due to climate change may alter phosphorus availability and abundance.

If the stratification processes occur earlier annually, we can also assume that they will occur later in the fall, allowing for a longer total time for phosphorus availability annually. As temperatures increase, changes in growing season will occur, allowing for longer spring, summer and fall photosynthetic activity. Agricultural activity is also predicted to increase globally, which may be an outcome in an agriculturally dominated state such as Vermont. If little is done to mitigate the total phosphorous runoff from agricultural practice, we could expect phosphorous runoff to follow a similar temporal trend as agricultural practices. Additionally, as storm intensity is projected to increase, there may be higher influxes of total phosphorus into Lake Champlain.

De Senerpont Domis et al. (2007) currently expects that increases in temperature will favor cyanobacterial growth over other forms of algae. Temperature increases from climate change will result
in larger and faster growing cyanobacterial blooms. Cyanobacterial populations may not be present at all times, but blooms are harmful in their release of toxins that are can be unsafe to humans and other organisms alike. Along with this growth, cyanobacterial blooms can also block sunlight from reaching lower parts of the water column, limiting photosynthetic activity below a blanket of algal mass. These problems are especially of importance in watersheds heavily dominating by urban, suburban or agricultural land use as these areas release phosphorus in the form of non-point pollution.

**Recommendations:**

Algal blooms currently dominate areas of Missisquoi Bay each summer, releasing toxic substances during their blooming periods. Other parts of the Lake may become subject to the same blooms based on our findings, thus increasing the concern of this algal pollution. The toxins released by cyanobacteria are important to remediate; however, action to remediate these toxic blooms has been fairly unsuccessful. Agricultural and urban/suburban non-point pollution are the main sources of phosphorus in Lake Champlain Basin. Best Management Practices are currently applied to agricultural fields and farms as a State precaution, but that does not completely alleviate the problem. Also, it is more difficult to stop non-point pollution from urban and suburban sources as runoff moves quickly over imperious surfaces and easily into surface waters. Eliminating or mitigating the sources of non-point pollution is the ideal process; however, mitigation will not eliminate the problem completely. As a result, managers addressing this issue may be subject to the conditions that currently exist within the confines of the Lake itself. Two areas of the Basin should thus be addressed for remediation, the individual watersheds and reaches of rivers and secondly, the lake itself.

Annadotter et al. (1999) conducted research on the remediation of a phosphorus loaded eutrophic lake in southern Sweden. Lake Finjasjon is similar to Lake Champlain in many respects: it is a phosphorus-rich eutrophic lake surrounded by agricultural land and urban development. Differences include the size; Lake Finjasjon is significantly smaller than Lake Champlain at only eleven square kilometers (11 km$^2$) but the watershed of Lake Finjasjon is extremely large for such a small lake, again similar to Lake Champlain. Initial problems in of Lake Finjasjon’s eutrophication included murkier water as a result of untreated sewage entering the lake during the 1920’s and 30’s and then algal blooms, beginning in the 40’s, causing skin rashes and allergic symptoms from toxic cyanobacterial species (Annadotter et al. 1999). The treatment plant was improved but the algal blooms and eutrophication did not cease. In the mid 1990’s, after failed dredging attempts, constructed wetlands were installed along the littoral zone of the lake. Riparian buffers along agricultural lands were also mandated, creating a 5 m riparian buffer along all agricultural land bordering surface waters (Annadotter et al. 1999). After only two years of implementation of both the constructed wetland and riparian buffers, eutrophic conditions decreased and Secchi dish transparency increased from 0.9 m to 1.5m in one year. Constructed wetlands act as large phosphorus sinks, helping to eliminate nutrient pollution, eutrophic conditions and possibly eliminating algal blooms, as evidenced in Lake Finjasjon. Although Lake Champlain and its watersheds are significantly larger than Lake Finjasjon, constructed wetlands and riparian buffers may be the best way to remediate the eutrophic conditions of Lake Champlain. The construction of the wetland and riparian buffers in Sweden were very expensive, thus constructed in the Lake Champlain Basin should be isolated to highly prone areas of phosphorus runoff and algae growth, such as Missisquoi Bay, the Missisquoi River Watershed, the Otter Creek Watershed and parts of the Winooski River Watershed. All
of these areas are responsible for high levels of phosphorus runoff or catchment. Riparian buffers along these agriculturally dominated watersheds should help to alleviate nutrient runoff. A constructed wetland in Missisquoi Bay may help to alleviate algal blooms as well.

In the 1980’s, Ripl & Leonardsson researched the addition of calcium nitrate to sediments in Lake Finjasjon (Annadotter et al. 1999). The addition of nitrates to the waters of Lake Finjasjon limited phosphorus release from sediments. The chemical processes of the calcium nitrate addition caused the sediments to nitrify, helping to trap phosphorus and limit the release of labile phosphorus from these sediments. Nitrification of sediments in Lake Champlain may help to limit labile phosphorus release in key areas of the lake, such as Missisquoi Bay. Sediment nitrification should occur at relatively shallow depths and in areas prone to phosphorus release from sediments or algal blooms.

Other attempts to stop the growth of algae may be to create turbidity in areas where high growth occurs. If phosphorus is never totally available in the epilimnetic zone of the lake and its vertical circulation is continually attempted, it will not allow for access by phototrophic plants. Water pumps or turbines can be used to circulate the water vertically through the system, mimicking the semi-annual turnover events. If algae do start to reproduce, they may be swept to the hypolimnetic zone with the water and phosphorus. Upon reaching the base of the water column, photosynthesis is highly retarded and may even stop, essentially eradicating portions of the algal population. Also in the hypolimnetic zone, anoxia occurs as time increases between turnover events. Rather than creating a continually oxygen rich environment, sinking of such algae into a hypoxic environment may retard or stop their growth as well.

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