Potential Effect of Climate Change on Algal Growth

By Zafer Ibrik

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Abstract

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Climate change is considered one of the most important problems in the last few decades. It affects all aspects of life such as water quality and quantity, air quality, and public health. Recently the United Nations and various governments started to evaluate the impact of climate change on environmental systems, and issued protocols in order to decrease the gas emissions from industry and petroleum companies, which are considered the driving force for global warming.

Canadian water resources in rivers, lakes, and reservoirs are becoming progressively more exposed to a range of stresses. One of the most important stresses is climate change. Increased climate changeability and extreme weather events will affect the water quality and quantity. Research is needed to develop an effective method for analysis and modeling techniques to understand the potential effect of climate change on the water quality.

The Aqueduct Canal in Lasalle, Montreal was chosen to determine the potential effect of climate change on water quality parameters. Algae was selected as an indicator of water quality and temperature was selected as the climate change component, in order to study the effect of temperature on algal growth. To achieve this goal, raw water samples were collected from two water treatment plants for a period of six months (started in June 2003). The two treatment plants were chosen for sampling, the Usine Atwater Plant and Usine Charles Des Baillets Plant (D.B).

Nitrate and phosphate concentrations were monitored, because they influence algal growth. The effect of temperature on nutrient levels was established for both plants, and the results showed that the maximum concentrations of nitrate and phosphate occurred in June and were 0.46 and 0.027 mg/l, respectively, whereas the minimum concentrations occurred in August were 0.2, and 0.006 mg/l. The decrease in the nutrients level was due to the uptake of nutrients by algae. This decrease was reflected by the algal concentrations in August, when algae had a maximum growth rate in August of 0.033 day^{-1}.

Algae growth models (Michaelis-Menten kinetics and the Eppley temperature model) were applied to the data to compare the observed and calculated growth rates. The results illustrate that the relative difference between the observed and calculated rates ranged between 12%- 50%. Predicted daily temperatures in August in the years 2010, 2020, 2050, and 2099 were obtained from a CGCM1 (GHG+A) simulation model from The Canadian Centre for Climate Modeling and Analysis (CCCma), and were used to estimate the future algae growth. The results showed that, there will be a positive trend in algal growth. For example, the calculated growth rate for algae in 11/Aug/2003 was 0.015 day^{-1}, whereas the future rates for the same day in 2020 and 2099 would be 0.019 and 0.028 day^{-1} respectively.

Therefore algae could significantly impact on both treatment processes and public health in the future. Algae can decrease the treatment efficiency by clogging treatment units such as the screening unit. Also heavy loads of algae affect the filtration process by increasing the sedimentation rate.

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Chapter 1

Introduction

Climate change is considered one of the most complex environmental problems in the last decades. It affects all aspects of life, air pollution, land use, toxic waste, transportation, industry, energy, government policies, development strategies, and individual freedom and responsibilities.

In the last two hundred years, rapid expansion of activities and industrialization and increased human population have added heat- retaining green house gases, such as carbon dioxide, to the atmosphere (Atmospheric Environment Service, 1994). The world now faces many risks from climate change; the direct effects of climate change will include changes in temperature, precipitation, soil moisture and sea level. It's important to understand the nature of those risks, where natural and human systems are likely to be the most vulnerable, and what may be adaptive responses. In the late 1980s and early 1990s, the terms "greenhouse effect" and "global warming" came into everyday use and there was a tremendous rise of interest in climatic change (Whyte, 1995). Greenhouse gases are considered the main cause of global climate change.

In Canada, many aspects of our economy and everyday life, particularly in resource sectors such as agricultural, forestry, fisheries, water resources and quality, are highly sensitive to extreme weather events, and other variations of our climate.

The goal of this thesis is to establish a scientific method to estimate the impact of climate change on water quality parameters. For this purpose algal growth was chosen as the water quality parameter, and temperature was chosen as the climate change parameter. The relationship between algal growth and temperature were determined in order to establish the relationship between these parameters.

Water samples were collected from two water treatment plants at the influent and effluent of the plants. Nitrate and phosphate were monitored in both plants, since their levels play an important role in algal growth in addition to temperature. Behavior of these parameters during the summer and winter seasons (from June to December) was studied. Their concentrations were determined under variations in temperature and pH. Statistical relations were established to determine the sensitivity of these parameters to temperature.

Finally, the measured concentration of algal growth was compared with the calculated values using algae growth model factors. The future values of temperature were used to calculate the future algal growth, to determine the potential effect of temperature on algal growth.

Objectives

The objectives of this study are:

- To estimate the relationship between algal growth and nutrient levels in the Aqueduct canal.
- To determine the nutrient limiting factors that control the algae growth in the Aqueduct canal.
- To evaluate the effect of temperature increase on the water quality index.
- To estimate the potential effect of climate change on algal growth.

Chapter 2

Climate Components and System

2.1 Climate Contents

To obtain a better understanding of the nature of climate change problems, it is important to discuss the climate system and components. The climate components can be thought of as a heat engine composed of four subsystems: 1) radiative energy 2) flow system, 3) circulation system, 4) water cycle. The climate system is divided into five composite systems: 1) the atmosphere, 2) the hydrosphere, 3) the cryosphere, 4) the lithosphere, and 5) the biosphere (Robinson and, Henderson-Sellers, 1999).

Climate is generally defined as a description of the average behavior of the atmosphere, and thus the aggregation of the weather climate is usually expressed in terms of the mean (or average) conditions and variances, including the probability of extremes and space covariance properties. Energy in the form of sunlight is considered the most important parameter that controls the other components.

2.1.1 Climate components

a) Radiative energy

Radiative energy flow represents the driving force for the heat system. Short wave radiation from the sun provides the energy that heats the earth's surface and atmosphere. Long wave heat energy radiated back to space from the earth's surface and atmosphere cools the system again. In equatorial latitudes, the heating caused by incoming solar energy exceeds the cooling by the outgoing long wave energy while in polar regions, the cooling exceeds heating. The resulting temperature difference between the equator and poles drives the climate's circulation system, which sets the winds and ocean currents in motion (Drake, 2000).

Incoming solar radiation also evaporates water at the earth's surface to drive the water cycle. When it reaches a higher level in the atmosphere, the heat is released again as the water vapors condenses to form clouds and eventually precipitation. Atmospheric winds can help transport clouds and precipitation a long distance from their source. Therefore, the hydrologic water cycle and the circulation system let the climate engine accomplish its work of redistributing heat and moisture both vertically and horizontally around the globe (Peixoto, and Oort, 1992). In addition to the basic mechanisms of the climate system, there are other factors which influence these mechanisms. In the atmosphere, fine particles and trace gases such as ozone, carbon dioxide, methane and sulphate dioxide, alter the amount of energy entering and leaving the climate system.

The imbalance in the atmospheric composition resulting from incoming and outgoing radiation is referred to as "radiative forcing". The climate system responds to positive radiative forcing by attempting to restore the balance, primarily by warming the lower atmosphere. This shows the importance of the energy and temperature balances, because the rate at which the earth loses energy depends on its temperature (Peixoto, and Oort, 1992). There is strong evidence that appreciable change has occurred in the energy output of the sun in the last two centuries.

b) Energy balance

The surface energy balance is the resultant of radiative components such as incoming and outgoing short-wave and long-wave radiation. Energy released from the sun as electromagnetic radiation has a temperature of approximately 6000 ^{0}C (Mcllive, 1986). At this temperature, electromagnetic radiation is emitted as short-wave light and ultraviolet energy. Electromagnetic radiation travels across space at the speed of light. When it reaches the earth, a portion is reflected back to space by clouds, while some is absorbed by the atmosphere and the earth's surface.

In a stable climate system the energy must be balanced, with energy returning to space as long wave radiation from the earth's surface and the atmosphere. As solar radiation passes through the atmosphere, it encounters particles of atmospheric gases such as ozone. Some of these gases absorb the incoming solar radiation before it reaches the earth's surface and thus warm parts of the atmosphere directly, whereas others scatter it and reflect it back to space. The earth's surface itself also reflects a portion of incoming radiation.

Greenhouse gases absorb electromagnetic radiation at some wavelengths but allow radiation at other wavelengths to pass through unimpeded. The atmosphere is mostly transparent to visible light (which is why we can see the sun), but significant blocking (through absorption) of ultraviolet radiation by the ozone layer, and infrared radiation by greenhouse gases, occurs (Drake, 2000). The absorption of infrared radiation trying to escape from the earth back to space is particularly important to the global energy balance. Such energy absorption by the greenhouse gases heats the surface, and so the Earth stores more energy near its surface than it would if there was no atmosphere. This heating effect is called the natural greenhouse effect.

The Earth's annual and global mean energy balance of the incoming solar radiation, 49% (168 Wm^{-2}) (McCarthy, 2001) is absorbed by the surface. That heat is returned to the atmosphere as sensible heat, as evapotranspiration (latent heat) and as thermal infrared radiation. Most of this radiation is absorbed by the atmosphere, which in turn emits radiation both up and down. The radiation lost to space comes from cloud tops and atmospheric regions much colder than the surface. Figure 2.1 shows the absorbed energy by the earth.

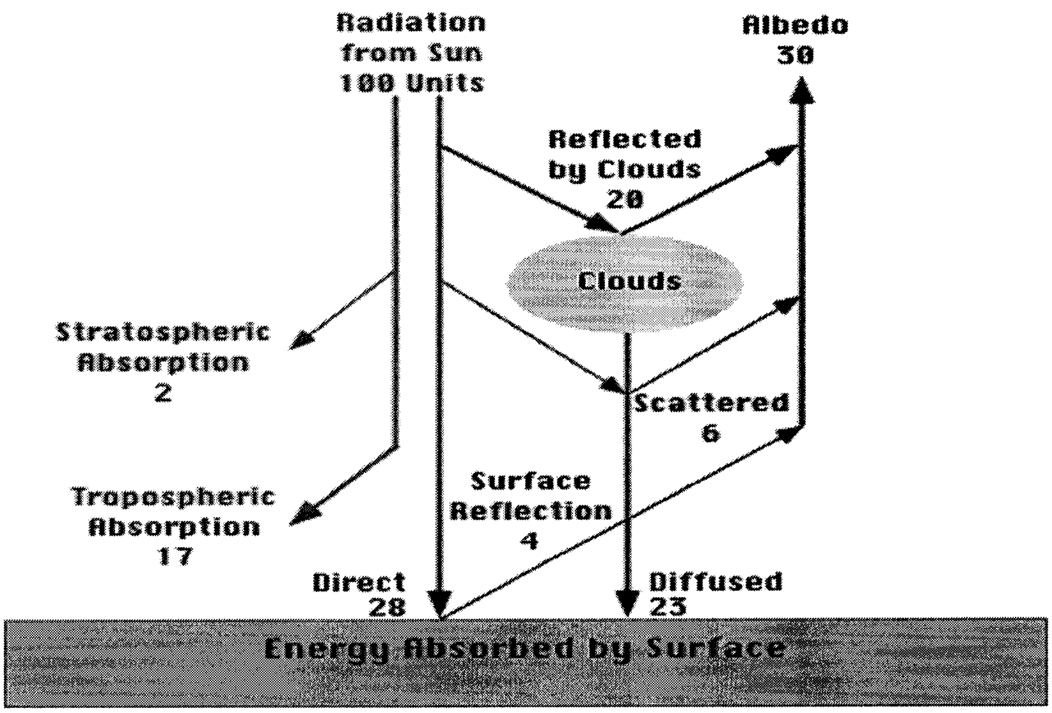


Figure 2.1 Annual energy balances on the earth (McCarthy, 2001)

c) Circulation system

Temperature gradients drive an atmospheric and oceanic circulation system, which carry warm air and water towards the poles and brings cold air and water back toward the equator, whereas the thermohaline circulation is due to water salinity gradients in the ocean (Drake, 2000). Thermohaline circulation will be affected by human induced global warming and is strongly dependent on the future temperature distribution and fresh water supply over the North Atlantic region. Most models like the General Circulation Model (GCM) and Hadley British models predict an increase in precipitation at high latitudes and a region of minimum warming over the North Atlantic using a scenario of doubling CO_2 emissions within the next 70 years (Stephen and Niles, 2002). Most of the models also predict a decrease in the strength of the thermohaline circulation. However, the exact reduction varies from 30% to only 10% (Houghton, 1997). It shows that circulation not only reduces, but may shut-down completely under strong global warming with a fourfold increase of CO_2 concentration within the next 140 years (Whyte, 1995). This illustrates that global warming can affect the climate system in a very non-linear trend.

d) Water cycle

The hydrologic cycle or water cycle is the circulation of water from land to sky, and sky to land. Water exists on earth as a solid (ice), liquid or gas (water vapor). Oceans, rivers, clouds, and rain, all contain water, but, the total amount of water in the earth is constant. The heat provided by the sun, and the air pressure determines the amount of water vapor it can hold. The heat evaporates water from the earth's surface and causes transpiration (loss of water from plant to air). The water vapour eventually condenses, forming tiny droplets in clouds. When the clouds meet cool air over land, precipitation (rain or snow) is triggered, and the water returns to the land. Some of the precipitation penetrates into the ground, forming groundwater. Most of the water flows downhill as runoff (above ground or underground), eventually returning to the seas as slightly saline water. Figure 2.2 illustrates the basic water cycle elements.

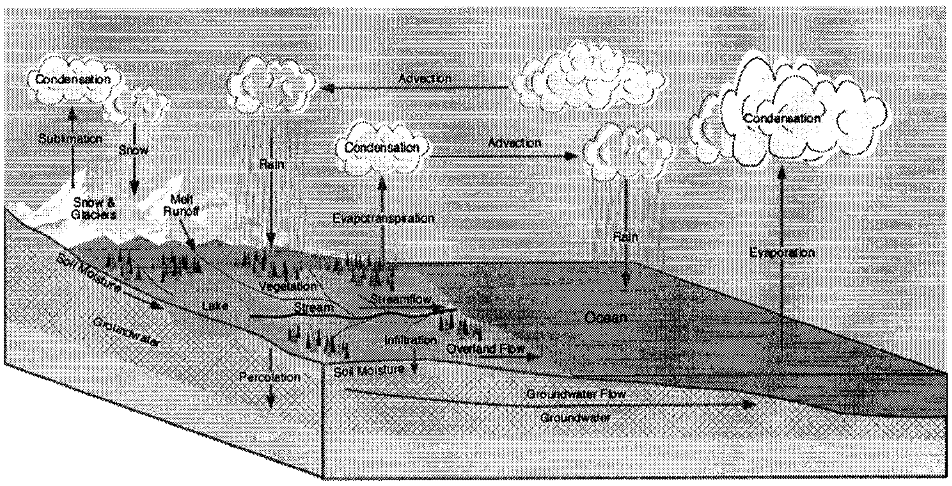


Figure 2.2 Hydrologic cycle (Gleick and Adams, 2000)

Figure 2.2 shows five processes and their importance to the hydrologic cycle. It displays how any change in a process will directly affect the others. It clearly shows that as the evaporation rate increases due to global warming, there will be a direct increase in the precipitation rate in some areas, but drought will occur in another area in order to maintain the planet's balance.

In 1997, Dundee University published an effective study related to the amount of water in the earth and they correlated these percentages with climate change. Approximately 70% of the earth's surface is covered by water and can be divided into six main reservoirs. Table 2.1 shows these reservoirs and their proportion.

Table 1.1 Water Distributions in the Earth (Natural corner at Dundee University, 1997)

Reservoir	**Volume (km^3 x 1,000,000)**	**Percent**
Oceans	1370	97.25
Ice Caps and Glaciers	29	2.05
Groundwater	9.5	0.68
Lakes	0.125	0.01
Soil Moisture	0.065	0.005
Atmosphere	0.013	0.001
Streams and Rivers	0.0017	0.0001
Biosphere	0.0006	0.00

As shown, in Table 2.1, 97% of earth's water cover is saline, of the remaining 3% fresh water, 75% of 3% is unusable as glaciers and ice. It follows that the remaining 25% which is actually 0.75% of the total is available as fresh water. The distribution is as follows:

- 0.03% in rivers
- 0.06% in soils as groundwater
- 0.3% in lakes
- 11% is in shallow groundwater < 800m below the surface
- 14% is in deep ground water.

These facts show that water shortage will be an important problem in the next decade. The two major reasons for global water shortage are the growth of demand and reduction of supply. The growth in demand is due to population growth, as displayed by the fact since 1950 that the water supply per capita has fallen by 50%. A reduction in supply is due to the following :

1) Contamination of supply.

2) Climate change: significant reduction of water supplies in areas which have had a abundant supplies, less rainfall, potential for conflicts between users, for example by 2025, 48 countries are expected to face water supply shortages:

-19 countries will be stressed: annual water supplies of between 1700 and 1000 m^3/ person.

- 29 countries will be scarce: annual water supplies of less than 1000 m^3/person (Natural corner at Dundee University, 1997).

The Dundee University study provides a prediction of the effect of climate change on people for a study period of 50 or 100 years. What will be the quality of water at this time, and does the climate change affect the quality of water?. The object of this thesis is to discover the relation between climate change and water quality. Global warming will lead to a rise in the temperature, which will affect the quality of water, and increase algae bloom in water. There are uncertainties concerning algae concentration in the water in response to a temperature increase. These assessments are of interest in this thesis. In the next chapter, an introduction to climate components will be discussed because it is important to understand the climate system.

2.2 Climate System

2.2.1 Climate System Components

The climate system is considered to be the largest system on earth. It contains five major components. All physical, chemical, and biological processes occur within the system. The atmosphere is considered the most variable component of the climate system. This component will be discussed in detail, since the atmosphere represents the container of the climate change, and all climate models concentrate on this component. Climate components contain the hydrosphere, cryosphere, lithosphere, biosphere, and atmosphere. The definitions of these components are (Drake, 2000):

1) Hydrosphere

The hydrosphere consists of all water in the liquid phase distributed on the earth. It covers 2/3 of the earth and includes oceans, rivers, lakes, interior seas, and groundwater. The ocean is the largest water reservoir on earth. It stores energy and has a relatively small change in surface temperature because it acts as a buffer for temperature. Also the oceans exchange carbon dioxide and other important gases and aerosols, with the atmosphere. For this property ocean is considered a reservoir for carbon dioxide.

2) Cryosphere

The cryosphere comprises all frozen water, including glaciers, seasonal snowfalls, polar ice caps, and permafrost. It is considered to be the largest fresh water basin on the earth. The strong cooling of the atmosphere near the earth's surface stabilizes the atmosphere against convection and contributes to the occurrence of a colder local climate (Markandya, 2002). Therefore the cryosphere plays an active role in the climate.

3) Biosphere

The biosphere includes plants on the land, sea and all animals. The vegetation affects the surface roughness, evaporation, runoff, and field capacity of the soil. Moreover, the biosphere influences the carbon dioxide balance in the atmosphere and oceans through photosynthesis and respiration, and these processes take part in climate change and play a modulating role.

4) Lithosphere

The lithosphere includes the surface crust of the earth, mountains, rocks and ocean basins. For climate change modeling, the lithosphere is considered to be unchanging.

5) Atmosphere

The atmosphere is the basic component of the climate system, and is a mixture of gases distributed almost uniformly over the earth. These gases are shown in Table 2.2.

Table 2.2 Earth's Atmospheric Compositions (Houghton, 1997)

Constituent Gas	**Chemical Formula**	**Percent by volume (%)**
Nitrogen	N_2	78.1
Oxygen	O_2	20.9
Argon	Ar	0.93
Water vapour	H_2O	0.1
Carbon Dioxide	CO_2	0.0355
Methane	CH_4	0.000172
Nitrous Oxide	N_2O	0.000031
Ozone	O_3	0.00005

Of particular importance for climate change modeling are the greenhouse gases such as water vapour. These gases will be discussed in detail in the sections to follow. Another important criterion for the atmosphere is the vertical temperature profile, which is distributed over layers defined by temperature structure. These layers based on vertical temperature gradients are shown in Figure 2.3 based on vertical temperature gradients

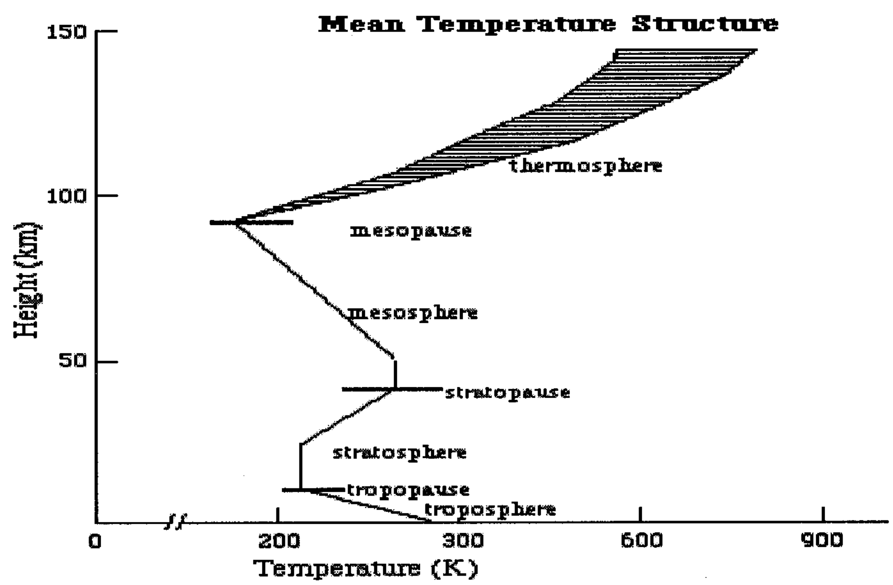


Figure 2.3 Vertical temperature gradients (Robinson and Henderson, 1999)

2.2.2 Greenhouse Gases

Greenhouse gases are directly related to climate change, and are considered the driving force for global warming. All protocols like the Montreal protocol in 1987 and the Kyoto protocol 1997 have targeted these gases, attempting to limit their emission in the atmosphere. Carbon dioxide (CO_2) has risen from 280 ppm to approximately 370 ppm, methane (CH_4) has risen from about 700 ppb to over 1700 ppb, and nitrous oxide (N_2O) has increased from 270 ppb to over 310 ppb over the last century (Claussen, 2001).

Human activity, fossil fuel burning, land use change, production and use of halocarbons are the dominant causes of global changes in atmospheric gases. Each one of these gases has a cycle that functions according to its capacity to absorb the radiation, therefore affecting climate change. There are four principal greenhouse gases as shown in Figure 2.4.

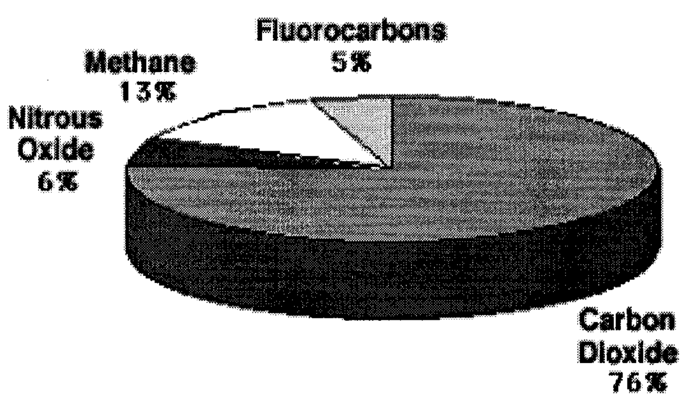


Figure 2.4 Greenhouse gases and their relative proportions (National Research Council, U.S, 1998)

1) Carbon Dioxide (CO_2)

Carbon dioxide comprises more than three quarters of the greenhouse gases in the atmosphere, and is recycled in nature by a chemical process in plants (photosynthesis) that transfers CO_2, water and other compounds into oxygen and energy rich organic compounds. Due to the large increase in population and their subsequent needs (food, clothing, transportation), and the fact that most of the energy needed originated from burning fossil fuels such as coal or oil and from gas burning, there has been a significant increase of CO_2 levels in the atmosphere.

An increase in CO_2 can cause severe problems. For example, the oceans are considered a warehouse of CO_2, since they control the CO_2 in the atmosphere and work as a buffer to prevent any sudden changes in the acidity or alkalinity of the sea. Therefore any change in sea level or ocean movement will have a strong effect on the CO_2 concentration (Gleick, 2000). The chemical movement from the atmosphere to the ocean and water is given by equation 2.1:

$$\mathbf{CO_2 + H_2O \longrightarrow H_2CO_3 \longrightarrow HCO_3^- + H^+ \longrightarrow CO^{-2}_3 + 2H^+}$$

Vast amounts of CO_2 are trapped in marine sediments in this way. The movement of carbon down into the deep ocean is often referred to as the biological pump because biological processes control the transfer. Oxygen is utilized by organisms during respiration and CO_2 and water vapour are released back into the atmosphere. Carbohydrates are also converted to CO_2 and water vapour during respiration.

The fertilization effect is an example of a negative feedback process (decreasing the rate of global warming), since it increases the amount of CO_2 taken up by plants and therefore reduces the amount in the atmosphere (National Research Council (U.S), 1998). Drought is considered to be a positive feedback process (increasing the rate of global warming) since a decrease in photosynthesis will occur as a result in the drop in vegetation. Scientists are not yet able to precisely predict how positive and negative feedbacks will affect the CO_2 cycle.

All the models and evidence show that CO_2 concentrations increase as shown in Figure 2.5.

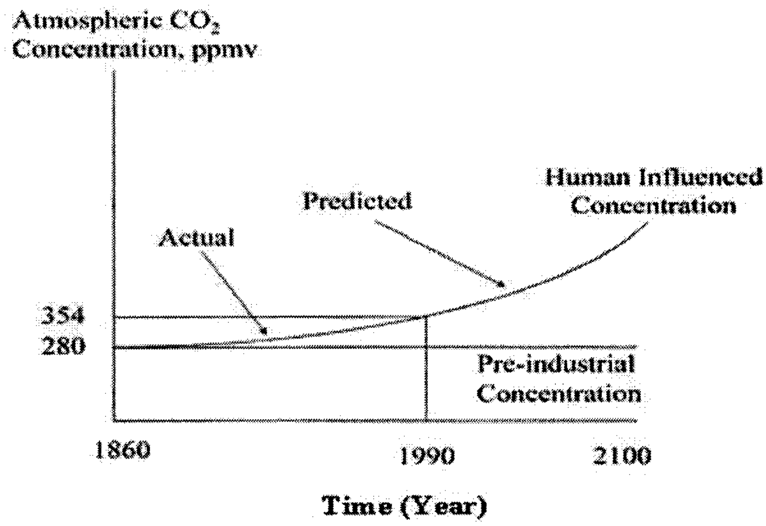


Figure 2.5 Current and predicted CO_2 concentrations (Sohugen, 2003)

2) Methane (CH_4)

Methane is a greenhouse gas with no color and has a flammable nature. It is produced by bacterial activity that transforms organic matter in a relatively oxygen- free condition (anaerobic digestion, landfilling). This gas is much stronger than CO_2 in trapping heat in the atmosphere, but has less of a commutative effect on the global warming since it is only in the atmosphere for a maximum of 12 years. The problem is that the concentration of CH_4 is increasing twice as fast (Markandya, 2002).

Methane concentration typically varies linearly with temperature. In the 18^{th} century the methane concentration was approximately 700 ppb, and by the year 1988 the concentration more than doubled to 1720 ppb (Leggett, 1996). The principle removal process from the atmosphere is through chemical destruction, via reaction with hydroxyl (OH) radicals, which are present in the atmosphere because of processes involving sunlight, oxygen, ozone and water vapour.

Approximately 90% of the annual CH_4 is destroyed via this mechanism (Drake, 2000).

3) Chlorofluorocarbons (CFCs)

Any group of organic compounds that contain fluorine and carbon are called chlorofluorocarbons. These greenhouse gases rarely occur naturally and humans are the main producers for these gases, primarily. Certain types of fluorocarbons including CFCs, damage the earth's protective ozone layer, and have therefore been replaced by hydrofluorocarbons that do not harm the ozone layer but still trap heat and radiation inside the atmosphere, which increases the greenhouse effect. The recent increase of these gases in the atmosphere has been between 5 to 5.5 percent per annum (Leggett, 1996), which is faster than any other greenhouse gas.

4) Nitrous Oxide (N_2O)

N_2O is a colorless gas with a pleasant odor produced in the agricultural sector. When nitrogen fertilizers are spread onto the soil, soil bacteria break it down and release a portion into the atmosphere as N_2O. Due to the huge rise in the production of fertilizers in recent years, the release of N_2O has subsequently increased. N_2O is fairly stable in the atmosphere with a lifetime of close to 150 years (Alber, 2002). Although its concentration is lower than CO_2, it contributes greatly to global warming. It accounts for approximately 6% of the cumulative radiative forcing to date and it absorbs more heat per molecule than CO_2. (Drake, 2000).

5) Other atmospheric components

There are also gases which through their chemical action on greenhouse gases, especially on the lower atmospheric layer, such as carbon monoxide (CO), and nitrogen oxides (NO, NO_2) emitted by motor vehicles and fossil fuel. CO has no direct greenhouse effect, but can be transformed to CO_2. These gases also affect the amount of hydroxyl radicals (OH) present, which in turn affects the concentration of CH_4.

Water vapour is also considered a greenhouse gas, since it traps earth – emitted infrared radiation. This warms the troposphere as a whole, which leads to infrared emissions back to the earth's surface, thereby increasing the temperature.

Ozone is a major absorber of short-wave ultraviolet radiation and it is a greenhouse gas which controls the temperature of the stratosphere. Approximately 10% of atmospheric ozone occurs in the troposphere where it acts as a greenhouse gas (Peixoto and Oort, 1992). It is produced by photochemical reactions involving gases such as methane, hydrocarbons, carbon monoxide and nitrogen oxides, which are all formed during combustion of fossil fuels. Tropospheric ozone breaks down under ultraviolet is radiation into oxygen atoms which then react with water vapour to produce hydroxyl radicals, which helps regulate levels of methane. Ozone has a lifetime of only a few weeks and its level has only been monitored since 1970 (Whyte, 1995).

Aerosols are small particles of dust, salt, soil, and sulphate produced from fossil fuel combustion. Their effect on the atmosphere is complex and not well understood and at high levels in the atmosphere, they tend to cause cooling. Lower levels in the troposphere may enhance the greenhouse effect. Approximately half of aerosol particles are naturally occurring and originate from the oceans, and biological waste product. For example, dimethyl-sulphate is emitted from the ocean surface and is oxidized in the atmosphere to form sulphate aerosols (Robinson and Henderson, 1999)

2.2.3 Feedback mechanisms and greenhouse effect

It is important to understand the effect of greenhouse gases on the greenhouse effect, and the concentration of these gases will create unbalanced conditions. The basic effect of greenhouse gases is the warming of atmosphere, of, since the harmful ultraviolet waves which are reflected by earth is absorbed by greenhouse gases, and the amount of solar radiation will be blocked by these gases and temperature will increase (Whyte, 1995).

Water vapour is very important natural greenhouse gas, and tends to increase in warmer conditions due to evaporation. The oxidation of methane in the stratosphere also produces water vapour which has similar effects as evaporation. This is another feedback mechanism that may come into play to enhance, and in some cases, mitigate the effects of rises in greenhouse gas levels (Atmospheric Environment Service, 1994).

As the atmospheric temperature increases, the surface layer of the ocean will warm and release additional CO_2 to the atmosphere. The depletion of stratospheric ozone as a result of reactions involving CFCs will reduce the absorption of incoming radiation. Recently researchers have suggested that this may be approximately equal in magnitude to the additional contribution of CFCs to greenhouse warming (Drake, 2000), effectively negating their impact. The balancing of these two influences may be one of the reasons why global temperature has not risen as much in recent decades as predicted.

Clouds form another source of feedback. As the temperature rises, there should be more evaporation from the oceans and increased cloudiness. This could result in more radiation being reflected back, thereby reducing temperature. This example shows the inherent uncertainty in the prediction of climate change (Houghton, 1997).

Concentrations of greenhouse gases depend not only on levels of emissions but also on chemical processes operating in the atmosphere. Chemical reactions involving carbon dioxide are the main processes that affect the rate of removal of greenhouse gases. The main removal mechanism for methane is via reaction with hydroxyl radicals in the troposphere. N_2O and CFCs are destroyed by photodissociation (dissociation of molecules involving reactions with a solar photon) (National Research Council (U.S), (1998).

Chapter 3

Climate change impact and adaptation

Over the centuries, human communities have accommodated their activities and lives to the present climate condition. This created a strong need for scientists and decision makers to estimate the future change in climate and its impact on life aspects. Any adverse impacts on the environment have forced people to adapt their life for the new change. An example of this is in Asia, where crop production and aquatic culture would be threatened by a combination of thermal and water stresses, sea level rise, flood increase, and strong winds associated with intense tropical cyclones (McCarthy, 2001). These conditions will force people in this region to adapt to their new conditions.

Adjustment to environmental conditions by both ecosystem and human communities are in some cases relatively easy to achieve. In other cases, adaptation may be difficult, very costly or impossible. In assessing the effects of global warming and their severity, allowances must be made for response and adaptation .

Estimation of the impacts of global warming becomes more complex, because the effect not only has an impact on humans, but also on the environment. This may lead to environmental degradation on local or regional scales. Any aspect that will be affected by climate change must consider two factors: 1) how will climate change affect some of our basic needs and requirements, 2) how will the natural world be affected and what is the response of this aspect to the change.

The Intergovernmental Panel on Climate Change (IPCC) which was established by the World Meteorological Organization and United Nations

Environment Program, tried to assess the implications of greenhouse gas emissions and other human activities on the climate and their environmental and socioeconomic consequences. The IPCC suggests that climate change will affect all aspects of the hydrological cycle and the prospect of an enhanced greenhouse warming poses additional challenges for water users (McCarthy, 2001).

The third IPCC report concluded that the average global surface temperature will increase between 1.4 and 5.8 ^{0}C by the year 2100 (Natural Resources of Canada, 2002). Changes of this magnitude would significantly impact water resources in Canada. This has forced researchers to concentrate their efforts on water quality, quantity, and public health.

Another important field of study is quantifying the effect of climate change on many aspects of life. Climate change models such as Global Coupled Model (GCM), the British Hadley Centre Coupled Model (HadCM2), and the Canadian Centre for Climate Change (CCMA) has estimated climate parameters for the next century until 2100 (Gleick and Adams, 2000). These parameters can be used to estimate the future impact of climate change on environment systems such as water quality, public health and water resources.

The object of this thesis is to determine how the increase in the temperature will affect the nutrients and algal level in the aqueduct canal to create a correlation between temperature and algal growth in the canal. Before studying the impact of climate change on water, some impacts of the climate on the other parameters will be discussed in order to understand its impact on environmental aspects.

3.1 Temperature

Temperature is the most important index of climate change, and it is clear that the temperature has increased in the past decades. The temperature records show a number of other important features, such as large variations in temperature from year to year. Gleick and Adams (2000), showed that both models (Canadian general couples model CGCM, and the British model) predict an annual average warming by the year 2090, of between 3 to 6 ^{0}C over the North American continent. These models were established under the assumption that carbon dioxide will increase by 1% per year and sulfur emissions will double by 2100. Table 3.1 displays the simulated temperature in 2030 and 2095.

Tables 3.1 Future Increase in Annual Mean Temperature ^{0}C (Gleick and Adams 2000).

	Temperature increase (^{0}C)			
Region	**Canadian Model for 2030**	**Hadley Model for 2030**	**Canadian Model for 2095**	**Hadley Model for 2095**
Northwest	1.8	1.7	4.9	4.1
Southwest	2	1.8	5.5	4
Great Plains	2.2	1.6	6.3	3.6
Great Lakes	2.4	1.1	6.1	2.7
Southeast	1.8	1	5.5	2.3
Northeast	1.8	1	5.6	2.7
United States	2.1	1.4	5.8	3.3

Temperature increase may affect both surface water and groundwater. Water vapour will increase by 6 to 8 % per 1 ^{0}C, thereby augmenting evaporation rates. In addition, droughts will pollute runoff to surface water and decrease infiltration to aquifers (Levin, 2000). Warmer temperatures will contribute to increased harmful algal blooms which will degrade drinking water affecting odor and taste, and may cause fatalities to farm animals that drink directly from the water source. Drinking water contaminated by algae will cause health problems to children and adults, due to the consumption of cyanbacterial toxins like microcystin. Several algal biotoxins are associated with contaminated shellfish and these toxins produce asthma-like and other respiratory effects (Levin, 2000).

3.2 Sea Level Rise

Melting and growth of the large ice sheets that cover the polar regions are the main cause of sea level rise. Historically, the 5-6 m rise in sea level during the last warm interglacial period caused a reduction in the Antarctic and Greenland ice-sheets (Claussen, 2000). Over shorter periods, other factors affect snow melt, such as thermal expansion of water in the oceans (as water expands the sea level rises).

The sea level rise will affect groundwater aquifers by increasing the intrusion of salt water into coastal aquifers, which also depend on groundwater gradients and pumping rates. Another impact is salinity distribution in estuaries, which increases the salt water contamination at water supply intakes, increases pressure on coastal regions and affects biodiversity. Researchers have shown that a rise in level will impact coastal ecosystems and delta levees (Stephen and Niles, 2002). These levees are vital for protecting the transportation system, agriculture, and homes in the region.

An example of a predicted disaster due to a rise in sea level is in Bangladesh. It has a population of 120 million and is located in a complex delta region in Asia. Approximately 7% of the land is habitable and 6 million people live near the delta. Predictions indicate that the sea will rise by 1 meter by 2050 (Houghton, 1997). This rise creates a very strong stress on this region. Since the delta region is agricultural land, it will be lost or damaged during sea rise, and due to increasing salinity. A similar situation will occur in delta region of the Nile River in Egypt. For effective management in Bangladesh, researchers recommended that the sediment brought by the Meghna River into the delta will have to be managed (Markandya, 2001). In the Netherlands, with over half of its land consisting of coastal lowlands, they have developed an effective solution for this problem. They created solid bulwarks, thereby making use of the effects of various forces (tides, current, waves, wind and gravity) on sand and sediments, to create a stable barrier against sea rise. Protection against sea level rise in the next century will require more research and the development of new technologies.

3.3 Agriculture

People mainly depend on agriculture to obtain their food. This vital sector is considered to be untouchable since any impact on agriculture will create a serious problem for human life. The impact of climate change is very important from a public policy perspective, since food, prices, and farming income will be affected.

There are two major mechanisms that control the impact on agriculture. First the carbon dioxide fertilization effect and second climate change scenarios, which affect growth and yields. A decrease in crop yields will occur due to heat stress, decreased soil moisture, and soil erosion and drought. In addition, the pests and diseases that affect crops are also influenced by climate and this in turn will affect agriculture. At the same time, there are some benefits from climate change by increasing carbon dioxide fertilization which aids crop growth (Alber and Shortle, 2002). For example, most commercial crops in United States such as wheat, rice, barley, potatoes will increase between 15 to 20%. Higher temperature in regions can speed plant development but will reduce yields and quality, particularly during critical crop growth periods. Table 3.2 shows the climate change effects on selected crop yield.

Table 3.2 Climate Change Effects on Selected Crop Yields in North America (Claussen, 2001)

Location	**Impact (crop: percent change in yield)**	**Climate change Scenario**
Canada (Alberta, Ontario, Manitota ,Saskatchewan)	Wheat: (-40 to +234%) Results varied by site and scenario	Incremental* with CO_2
United States	Wheat (-20 to -2 %) Corn (-30 to -15%) Soybean (-40 to +15%)	Incremental* with CO_2
Mexico	Corn (-61 to -6%)	Incremental* with CO_2

*Incremental scenarios = $+2^0$ and $+4^0$ C, +20%.

Livestock also will be affected by climate change by the decline in the quality and quantity of forage from grasslands and supplies of other feeds (i.e. corn).

In addition, direct effects of higher temperatures can stress animal physiology and performance.

Agricultural adaptation to climate change is very important in order to protect crop yields and in order to benefit from the positive impact on crop yields. For example, farmers in Peru adjust their main crops (rice and cotton) by forecasting on EI Nino events. These crops are very sensitive to the amount and timing of rainfall and in 1987 forecasting was sufficiently good for farmers and production increased by 3% (Whyte, 1995). In the future, there is a need for technical advances in agriculture to develop programs for crop breeding and management, especially in conditions of heat and drought, and management of water irrigation in arid and semi arid areas.

Another important topic in agricultural is how nutrients will be affected by global warming and greenhouse gases, and how these nutrients will be released from fertilizers to the atmosphere. All forms of nutrients, such as phosphorus, potassium, and sulfur, can emit N_2O, with nitrogen fertilizers being the main source of N_2O. Nutrients fixation by plants will contribute to a decrease in the concentration of nutrients in soil. This process is influenced by extreme climate events and changes in environment conditions will affect the crop growth. Brunlsema and Johnston (2000) suggested practices to adapt this problem by:

a) Fertilizer addition before crop uptake.

b) Placing the N where it can easily be absorbed by the plant.

c) Depending on soil tests and crop sensing, site-specific application methods must be applied for nitrogen fertilizers.

d) Developing cover crops during the off-season, to minimize the amount of soil NO_3 available for conversion to N_2O, and retaining the N for the next crop in rotation.

3.4 Precipitation

Precipitation is the main driving force that controls the water balance in the atmosphere. Any change in the hydrological cycle will affect the quality and timing of precipitation as mentioned in Chapter One. Increasing global surface temperatures are very likely to lead to changes in precipitation and atmospheric moisture. Due to changes in atmospheric circulation, a more active hydrological cycle will occur, and increases in the water holding capacity throughout the atmosphere (Vellinga and Verseveld, 2000).

Changes in precipitation also affect other water resources such as runoff, flood frequency and rivers. Most studies show a trend in increasing precipitation in the northern hemispheres mid and high latitudes, and a decrease in the tropics and subtropics in both hemispheres. The largest precipitation changes over land are found in high latitudes, some equatorial regions and southern Asia. Globally the mean increase in precipitation will be 15% over the next 30 years (Mimikou, 2000). In Britain, the annual precipitation will increase by 2050, from less than 5% in the south to over 15% in the north (Nigel, 1996). There is also a large variation between climate models where Canadian models predict a decline in precipitation by 2030 in USA, while the Hadley models show an increase in precipitation.

Precipitation intensity (centimeters of water per unit time) is expected to increase when the temperature rises. The absolute humidity, the concentration of water vapour in the air at the moment when the saturation value is reached (maximum water vapour concentration increases 6 percent for each degree Celsius temperature increase) is also predicted to increase (Vellinga and Verseveld, 2000).

3.5 Evaporation and Transpiration

Evaporation is the conversion of water from liquid to vapour, and transpiration is the release of water from plants to the atmosphere. It is affected by conditions such as wind speed, humidity, vegetation, and soil characteristics. Therefore the mean evaporation is very sensitive to any change in climate system. For example, if radiation increases, the availability of energy increases and the water holding capacity of the air will increase along with evaporation increase.

The real evaporation rate depends on water availability on land and soil, vegetation and humidity. In dry regions the evaporation is controlled by energy not humidity, whereas in humid regions, humidity controls evaporation. Climate models project that evaporation will increase in the range of 3 to 15 % (National Research Council, U.S, 1998), and this is related to a doubling in CO_2 concentration.

Plants control the transpiration process, and each type of plant has a different transpiration rate. In addition, the rate of transpiration depends on root depth, and stomatal behavior (Claussen, 2001). Stomatal conductance in many plants falls as the vapor pressure deficit close to the leaf increases as temperature rises. Increased CO_2 concentration reduces stomatal conductance, although studies show that the effects vary considerably between species and depend on nutrients and water status.

2.6 Snow

Snow and ice caps represent a reservoir of water over long time. Runoff is dependent on ice melting in the summer, and the amount of ice melt is the difference between the accumulation of ice, and the rate of melt. An increase in temperature will have three major effects (Gleick and Adams, 2000):

1) Ratio of rain to snow will increase.

2) Declines and delays in the overall snowfall season.

3) Acceleration of spring snowmelt.

Climate models predict that for 0.1 ^{0}C increases in temperature there will be a reduction in the glacial volume of 10 to 25 % (Gleick and Adams, 2000). Glacial decline will affect hydropower sites in Alaska which obtain runoff from melting. Decreasing snowmelt will affect electrical generation (Leggett, 1996). In some areas, researchers suggested that the snow will increase. On the contrary, an effective study by Wahl and the University of Toronto (Wahl, 2003), for Canada's Height Mountain in Yukon Territory, concluded that due to increasing temperatures over the 150 years, there will be a marked increase in snow accumulation, with the largest changes taking place in the next decade.

2.7 Groundwater

Groundwater is a major source of drinking water in the world, especially in arid and semiarid regions. Many countries depend on groundwater to supply their needs. It accounted for 22% of the total U.S fresh water (Loaiciga, 2003). Climate change has an effect on groundwater quality, recharge and withdrawal rate. If the amounts of rainfall change, this will affect the recharge rate. The recharge rate depends on soil moisture and pore water velocity and these factors depend on soil type, evaporation and precipitation rates. Studies show that shallow aquifers in arid and semi arid areas, which recharge by seasonal stream flow, can be depleted by an increase in evaporation rate. In Africa a 15% reduction in rainfall will lead to a 45% reduction in groundwater recharge (Markandya, 2002). Sea level rise will affect the quality of groundwater, in delta regions as mentioned in section 2.2, via saline intrusion into coastal aquifers.

Loaiciga (2003) studied the effect of a doubling of the CO_2 scenario on groundwater. He analyzed the recharge dynamics in Edward Aquifers, Texas. One of the four cases is the effect of doubling CO_2 on the recharge rate, and he concluded that stream recharge is a dominant mechanism of aquifer recharge, linking climate change and aquifer response by:

$$R_{2CO2} = (Q_{2CO2} / Q_{1CO2}) * R_{historical} \quad (3.1)$$

Where:

$Q1_{CO2}$: inflow at doubling CO_2 scenario (m^3/L).

$Q2_{CO2}$: outflow at doubling CO_2 scenario (m^3/L).

Q_{2CO2} / Q_{1CO2}: flow scaling factor by GCM model (m^3/L).

$$R\ historical: = Qu_{\text{upstream flow}} + Qi_{\text{flow within recharge zone}} - Qd_{\text{downstream flow}} \quad (3.2)$$

Qu = upstream flow (m^3/L).

Qi = flow within recharge zone (m^3/L).

Qd = downstream flow (m^3/L).

By applying this model on aquifer springs, the results showed that the spring will decrease by 73% in 2050.

3.8 Ecosystem

The ecosystem is very sensitive to climate change; changes in climate affect the different species within the ecosystem and their adaptation in the environment. The effect of climate on ecosystem is complex, depending on the nature of change, and most aquatic systems are incapable of surviving climate change and harsh environmental conditions. This will lead to degradation of the ecosystem and loss of biodiversity in different areas. Biological diversity will be affected by rapid changes in climate, habitats may degrade and species that can't adapt enough may become extinct (Loaiciga, 2003). In addition, any media such as oceans and seas contain ecosystems, which imply that any change in these media will also have an impact on the ecosystem itself. Figure 3.1 shows examples for different ecosystems.

Forests are examples of ecosystems. Trees take a long time to grow compared with other livings things. For each 1^0C increase in temperature, the productivity of trees will be affected. As trees become less healthy, they are more prone to pests, die back and fires. Under doubled CO_2 scenarios, 65% of forested area could be affected (UNEP, 2001). In Canada, die back of trees is related to changes in climate conditions. Warmer winters and drier summers have an economic effect by decreasing the wood production due to a loss of forest area.

Figure 3.1 Examples of different ecosystems (UNEP, 2001)

A doubling of CO_2 concentration has a positive impact in some cases such as increasing vegetation biomass and dissolved oxygen. Consequences of a warmer climate are an increase of cold water fish habitats in hard waves and shifts in the competitive salmon species. A recent estimation of the impact of changing water temperature and cold water fisheries showed that net losses ranging from 85-320 million could result (Natural Resources of Canada, 2002).

Increasing runoff will raise the nutrient loading into rivers and lakes. The transport of phosphorus and nitrates will affect the quality of water in the rivers and lakes that provide water treatment plants. This may have an effect on the efficiency of treatment plants, and force them to improve their operations in order to adapt to the inflow water quality. Generally, increased deviation of water quality parameters that exceed ecological thresholds, will limit the effectiveness of policies designed for mean conditions. Another important parameter is dissolved organic carbon (DOC), which is predicted to decrease because of the reduction in runoff from drier catchments (Levin, 2001).

Canadian studies (National Water Research Institute, 2004) predict that water levels in the southern lakes will decline, thereby affecting the drinking water quality, transportation, recreation and fishing. Systems for storm sewer and sanitary purposes must be improved in order to deal with increased precipitation.

3.9 Health Effects

Good human health is reliant on proper climate conditions, and health is sensitive to climate change. Global warming could be responsible for the spreading of diseases in the last few decades. With the exception of measuring pollution in air, water, and soil, the estimation of the impact of specific changes on health is very difficult, because human health is related to all aspects. However, the main impact is an increase in temperature.

Numerous studies have been conducted linking extremely hot weather and morality rates. More intense heat waves may cause an increase in heat-related illnesses (heat stroke and dehydration). High temperatures also enhance the spreading of some diseases, such as viral encephalitices which are carried by mosquitoes. Malaria is an example of a high temperature disease which occurs in a temperature range of 25-32 ^{0}C, with a humidity of 50 – 60 % (Whyte, 1995). This disease is responsible for 2 million deaths per year. Other diseases that can be included in this category are yellow and dengue fevers. Air pollution by greenhouse gases will produce respiratory problems such as asthma. Ground-level ozone, a primary ingredient of smog, results when sunlight and heat interact with pollutants such as nitrogen oxides and volatile organic compounds. Table 3.3 gives examples human health problems associated with climate change in Canada

Table 3.3 Canada Health Concerns from Climate Change and Variability (Health Canada, 2002)

Health Effect	Example of Health Vulnerabilities
Temperature-related morbidity and mortality	1) Cold and heat related illnesses. 2)Respiratory and cardiovascular illnesses. 3) Increased occupational health risks
Health effects of extreme weather events	1) Damaged public health infrastructure. 2) Social and mental health stress due to disasters. 3) Occupational health hazards 4) Injuries and illnesses
Air pollution-related health effects	1) Air pollutants and allergens 2) Asthma and other respiratory diseases. 3) Heart attacks, strokes and other. Cardiovascular diseases.
Health effects of water- and food-borne contamination	Diarrheas and intoxication caused by chemical & biological contaminants
Vector-borne and zoon diseases	Changing patterns of diseases caused by bacteria, viruses and other pathogens carried by mosquitoes, ticks and other vector

In Canada the extremely rapid and unexpected spread of West Nile virus, can be attributed to warmer weather (National Water Research Institute, 2004). Knowledge of how climate change impacts human health is required in order to have early warning indicators. The IPCC recommended establishing monitoring networks for adaptation, adaptation data management, baseline analysis, information and development of early warning indicators (MacIver and Dallmeier, 2000). However water quality parameters must be studied under different scenarios in order to have an idea what will happen to water supplies and what is required to keep water fresh and healthy.

3.10 Water quality

The most important natural resource in the world is water. People can't stay without water more than three days. Drinking water quality is therefore of paramount importance. Over the centuries, people have established their cities in close proximity to water sources. During the Industrial Revolution, raw water treatment was initiated.

The first municipal water filtration plant started operations in 1832 in Paisley, Scotland (American Water Work Association, 1999). Scientists began to develop drinking water standards, and the United States developed regulations over a period of 100 years. As knowledge of the health effects of contaminants increased and the treatment technologies to control contamination improved, recommended maximum contaminant level (RMCL) goals were replaced by maximum contaminant level goals (MCLGs).

In the last decade, climate change has been considered to be a source of pollutants, and new research has attempted to introduce engineering management for global warming to fundamental environment processes that regulate the potential impact of climate change on water quality parameters.

The target of this thesis is to establish a correlation between temperature increase and two important water quality parameters, and its effect on drinking water treatment. These parameters are nutrients (phosphate and nitrates), the second parameter, which is related to the first one, is algae (chlorophyll). Prior to introducing these parameters, the impact of climate change on water quality will be introduced.

Climate change will lead to changes in water temperature and stream flow conditions. These changes will have an adverse impact on water quality.

For example, dissolved oxygen tends to decline as temperature rises, since the solubility of oxygen in water is inversely proportional to temperature. Major surface water inputs determine the quality of water. These inputs are as follows:

1) Atmospheric inputs
2) Catchments geology
3) Chemical and biological operation in rivers, lakes.

Nigel (1996) described four mechanisms by which greenhouse gases will affect water, these mechanisms are:

1) High temperature affects the rate of biogeochemical processes that determine water quality.
2) Increased CO_2 affects the rate of most chemical process and enhances the concentration of some parameters such as chemical oxygen demand (COD).
3) Change in stream flow volumes affect dilution for some chemicals.
4) Change in chemical transport load from land surface to water bodies.

These four mechanisms control the potential effect of climate change on water quality parameters, and how these processes will affect water quality. Higher flows of water reduce pollutant concentrations, but at the same time increase erosion of land surfaces and stream channels, leading to higher sediment, chemical and nutrient loads in water bodies. Lower flows could reduce dissolved oxygen concentrations, and increase zones of high temperature. Low flow volumes coupled with a temperature increase creates self purification, because biological degradation and settling rates are temperature dependent. This advantage is limited by the decreased stream flow which affects the water velocity, and decreases oxygenation of the water (Mimikou, 2000). Murdoch concluded that significant changes in water quality will occur as a result of short-term changes in climate (Murdoch, 2000). Mechanism one (high temperature) affects the aquatic ecosystem, human use of rivers, and influences the ability of water to absorb gases such as nitrogen, oxygen, and carbon dioxide.

Chemical inputs from land and air determine the quality of water. Temperature increases will affect the quality in the absence of a change of precipitation, because warming increases biological production and decomposition by increasing rates of metabolism, and the duration of the growing season. High temperatures coupled with an increase in CO_2 concentration increase the volume of the epilimnion that is biologically active, thus creating nutrient cycle acceleration, and anoxia which will degrade the water quality (Murdoch, 2000). Warmer winters may induce higher microbial and nutrient loadings in drinking water supplies, encourage biofilm growth in distribution systems, and support the survival of some pathogens and their indicators (Levin, 2002).

Increases in water temperature may enhance the toxicity of metals in an aquatic ecosystem, and enhance the period of biological activity. This can lead to an accumulation of toxics in organisms. Mechanism three (change in stream flow volumes) increases sedimentation, concentrates pollutants, and reduce non-point source runoff. As a result, the clarity of lakes is increased and penetration of ultraviolet light is easily facilitated. To the contrary, as the dissolution of ions from sediments increase, iron phosphate transfer from the anoxic bottom to the water column enhances biological activity (Weare, 2002).

Chemical reactions of water species depend on water temperature, acidity and the concentration of species and ions. CO_2 concentrations affect the major processes in water. Under the double CO_2 scenario, for example, CO_2 in solution produces H_2CO_3, which increases the alkalinity of water. In addition, the dissociation of H_2CO_3 to HCO_3^- and CO_3^{-2} releases H^+, thereby increasing the acidity of water. Climate change also has an impact on water quality in a reservoir, under a doubled CO_2 scenario (666 ppm) (Ruzicka, 2000). An increase in surface temperature will enhance shorter stratification periods and time of ice cover. In the summer, phytoplankton will increase and the maximum concentration will shift towards a lacustrine part of reservoir.

Drought plays an important role in water quality in arid and semi arid areas. Drought will decrease stream flow volume (mechanism 3) and residence time for chemical constituents will increase. Dissolved phosphorus will have a longer residence time and will be available for biological uptake and chemical reactions.

Orlob and Asce (1992) investigated a doubling of CO_2 with temperature increase scenario on a river dam system. They concluded that under previous conditions, the thermal region of the Shasta dam on the Sacramento River will be modified downstream, and salmon will be affected during periods of elevated temperature. Additionally, water quality and ecological processes would be accelerated such as algal bloom development in summer.

Dissolved organic carbon and UV exposure will be affected due to climate change, and these changes will affect the water species and organic materials (Lean, 1994)

Climatic warming and drought will cause increases in the concentrations of nutrients and other chemicals in lakes by increasing water residence times. In addition the dissolved organic carbon (DOC) concentration in lakes declines under warmer, drier climates due to both decreased sources and increased exposure in lakes to UV light, bacterial action, and chemical flocculation reactions. UV penetration, and subsequent exposure of aquatic organisms, is significantly affected by lake acidification. Photochemical reactions can increase the availability of such toxic metals as mercury, copper, and arsenic (Lean, 1994).

3.10.1 Nitrate and climate change

Nitrates naturally exist in water as part of the nitrogen cycle. They are a stable final oxidation product of nitrogen, and these nitrogen products in water are:

- Organic nitrogen: nitrogen in the form of proteins, amino acids and urea,
- Ammonia (NH_3) nitrogen: nitrogen as ammonia salts ($(NH_4)_2CO_3$), or as free ammonia.
- Nitrite (NO^-_2) nitrogen: intermediate oxygen stage
- Nitrate (NO^-_3): final oxidation product of nitrogen

The oxidation of nitrogen compounds (Nitrification) proceeds as follows:

Organic nitrogen + O_2 $\rightarrow$ Ammonia nitrogen + O_2 $\rightarrow$ $N_2O + O_2$ $\rightarrow$ NO_3^-

The reduction of nitrogen, denitrification, (Tebbutt, (1998) :

$$NO_3^- \longrightarrow N_2O \longrightarrow NH_3 + N_2 + 2O_2$$

The concentration of nitrogen species gives an indication of water quality. If the sample has a high concentration of organic nitrogen and ammonia, the water is considered unsafe. On the contrary, when water has high levels of nitrate due to the nitrification process, water quality is considered poor.

Major sources of nitrate in water are runoff due to inorganic fertilizers, nitrate added to food as a nitrate reservoir, and oxidizing agents for industrial processes. The oxidation state of nitrogen varies from -3 to +3 (Waitf, 1984). These variations in valence support nitrogen in environmental situations, because of the ability of nitrogen to be oxidized or reduced by many environmental processes. The pH also plays an important role in the determination of nitrogen speciation in water. For example, when the pH increases, the production of ammonia gas is increased. Table 3.4 presents all inorganic nitrogen forms.

Table 3.4 Inorganic Species of Nitrogen (Waitf, 1984)

Species	**Symbol**	**Valence**
Molecular Nitrogen	N_2	0
Nitrate	NO_3^-	5
Ammonia	NH_3	-3
Nitrite	NO_2^-	3
Ammonium	NH_4^-	-3

These forms of nitrogen are available in nature via the nitrogen cycle, Figure 3.2 shows a schematic diagram of the nitrogen cycle.

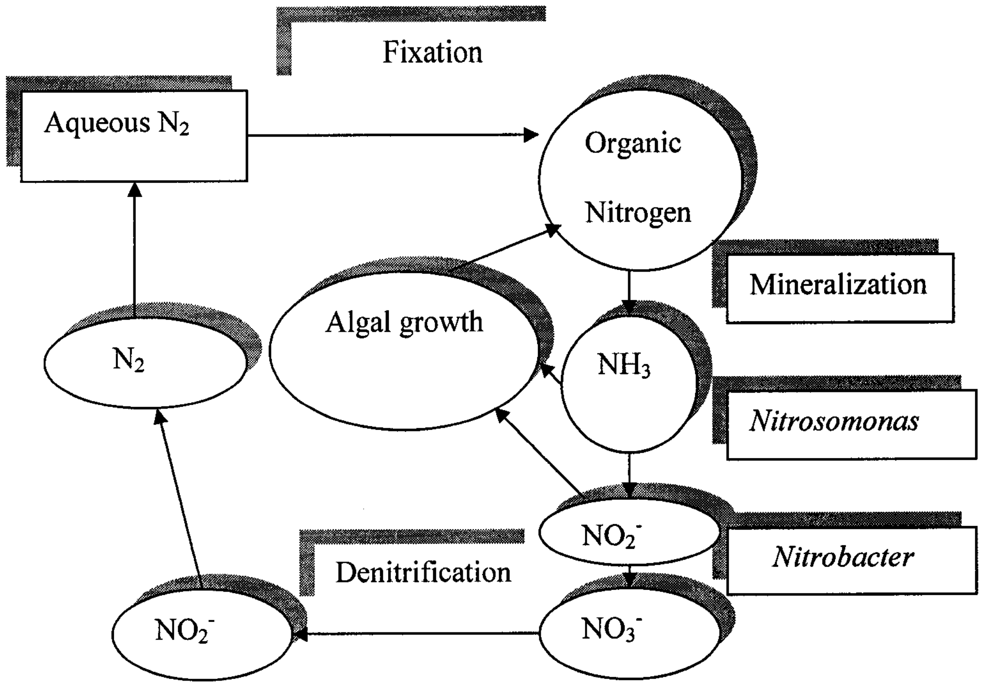


Figure 3.2 Nitrogen Cycle

3.10.2 Uptake of Nitrate by Algae

Nitrate is taken up by algae and plants in water upon their growth and is used in the synthesis of organic nitrogenous compounds. Nitrogen is fixed by algae and plant bacteria, due to strong N-N triple bonds. These bacteria convert nitrogen to cellular organic nitrogen, and these bacteria are (Waitf, 1984):

1) Heterotrophic bacteria: *Achromobacter, Aerobacter, Bacillus polymyxa.*
2) Chemoautotrophic bacteria: *Methanobacillus omelianskii.*
3) Blue-green algae: *Anabaena, Anabaenopsis, Aulosira, Aulosira, Calothrix, Cylindrospeemum, Nostoc, Tolypothrix.*
4) Photosynthesis bacteria: *Chlorobium, Chromatium, Rhodomicrobium, Rhodospirillum.*

These bacteria influence the rate of algal growth, and algae and rooted plants using different nitrogen compounds during their growth cycle. When algae use nitrogen during metabolism, the nitrogen must be reduced to ammonia in order to be assimilated into the plant cell. Atmospheric nitrogen is fixed by a chemoautotrophic bacteria into ammonia, nitrate, and nitrite. This nitrogen then becomes available for general biological use and is taken up by algae in their growth cycle. During growth, the oxidized forms are reduced to organic nitrogen compounds, and these compounds are then returned to the aqueous system either by death of algae or natural leaching.

The focus of this research is to determine the behavior of nitrate during the growth phase of algae, in order to correlate growth with temperature. The Canadian guideline for nitrate for drinking water is 45 mg/l (Canadian Drinking Water guidelines, 2003) compared to 50 mg/l for the U.K (World health organization, 1998). This is a trend for all parameters because Canadian guidelines tend to be stricter than other countries.

3.10.3 Phosphate (PO_4^-)

Phosphorus occurs naturally in rock formations in the earth's crust, usually as phosphate. Of high nutritive value to plants and animals, phosphates are used in fertilizers and as animal feed supplements. They are also used in the manufacture of industrial chemicals and pharmaceuticals and as detergent builders.

High phosphate concentrations in surface waters may indicate fertilizer runoff, domestic waste discharge, or the presence of industrial effluents or detergents. Although phosphates from these sources are usually poly-phosphates or organically bound, all will degrade to "ortho" or reactive phosphates with time. If high phosphate concentrations persevere, algae and other aquatic plant life will develop causing decreased dissolved oxygen levels in the water due to the accelerated decay of organic matter.

Phosphorus found as orthophosphate (PO_4^{-3}), influences the eutrophication process. Phosphate is found in many forms in minerals such as hydroxyl apatite, $Ca_{10}(OH)_2(PO_4)_6$, and flouroaptite, $Ca_{10}F_2(PO_4)_6$ (Fagel, 2003). Phosphate can be found in particulate organic fractions suspended in a water column. The main differences between the phosphate cycle and the nitrogen cycle is phosphorus occurs in nature exclusively as PO_4^{-3} .

Phosphate is very sensitive to pH. In the natural pH range (6-9), the predominant forms are $H_2PO_4^-$ and HPO_4^{-2}. These species are designated as orthophosphate and will be considered to be available for uptake by algae and other plants. Figure 3.3 shows the phosphorus cycle in a natural system. The main input of phosphate is via the weathering of minerals and the main loss from the cycle is via precipitation of inorganic forms of phosphate.

Phosphorus is essential for the growth of plants and algae and once assimilated PO_4^{-3} is converted to organic phosphorus compounds, which are then converted to polyphosphate (Florida lake watch water body, 1998).

In many freshwater situations, phosphates have been shown to be the limiting nutrient for algae growth. Phosphates are considered the limiting factor in the growth potential of aquatic systems (Government of Canada, 2001). Figure 3.3 shows the phosphate cycle.

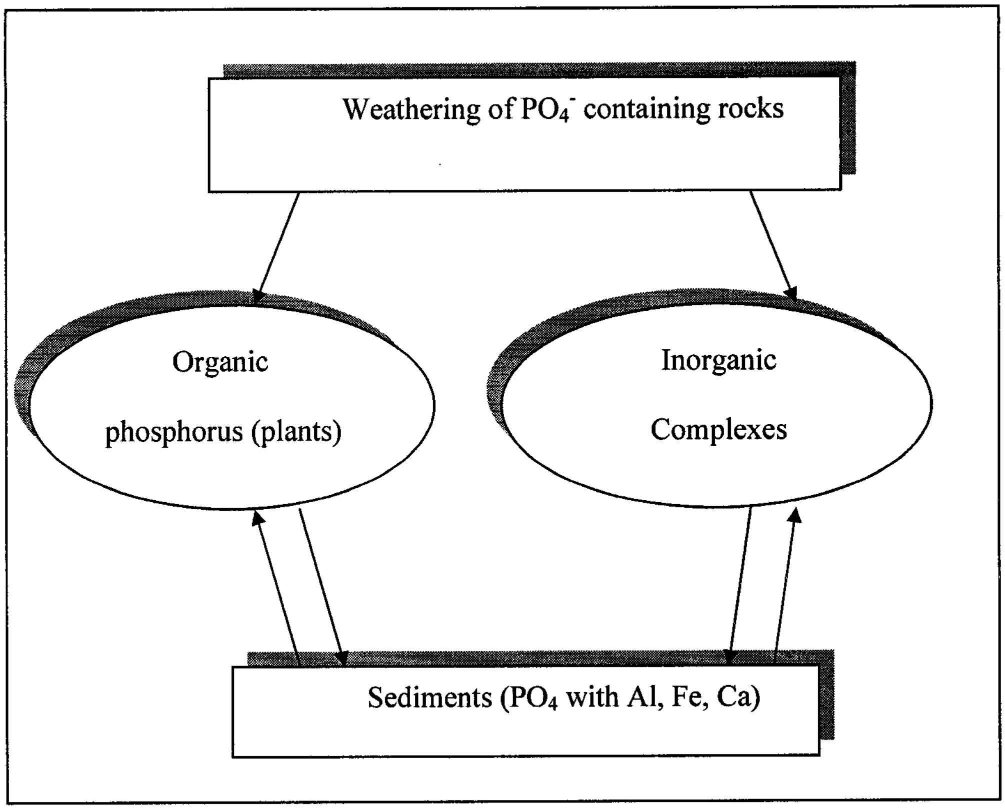


Figure 3.3 Phosphate cycle (Waitf, 1984)

3.10.4 Climate Change and Nutrients

Surface water pollution by nutrients is a major environmental problem and their concentration within a river depends on the water inputs to the river, volume of flow, rates of nitrification and denitrification and temperature. For example, for the Yamaska River in Quebec, runoff from agricultural activity is the principle source of nutrients in the basin. Mineral fertilizers are responsible for 13000 tonnes of N, and 3800 tonnes of P (Government of Canada, 2001), which represents 68% of the total N and 75% of the total P in the river.

Both nitrification and denitrification are biologically mediated reactions, and the rate for each process is controlled by temperature and residence time. When temperature increases, both processes increase, but denitrification rates are slightly higher than nitrification. In general, climate change affects nutrients in the following modes (Fagel, 2003):

1) Change in agricultural due to climate change will affect the inputs of agrochemicals in the water body.
2) Higher temperatures increase the rate of mineralization of organic nitrogen available to be washed into river system.
3) In some areas, nutrients decrease in growing season for aquatic life in river, due to uptake of nutrients by algae and other aquatic life.

Nitrate levels of streams are considered to be an indication of nutrient content. Some nutrients are essential for the ecosystem, but excessive levels can negatively impact the water quality. In the southern U.S, concentrations of N in some regions reach 4 to 5 mg/l (Orlob, 1992), due to high temperatures and high agricultural activity. Applying the Hadley British Model to this region, the predicted rainfall will decrease in 2020 – 2039. This will lead to extensive use of fertilizers during the growing season, leading to an increase in nutrient level in water and exacerbate water quality.

Nutrient concentration in water is hardly influenced by seasonal processes, in Erken Lake in Sweden (Petterson, 2003), the nutrient concentration is stable before the growth of phytoplankton. When summer begins, nutrient concentrations will decrease in comparison to the spring, and increase in the autumn. Accumulation of nitrate showed a decrease in the warming period and the concentration was 100 N μg/l instead of 200 N μg/l (Petterson, 2003). This was due to rapid uptake by algae, as nutrient uptake by phytoplankton reduces the nutrient concentration during the algae growth season.

Another important issue in nutrients is the nitrogen to phosphorus ratio (N/P ratio). This ratio controls algal growth, since the minimum concentration of N and P is considered to be a limiting factor and hence controls the rate of algae growth. In the Alton water reservoir in U.K (Perkins, 2000), phosphorus was the limiting factor, and an increase in phosphorus will increase the algae biomass. When the temperature increases in the summer, algal cells will be ready to utilize the nutrients, and for rapid growth. More details will be introduced in the following sections.

3.10.5 Algae

Algae are photosynthetic organisms that need light, water and nutrients to prosper, elements which are readily available in an aquarium. When algae are in balance, it is indicative of high water quality, and can be controlled by being eaten by fish. When algae are out of control it can be an indicator of poor water quality.

Chlorophyll is used to quantify algae, and its photosynthetic pigments are used to estimate phytoplankton biomass. Chlorophyll is a key biochemical component in the molecular apparatus that is responsible for photosynthesis. The critical process is one in which the energy from sunlight is used to produce glucose and oxygen by the following equation:

$$6CO_2 + 6H_2O \xrightarrow[\textbf{Chlorophyll}]{\textbf{Sunlight}} C_6H_{12}O_6 + 6O_2$$

Light and nutrient levels contribute to the growth of algae. An increased light intensity and temperature, in addition to nutrients like phosphates and nitrates, result in more algae. Based on where algae live, there are three types defined as follow (Department of Fisheries and Aquatic Science, 2000):

1) Phytoplankton: float freely in water.

2) Periphyton: attached to aquatic vegetation or other structure.

3) Benthic algae: grow on bottom sediments.

Algae may further be described as being single cell, colonial (grouped together as colonies), and filamentous (appearing as hair-like strands) as shown in Figure 3.4 (Department of Fisheries and Aquatic Science, 2000).

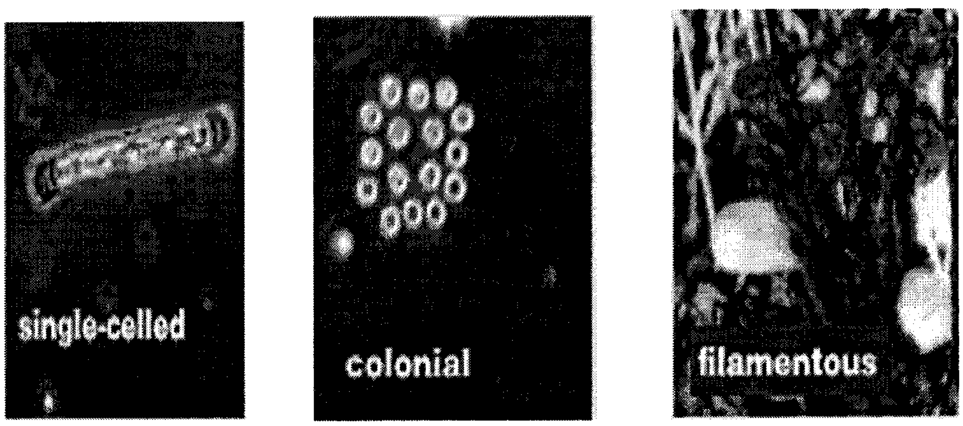


Figure 3.4 Microscopic pictures for different types of algae

Algae can be described by their colors; green, green blue, red, and yellow. All these classifications may be used together, for example: blue green algae, float freely on water as a single cell, or they could be referred to as single blue green phytoplankton.

This research focus on phytoplankton which are classified into three major groups:

1) Green algae: the most common type of algae, is a positive indicator of good water conditions, because fish will eat it readily. Reducing the amount of light and source of nutrients will control a green algae outbreak to algal blooms .

2) Brown algae (diatoms): usually grows on gravel and glass. Unlike other types of algae, this type requires silicate in order to grow (Leon, 2003)

3) Blue green algae (slime): dangerous to planted aquariums, it indicates poor water quality with high levels of phosphates and nutrients. This type of algae share some features of algae and bacteria. Some types are tiny cells that cannot be seen with the naked eye.

Under the microscope the colonies look like strings and can reach sizes of several millimeters as shown in Figure 3.5

Figure 3.5 Microscopic pictures for blue green algae (Department of Fisheries and Aquatic Science, 2000)

These blooms become visible during calm and hot weather. Algal cells contain small gas bubbles which cause them to rise to the surface of the lake and accumulate as blue green algae scum.

Some algal blooms can persist throughout the summer and early fall. It is very difficult to predict blooms with high accuracy, because factors which enhance the growth of blooms are very sensitive to climate such as temperature, wind velocity, nutrient inputs, and sunlight.

A direct effect of algae on water bodies is the decomposition of algae, since it consumes dissolved oxygen in the water. Under a high decomposition rate, depletion of oxygen in water and fish will occur, and fish will suffer and die. There also exists a toxicity risk from algae (Murphy, 2003), due to algae cyanbacteria. These bacteria like microcystin group are toxic and affect the nervous system of humans.

All types of algae contain chlorophyll (green pigments found in plants) and the concentration of chlorophyll in water is used to indicate the amount of algal biomass present, expressed as µg/L or mg/m^3. The primary type of chlorophyll is chlorophyll-a, but there is also chlorophyll b and c. Chlorophyll-a structure is shown in Figure 3.6.

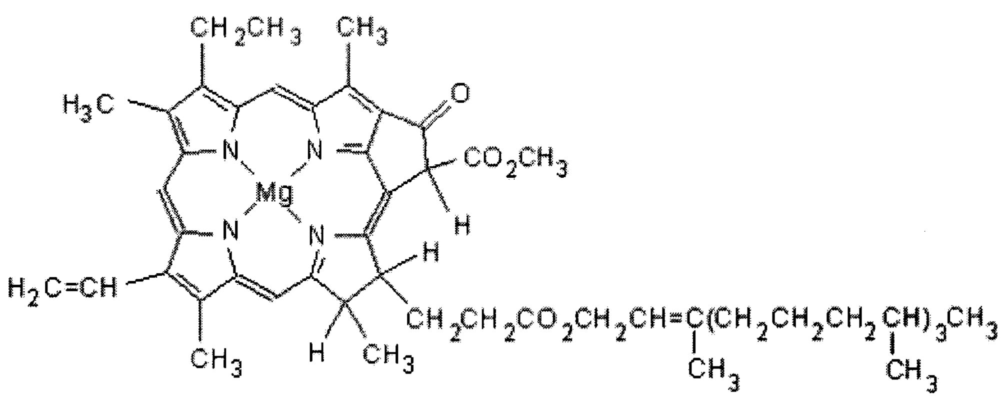


Figure 3.6 Chlorophyll structure (Simon and Helliwel, 1998)

Pheophorbide-a and pheophytin-a are two common degradation products of chlorophyll-a which can be determined by spectrophotometry or flourometry. Algae growth depends primarily on chlorophyll-a, and they need nutrients, carbon dioxide and warm conditions. Two major nutrients are nitrates and phosphates, but they are non-toxic, and are easily utilized by algal cells.

Carbon dioxide plays a dual role with respect to algae. The first role is a source for synthesis of new cell matter, where the light energy is trapped by pigments is used to convert the inorganic carbon into organic carbon contained within algal cells. The second role which is the respiration of algae at night and the addition of CO_2 by algae respiration can be more significant than that produced by fish.

3.10.5.1 Algae Effect on Water Quality and Health

"Swimming not safe for people or animals" and "Fish not safe for eating"

These messages can be seen when visiting Hamilton Harbor in Southern Ontario, or in Lake Champlain in Quebec (Murphy, 2003). These messages are due to toxic algae, and high concentrations of toxic bacteria such as cyanobacteria in the water. High levels of nutrients and algae degrade water quality. In 1996, over 2000 ducks at Whitewater Lake in Manitoba died due to an outbreak of avian botulism which is enhanced by toxic algae.

New research focuses on the Great Lake region where toxic algal blooms have increased from 1999 to 2001(Leon, 2003). They tried to link the factors that support algae growth and non native species such as Zebra mussels which may play a role in increasing the bioavailability of algae toxins. They concluded that nutrient discharge and climate change are playing an important role in algal growth (Leon, 2003).

Most algae are not toxic, but when chlorophyll concentrations reach 100μg/l (Simon and Helliwel, 1998), a sense of urgency results. In addition, if blue-green toxic algae species are present, rectifying measures must be taken irrespective of their concentration in order to have an idea about the toxic pollutant in the water basin and their relative safety with respect to Canadian guidelines (0.0015 mg/l) for microcystin (Canadian drinking water guidelines, 2003). Non toxic algae have an effect on the aquatic plants and organisms because its decreases light availability.

The potential effect of climate change on algae growth has been studied under changes of climate parameters like temperature (Levin, 2002). Warmer temperatures increased the harmful algae bloom, and degrade drinking water odor and taste. They have also caused fatalities in farm animals that drank directly from the water. Several algal blooms are bio toxins associated primarily with the consumption of contaminated shellfish. Some of the blooms cause dermatitis and are cytotoxic.

The Department of Environmental Health at Boston University studied the impact of climate change on algae growth on the Canadian- U.S border region; (School of Public Health, Boston, 2001). They noted that an increase in temperature increased harmful algal blooms. Over the last three decades, the expansion of blooms has been linked to climate change.

One of the most important modeling approaches of climate change on phytoplankton growth rate was conducted by Hassan and Hanaki (Hassan, 1998). They calculated the growth rate of phytoplankton by considering the effects of three principal components. These components were water temperature, solar radiation, and nutrients balance. Model results showed that dissolved oxygen will have a maximum reduction in summer (67%, 4.1 mg/l) for study area. In addition maximum phytoplankton concentration ranged between 0.83 - 6.4 mg/l during early July and mid August, and a noticeable reduction of 0.66- 1.32 mg/l resulted at the end of October until the end of November. The average growth rate for the entire season was 0.77 mg/l.

To determine the potential effect of climate change on algal growth, water samples were collected to archive this purpose. Analytical analysis was applied to estimate the nutrient and algal levels in water samples, and the correlation was estimated between these parameters and temperature. Chapter 4 will introduce the analytical methods which were used to monitor water samples.

Chapter 4

Material and methods

The objective of this study is to evaluate the potential effects of climate change on water quality. Nitrate, phosphate and chlorophyll-a are important water quality parameters that represent the aquatic system of water. Therefore, these three parameters were measured and used as an indicator of water quality.

The parameters were monitored at two drinking water treatment plants: 1) Atwater filtration plant, and 2) Charles-J.des Baillets treatment plant in Lasalle, Montreal. Both plants receive water from the Saint Lawrence River. Two reservoirs were constructed at the river to pump water through ducts to the plants. The aqueduct canal was built to feed Atwater Plant, and a tunnel was built to provide the des Baillets Plant.

Water samples were collected from the two plants and analyzed for nitrate and phosphate concentrations with temperature before and after treatment for both plants. Chlorophyll-a was also monitored in the aqueduct canal in Lasalle, Montreal in order to study the behavior of algae growth in canal.

The samples were taken twice a week from June to December in 2003. The data were used to construct a correlation between algal growth and temperature. Algal growth factors like nutrients factor G (N) and temperature factor G (T) were calculated to determine which factor has more influence on algae growth. Temperature was chosen as a climate parameter in order to determine the impact of climate change on water quality. Future values for temperature are available in Canadian climate models to estimate the future rise in temperature in order to predict the future level for algae growth. A detailed description of the two water treatment plants is provided in the next section.

4.1 Site description

4.1.1 Saint Laurent River

The St. Lawrence River is the dominant feature of the Quebec landscape. It flows a total distance of 1500 km, and over 70% of Quebec's population lives along its 4200 km of shoreline (Atwater treatment plant publication, 2003). The St. Lawrence is not a homogeneous unit. It is divided into three sections, (1) the freshwater reach, (2) the estuary, and (3) the gulf. Figure 4.1 shows water withdrawn from the river to the treatment plants.

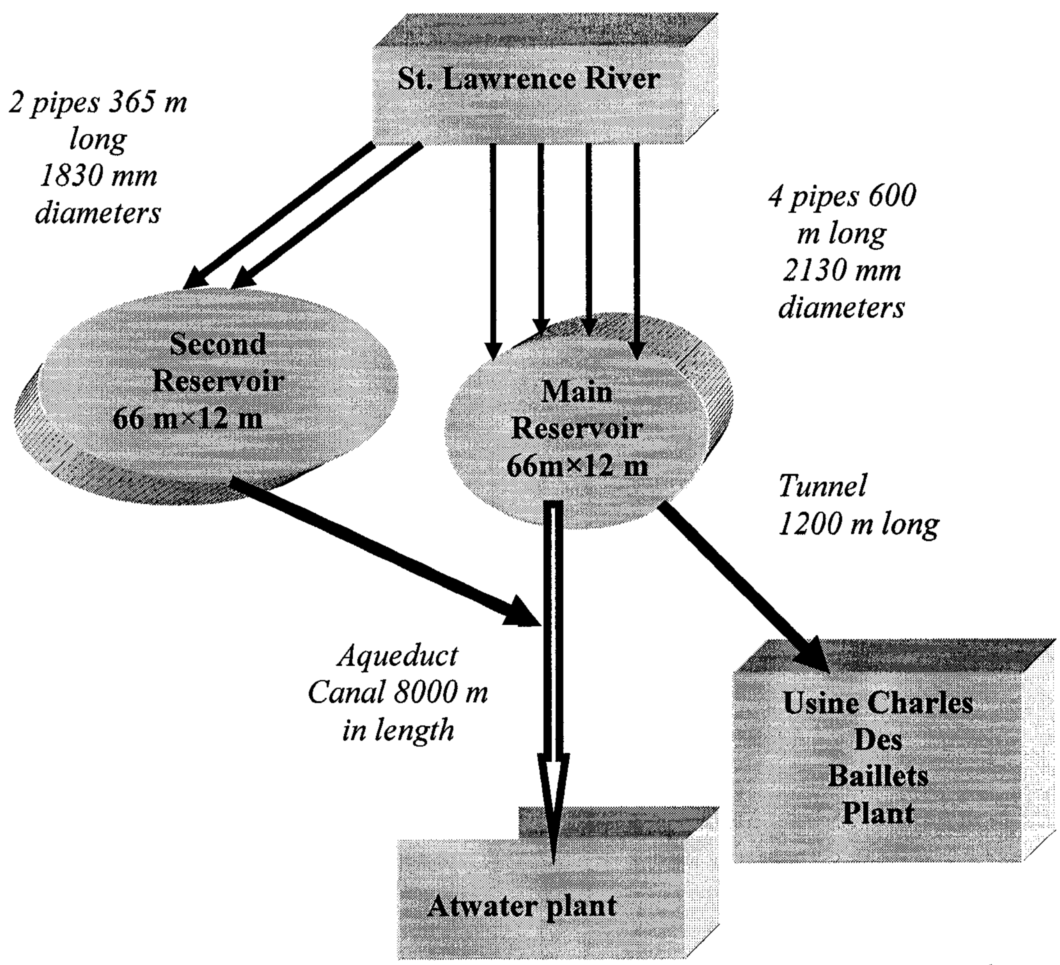


Figure 4.1 Water withdrawals from the St. Lawrence River (Atwater treatment plant publications, 2003)

4.1.2 Usine Charles Des Baillets Plant (D.B)

The D.B plant was established in 1978, its ozonation plant with maximum design capacity of 1 136 000 m^3/d (Gagne, 1996). In combination with the Atwater plant, it presently serves 1.5 million Montrealers. Figure 4.2 illustrates a schematic diagram for the main units of the D.B plant.

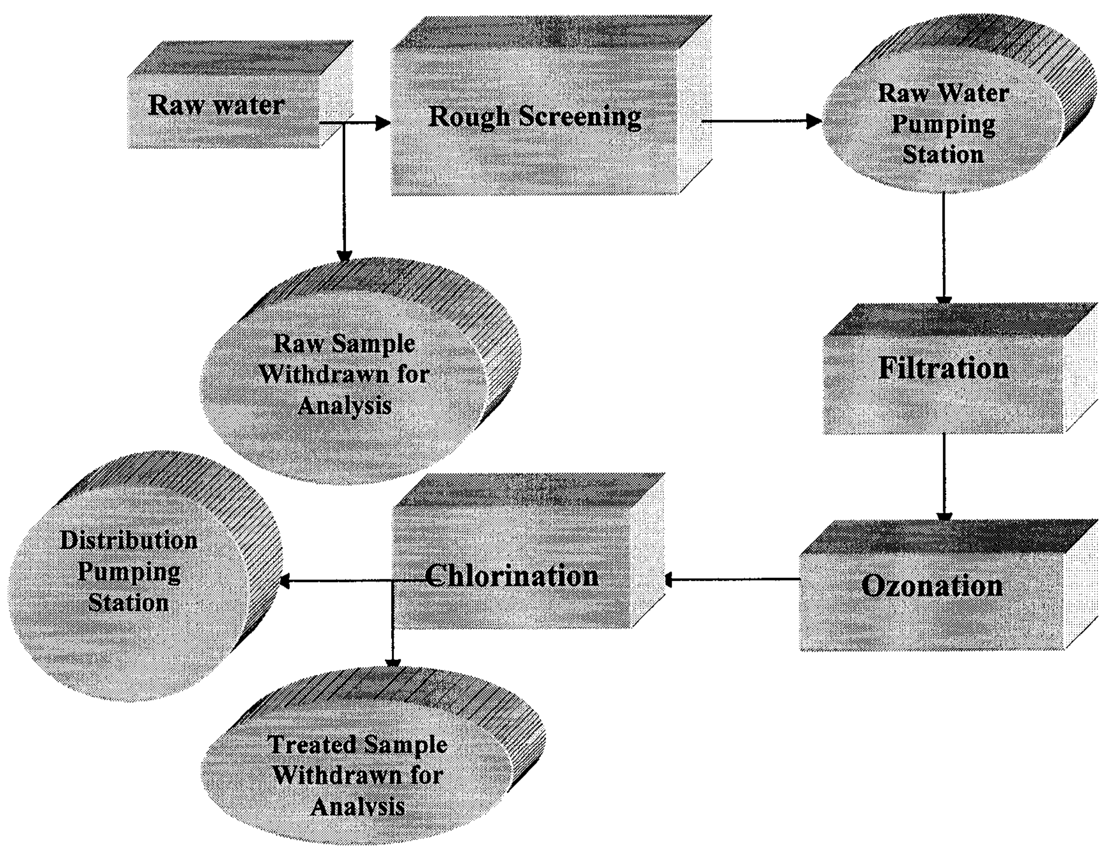


Figure 4.2 Schematic diagrams for D.B plant

Water enters the plant through a 1200 long tunnel as shown in Figure 4.1; at this location water samples were taken via plant workers in order to perform the analysis. The water then passes through a screening unit to intercept matter or objects which could damage pumps, and to separate leaves that enter in the plant as seen in Figure 4.3 and 4.4

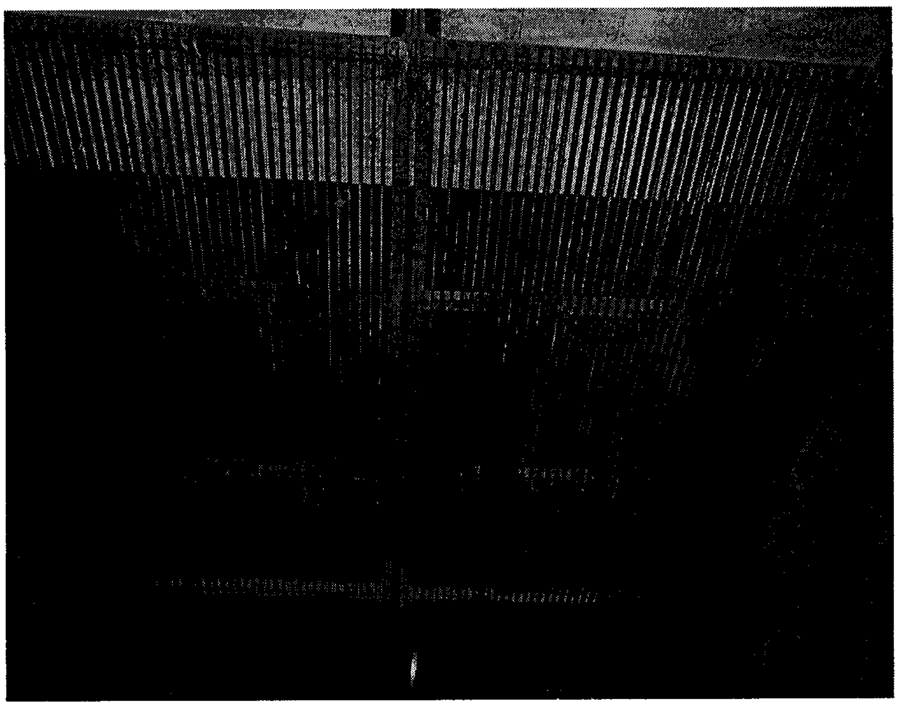


Figure 4.3 Screening unit at the D.B plant

Water is subsequently pumped to a filtration unit, which consists of a bacterial removed bed supported by siliceous sand. The filter eliminates floating material and bacteria and improves the water's color and transparency. Through the process, the water is regularly sampled and physical, chemical, and bacteriological analyses are conducted to ensure that taste, color and other parameters meet the effluent standards before being transferred to the ozonation unit.

Figure 4.4 Algae and plants removed by screening at the D.B plant

Ozonation is an efficient disinfection process, which eliminates odor and taste. Ozone is highly an unstable gas that is produced on-site by exposing ambient air that has been filtered and dried to an electric discharge in an ozonizer. A portion of the air is transformed into ozone when three oxygen atoms bind together. Ozone is immediately injected in the form of air bubbles at the bottom of the basin through which the water is pumped as shown in Figures 4.5 and 4.6.

The organic matter in the water is oxidized on contact with the ozone, destroying bacteria and rendering viruses harmless. An ozonation unit is comprised of three systems: air preparation, ozone generation and ozone dissolution. Using a typical dosage between 1-3 mg/l (Gagne, 1996); six ozone generators can produce a total of 4320 kg/d of ozone. The ozonation units are shown in Figure 4.5 and 4.6.

The next stage is chlorination which is performed by injecting gaseous chlorine into the water. Chlorination ensures that the water is disinfected and retains its quality at the point of consumption.

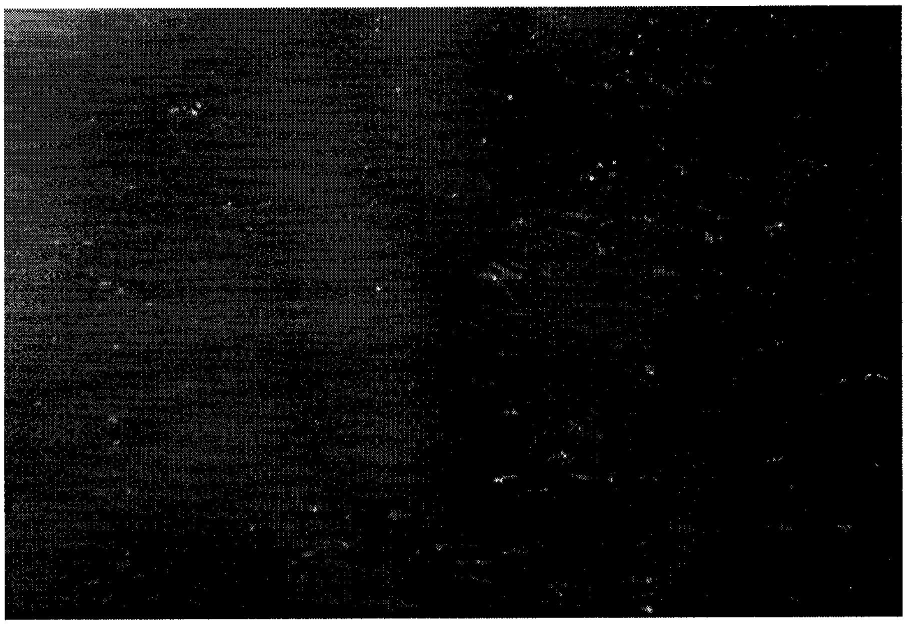


Figure 4.5 Air injection bubbles in the ozonation unit

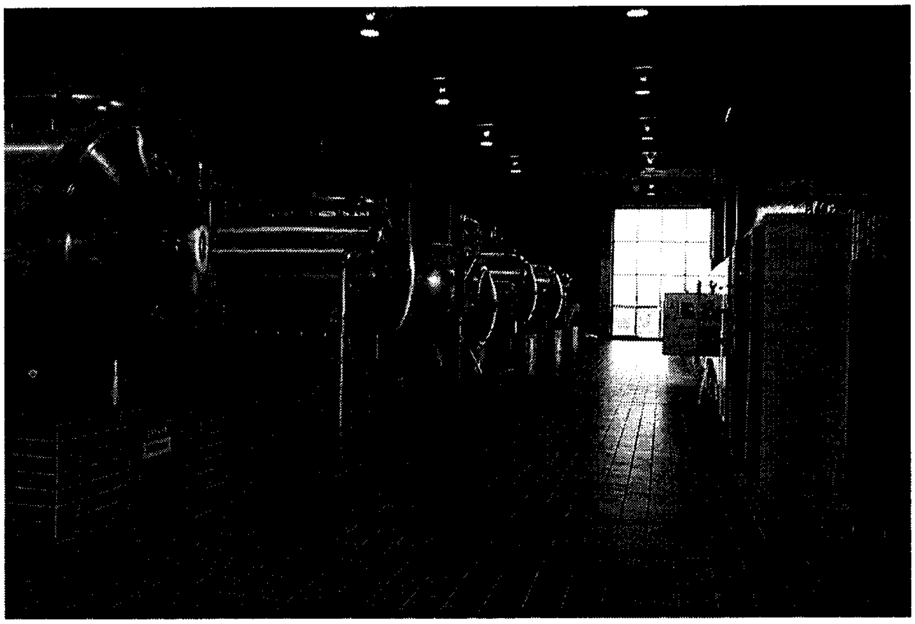


Figure 4.6 Ozonation unit at D.B plant

The final stages of treatment consist of pumping water to six distribution zones serving the entire territory. The surplus is stored in seven underground reservoirs; six are located in Montreal and the seventh is in the Rosemont district.

4.1.3 Usine Atwater Plant

The Atwater plant is modeled before the D.B plant, with subtle differences occulting in the following areas:

1) Ozonation unit.

2) Aqueduct Canal.

The Atwater plant has a higher nominal capacity. Its capacity is 1 590 000 m^3/d. The aqueduct canal feeds the Atwater plant by raw water. And is a 8 km in length, 49m wide and 5 m depth (Atwater publications, 2003). The quality of the raw water that enters the D.B plant is different from that entering the Atwater plant, because the open system (Aqueduct Canal) allows the plastic bottles, rough material and aquatic plants to enter the canal. In addition, the open system allows the water to come into contact with the atmosphere changing the temperature increase or decrease, which may affect the quality of water. As D.B plant, water samples were taken through plant workers before screening unit. Figures 4.7 show the Aqueduct Canal.

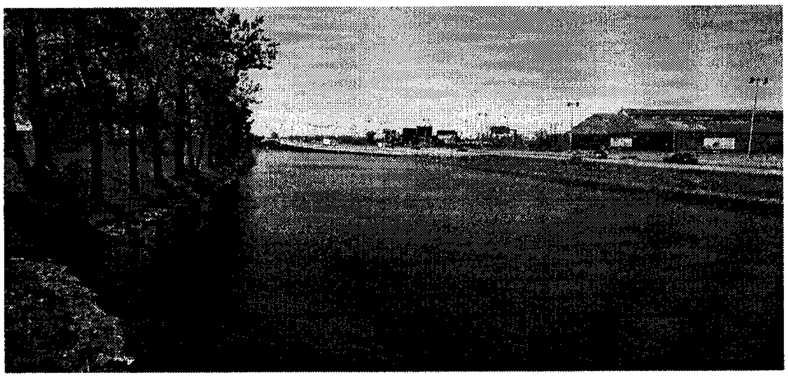


Figure 4.7 Aqueduct Canal in Lasalle, Montreal

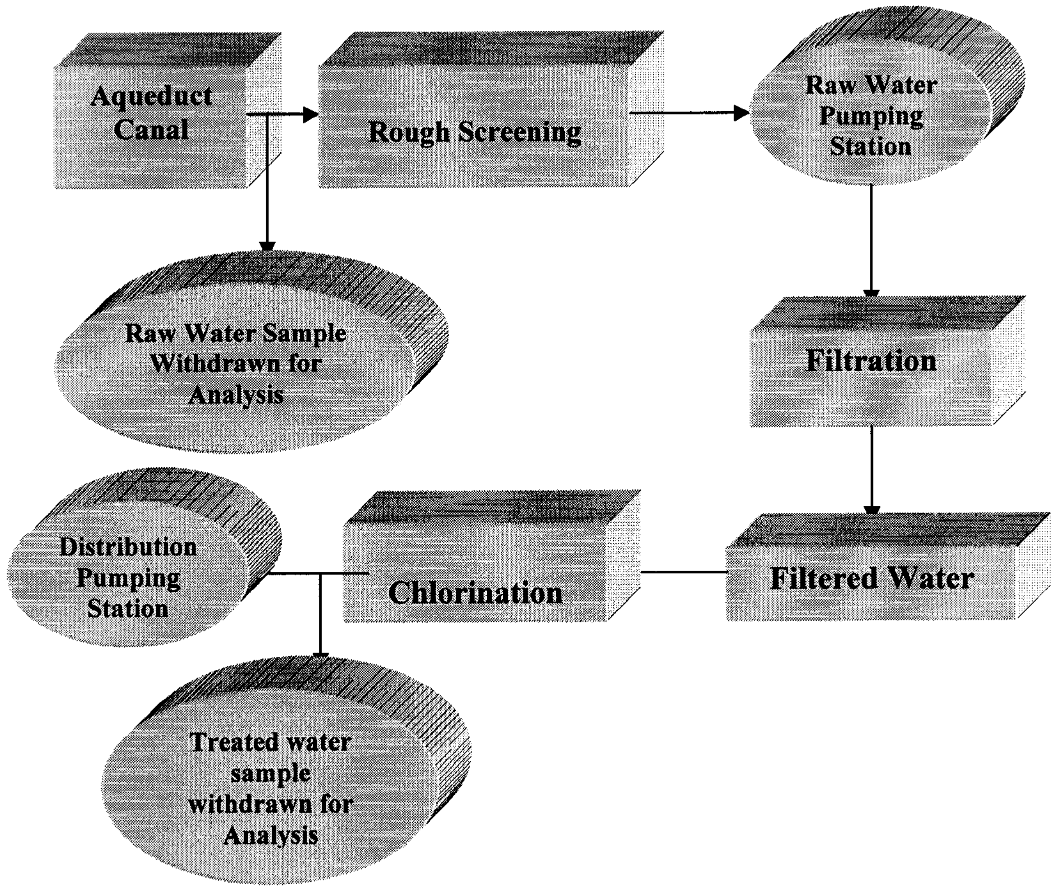


Figure 4.8 Schematic diagram of the Atwater plant

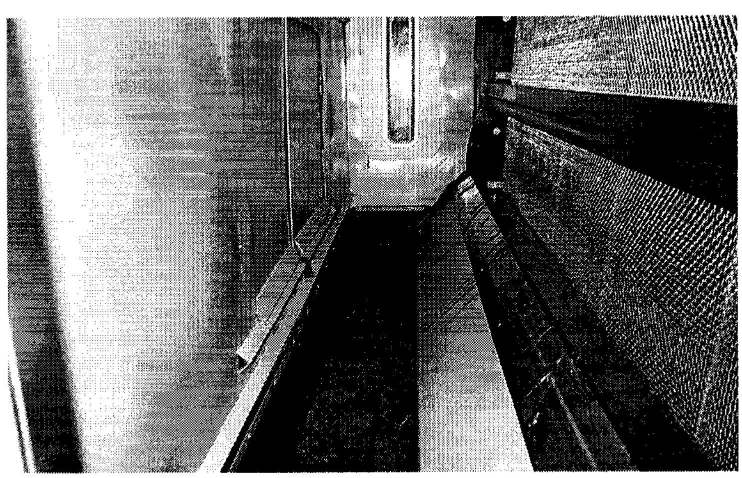


Figure 4.9 Screening unit at the Atwater Plant for removing algae

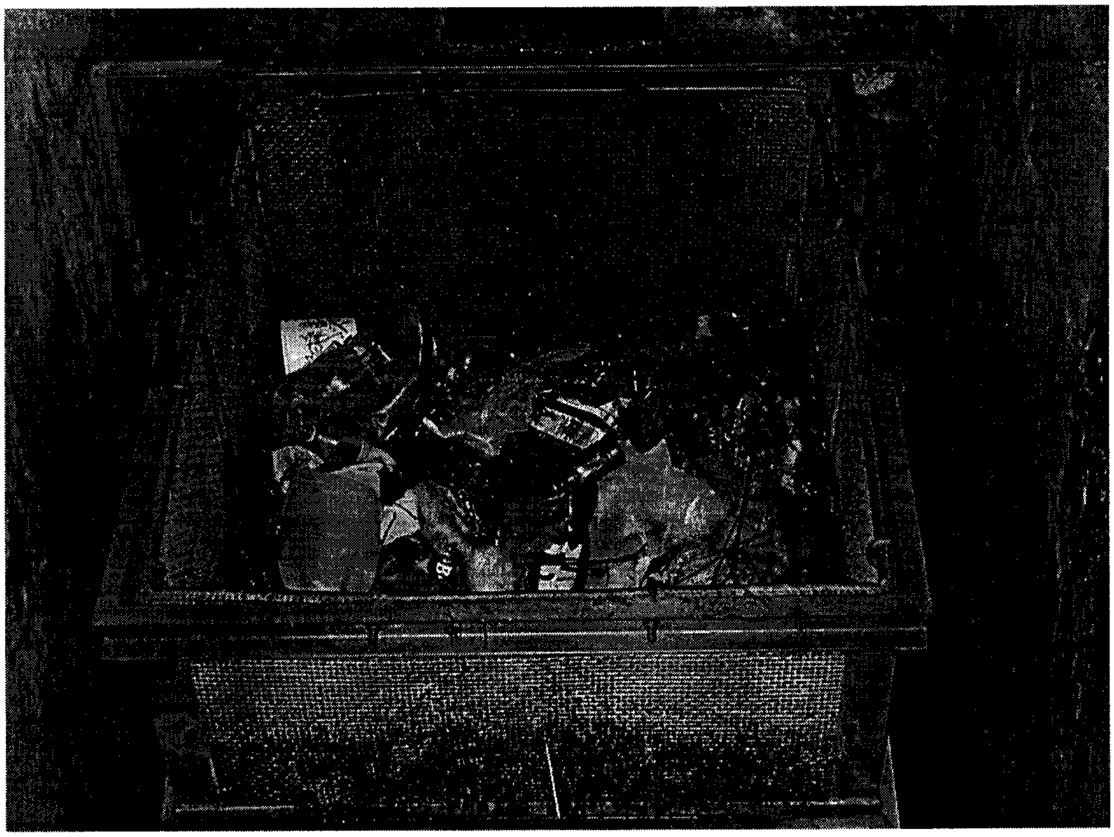


Figure 4.10 Algae and wastes from the Aqueduct Canal

4.2 Analytical Methods

The material and methods used in this thesis will be introduced in this section. Water samples were collected from the Charles Des Baillet plant and Atwater filtration plants, before and after treatment, twice a week from June to December.

After collection, each water sample was analyzed for nitrate concentration, phosphate concentration and chlorophyll-a using Standard Methods for the Examination of Water and Wastewater (American Public Health Association APHA, 1998). Temperature was also monitored during this period in order to study the behavior of the above mentioned parameters under changing of temperature from summer to winter. The pH of the raw water was monitored with nutrient levels. Measurements in this thesis include two sets of analysis. The first set deals with nitrate and phosphate concentration analysis, and the second one is related to determination of chlorophyll-a concentration.

Nitrate is essential for algae and plant growth. Its presence in excessive amounts in the water basin may cause major pollution problems like (blue babies) "methaemoglobinemia" in infants less than six months of age (Perkin Elmer spectrophotometer manual, 2000). Nitrates in conjunction with phosphate motivate the growth of algae with all of the related difficulties associated with excessive algae growth. A Canadian and Quebec guideline for nitrate-nitrite is 10 mg/l .

Phosphorus is an important nutrient for aquatic plants. Its concentration in water is less than 0.1 ppm (spectrophotometer manual, 2000). When phosphorus is present in excess of concentrations required for normal aquatic plant growth, a process called eutrophication occurs. This will enhance algae growth, and rapid decomposition of dense algae scum with associated organisms give rise to hydrogen sulfide gas.

Chlorophyll-a is a blue green microcystaline solid; all plant life contains the primary photosynthesis pigments. Chlorophyll-a is considered an indirect estimation of algal biomass, and growth rate. Planktonic algae contain about 1 to 2 % of chlorophyll dry weight. Its concentration is used to classify the trophic state of lakes and rivers. Oligotrophic lakes have chlorophyll values ranging between (0.3 – 2.5 μg/l) (Latif, 1997).

4.2.1 First Set

4.2.1.1 Nitrate analysis (Cadmium Reduction Method) (APHA, 1998)

a) Description:

Nitrate concentrations of sample from influent and effluent of water samples were determined by using a Perkin Elmer Lambda 40 UV/VIS Spectrometer. Nitrate-nitrogen was measured in the spectrometer against a standard at a wave length of 540 nm.

Powdered cadmium was used to reduce nitrate to nitrite. The nitrate that is originally present was reduced to nitrite and was then coupled with N-(1 naphthyl)-ethylenediamine dihydrochloride to form a highly pink colored azo. A standard calibration curve was formed with known nitrate concentrations ranging between (1-3 ppm) and was used to measure the nitrate in each water sample.

b) Materials:

- Water sample: raw and treated water were collected from Atwater and D.B plant using 2 and 3 liters dark bottles. The sample was kept in the dark to keep water away from a light source, because the light may affect the quality and algae concentration.

c) Sample preparation[*1]

1) Six centrifugal tubes were prepared as follows:

-Tube 1: 10 ml of distilled water (blank)

-Tube 2: 10 ml of standard nitrate concentration 3 ppm

-Tube 3: 2 ppm NO_3-N concentration (2/3 dilution). 7 ml of standard nitrate was added to 3 ml of distilled water

-Tube 4: 1 ppm NO_3-N concentration (1/3 dilution). 3.5 ml of standard nitrate was added to 6.5 ml of distilled water

-Tube 5: 10 ml of raw water [*2]

-Tube 6: 10 ml of treated water

Table 4.1 summarizes the concentration of acids and reagents in each tube.

Table 4.1 Tube Solutions for Nitrate Test

Tube	Water Type	Standard Nitrate Solution	Mixed Acid NH_4Cl	Nitrate Reducing Reagent "Cadmium powder"	Concentration of Nitrate
1	10 ml distilled water (blank)	0	1 ml	0.1 g	0
2	0	10 ml	1 ml	0.1 g	3 ppm
3	3 ml distilled water	7 ml	1 ml	0.1 g	2 ppm
4	6.5 ml distilled water	3.5 ml	1 ml	0.1 g	1 ppm
5	10 ml of raw water	0	1 ml	0.1 g	Unknown
6	10 ml treated water	0	1 ml	0.1 g	Unknown

*[1] Sample preparation was performed for water samples taken from D.B plant and Atwater plant.

2) 1 ml of mixed acid (NH_4Cl) was added in each tube.

3) 0.1 g of nitrate reducing reagent was added in each tube.

4) After 5 minutes a pink color development was achieved as shown in Figure 4.11

5) Tubes were shaken using shaker machine for 5 min and 150 rpm.

After that, the samples were ready for analysis. (See appendix).

Figure 4.11 Color developments in nitrate samples

4.2.1.2 Phosphate analysis (Ascorbic Acid Reduction Method)

a) Description

Ammonium molybdate and antimony potassium react in a filtered acid medium with a dilute solution of PO_4^{-3} to form antimony-phosphomolybdate complex. This complex is reduced to an intense blue color by ascorbic acid. The color is proportional to the amount of phosphate present. Only orthophosphate forms a blue color in this test. Polyphosphates and some organic phosphorus compounds may be converted to the orthophosphate form by sulfuric acid digestion (APHA, 1998).

b) Sample preparation

1) Six centrifugal tubes were prepared as in the nitrate test. Table 4.2 summarizes the phosphate solutions and concentration .

2) 1 ml of mixed acid (Ascorbic Acid) was added in each tube

3) 0.1 g of phosphate reducing reagent was added in each tube

4) After 5 minutes the blue color development was achieved as shown in Figure 4.12

5) Tubes were shaken using a shaker for 5 min and 150 rpm.

After that samples were arranged as shown in Figure 4.12.

Table 4.2 Solutions for the Phosphate Test

Tube	**Types of water**	**Standard phosphate solution**	**Mixed acid Ascorbic Acid**	**phosphate reducing reagent "Ammonium molybdate"**	**Concentration of phosphate**
1	10 ml distilled water (blank)	0	1 ml	0.1 g	0
2	0	10 ml	1 ml	0.1 g	3 ppm
3	3 ml distilled water	7 ml	1 ml	0.1 g	2 ppm
4	6.5 ml distilled water	3.5 ml	1 ml	0.1 g	1 ppm
5	10 ml of raw water	0	1 ml	0.1 g	Unknown
6	10 ml treated water	0	1 ml	0.1 g	Unknown

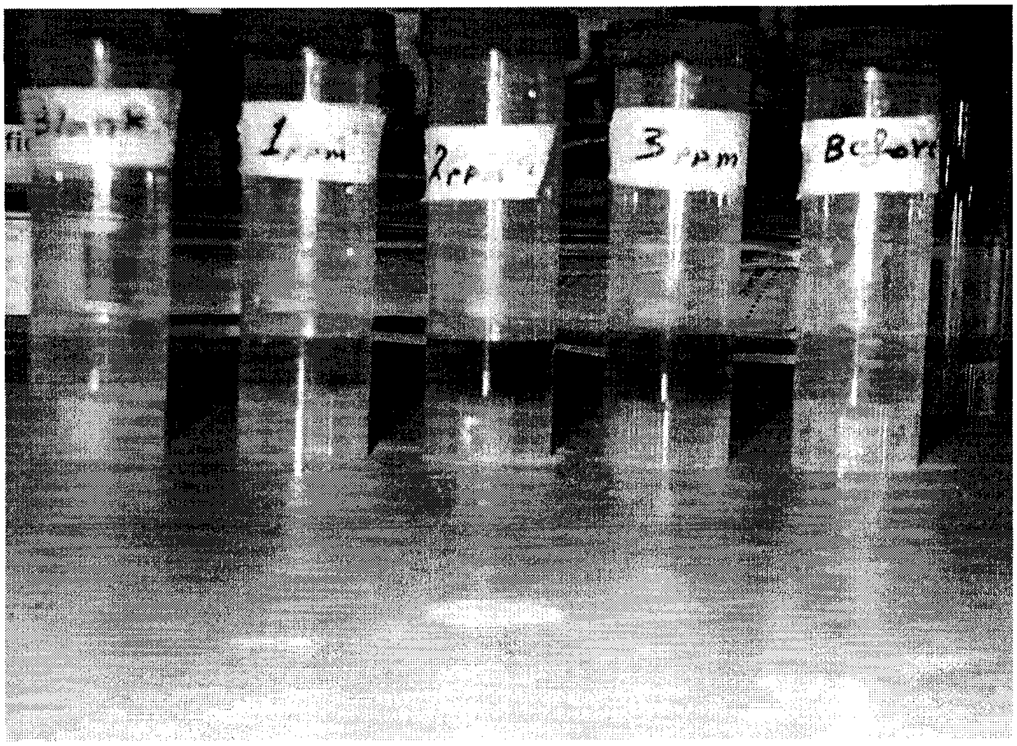


Figure 4.12 Color developments in phosphate samples

4.2.2 Second Set (chlorophyll-a determination)

Extraction and measurements of chlorophyll- a consist of several steps, each of which may be performed in several different ways, depending on the device used for the tests by HPLC and spectrometry, or the aqueous solution used to extract algae cells (acetone or methanol)(Simon and Helliwel, 1998) .

The method used to detect chlorophyll a was by spectrophotometric determination described by the American Public Health Association (APHA), American Water Works Association and the Water Environment Federation.

a) Materials

- Raw water: 2 to 3 liters were taken from Atwater Plant. Opaque containers were used to collect samples. Smaller amounts were used to obtain denser population. Water samples were measured immediately. If analysis was delayed, samples were stored in the dark at 4 ^{0}C .
- An aqueous magnesium carbonate solution was prepared: 0.1 g of finely powdered Mg_2CO_3 was added to 100 ml distilled water.
- An aqueous acetone solution was prepared: 90 parts acetone was mixed to 10 parts of distilled water .

b) Equipment

- Filtration equipment: membrane filters (0.45 μm porosity, 47 mm diameter), and vacuum pump as shown in Figure 4.13.
- Clinical centrifuge.
- Centrifuge tubes: 50 ml graduated, screw –cap.
- Tissue grinder: round bottom grinding tubes with a matching pestle having grooves in the TFE tip (Kontes Glass Company Glass/Teflon grinder).

c) Procedure

Pigment Extraction:

1) The sample was filtered through a glass-fiber filter as shown in Figure 4.13

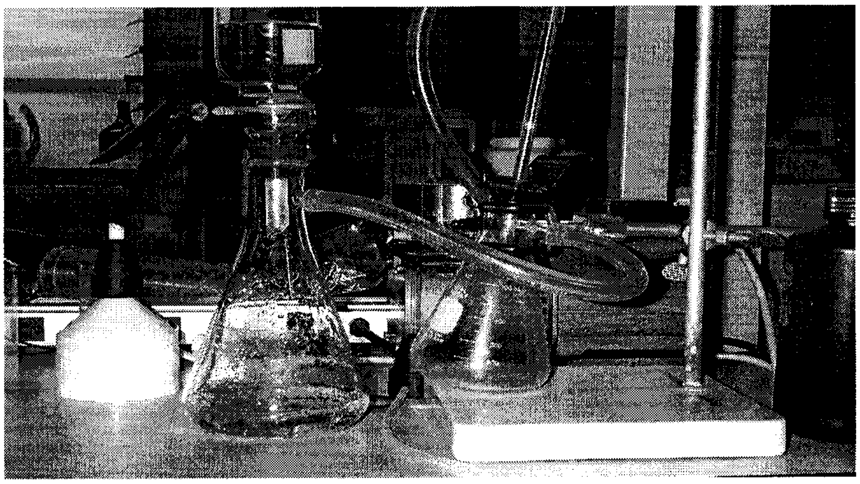


Figure 4.13 Filtration process

The filtration unit was attached to a suitable source of pressure (pump). During the process, 0.2 ml of magnesium carbonate solution was added. The volume of filtered sample was determined. The glass-fiber filter containing a green pigment was immediately analyzed for chlorophyll.

2) The filter was placed in a tissue grinder; filter was covered with 3 to 5 ml of 90% aqueous acetone solution, and the filter was crushed using a glass rod for 5 min, as shown in Figure 4.14.

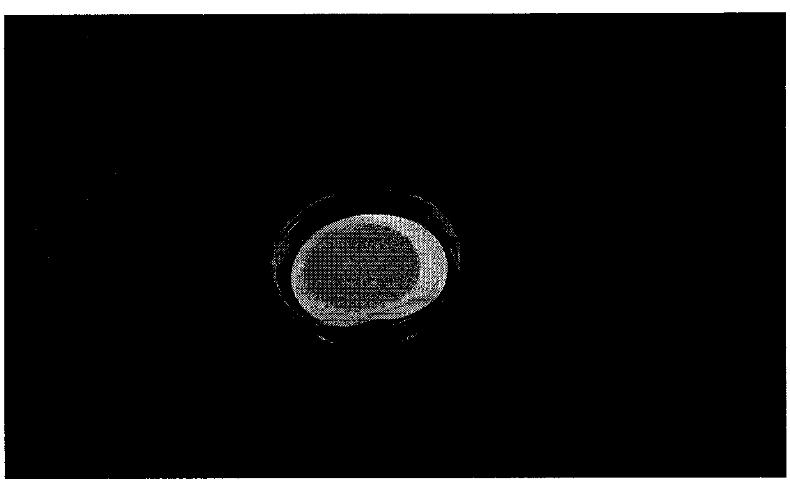


Figure 4.14 Filter after sample filtration

3) The extract was transferred to a centrifuge tube; the tube was rinsed with 90% aqueous acetone. Rinse was added the to extraction slurry and the total volume was adjusted to 10 ml with an aqueous acetone solution. The extract was stored in the dark for a minimum of two hours at 4 ^{0}C .

4) The extract was clarified by centrifuging in closed tubes for 20 min at 500 g (2050 rpm), as shown in Figures 4.15 and 4.16.

5) The extract was placed on filter paper (41 Ash less circle 110) in order to clarify the clearance of extract and to decrease turbidity as much as possible in order to get accurate results in the spectrophotometric analysis .

6) The clarified extract was decanted into a clean calibrated 15 ml vial and the final extract volume was determined.

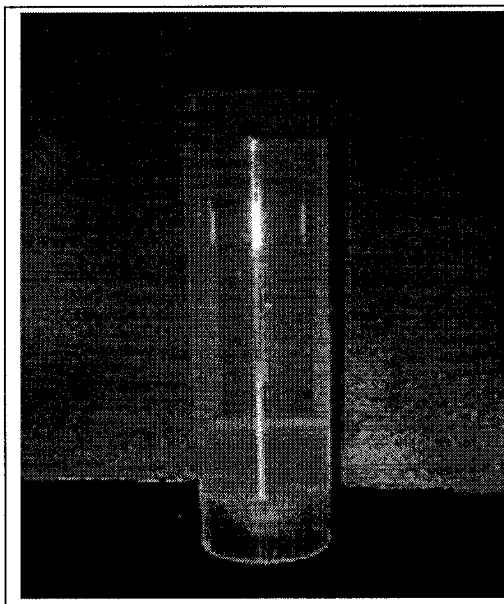


Figure 4.15 Sample before centrifuging

Figure 4.16 Sample after centrifuging

Spectrophotometric determination of chlorophyll:

1) The extract was transferred to a 1 cm cuvette and measured the optical density at 750, 664, 647, and 630 nm (APHA, 1998). The optical density reading at 664, 647 and 630 nm was used to determine the chlorophyll-a concentration. The OD reading at 750 nm is a correction for turbidity (in case of high turbidity). This correction is done by subtracting this reading from each of the pigments OD values of the other wavelengths before using them in the equations that follow.

2) The concentrations of chlorophyll-a were calculated using following equation (Latif, 1997 and APHA, 1998).

$$\mathbf{Ca = 11.85\,(OD664) - 1.54(OD\ 647) - 0.08(OD630)} \quad \mathbf{(4.1)}$$

Where

Ca = Concentration of Chlorophyll a in the extract mg/L

OD 664 = Optical density at 664 nm

OD 647 = Optical density at 647 nm

OD 630 = Optical density at 630 nm

After determining the concentration of chlorophyll in the extract, the amount of chlorophyll-a per unit volume was calculated as follows:

$$\mathbf{Chlorophyll\ a,\ mg/m^3 = (Ca * extract\ volume\ (L)) / (volume\ of\ sample)} \quad \mathbf{(4.2)}$$

4.2.3 Statistical Equations

The first-order linear model was used to relate temperature (quantitative independent variable) to measured parameters like nitrate, phosphate, chlorophyll-a to (quantitative dependent variable). The first order model is summarized in equation 4.3 (Sincich, 1994).

$$Y = B_0 + B_1 X \qquad (4.3)$$

Where

Y= quantitative dependent variable

X= quantitative independent variable

B_0= y-intercept of the line

B_1= slope of the line

The coefficient of determination R^2 which measures how much the errors of prediction of Y were reduced by using the information provided by X in equation (4.3). R^2 value is calculated by the equation 4.4

$$R^2 = (SSyy - SSE) / SSyy \qquad (4.4)$$

Where

$SSyy = \sum (yi - \bar{y})$

$SSE = \sum (yi - \hat{y})$

$\bar{y}$ = average measured concentration of parameters

$\hat{y}$ = calculated concentration of parameters by 3.3 equation

y = measured concentration of parameters.

Chapter 5

Results and Discussion

Water samples were collected to study the behavior of NO_3^-, PO_4^{-3} and Chlorophyll-a under a change of temperature from summer to winter. During this period, temperature plays a major role in algae growth. As temperature increases, Chlorophyll-a concentration increases. Appreciably, phosphate and nitrate concentrations decreased during the algal growth period (summer season).

The Canadian Council of Ministries of Environment (CCME) water quality guidelines task group prepared an index to determine the quality of a water basin (CCME, 2001). This water quality index (WQI) used to describe raw water quality that feeds water plants, and consequently, was chosen to examine how a temperature variation will affect this index and impact the quality of water.

It's important to determine which nutrient is more significant to algae growth depending on limiting factor (NO_3^-or PO_4^{-3}). The concept of this limiting factor will be introduced. Interaction between nutrient concentration, temperature and algal growth were estimated. Algal growth models were used to estimate the growth rate and behavior during summer and winter. These values will be used to calculate growth factors (temperature factor and nutrients factor) to determine which factor has more potential effect on algae growth in the aqueduct canal. Finally, future temperatures obtained from CGCM1 modeling were used to estimate the potential of temperature increase on algae growth, and its impact on the growth phase of algae under different phosphate concentration, and how the future increases in temperature will enhance the algae concentration taking in to consideration the limit of this concentration and the possibility of degrading water quality by toxicity of algae. This will allow for a clear description of the effect of climate change on the water quality parameters.

5.1 Nutrient results

Figures 5.1 and 5.2 show the nitrate concentration of the raw water for both plants from June to August.

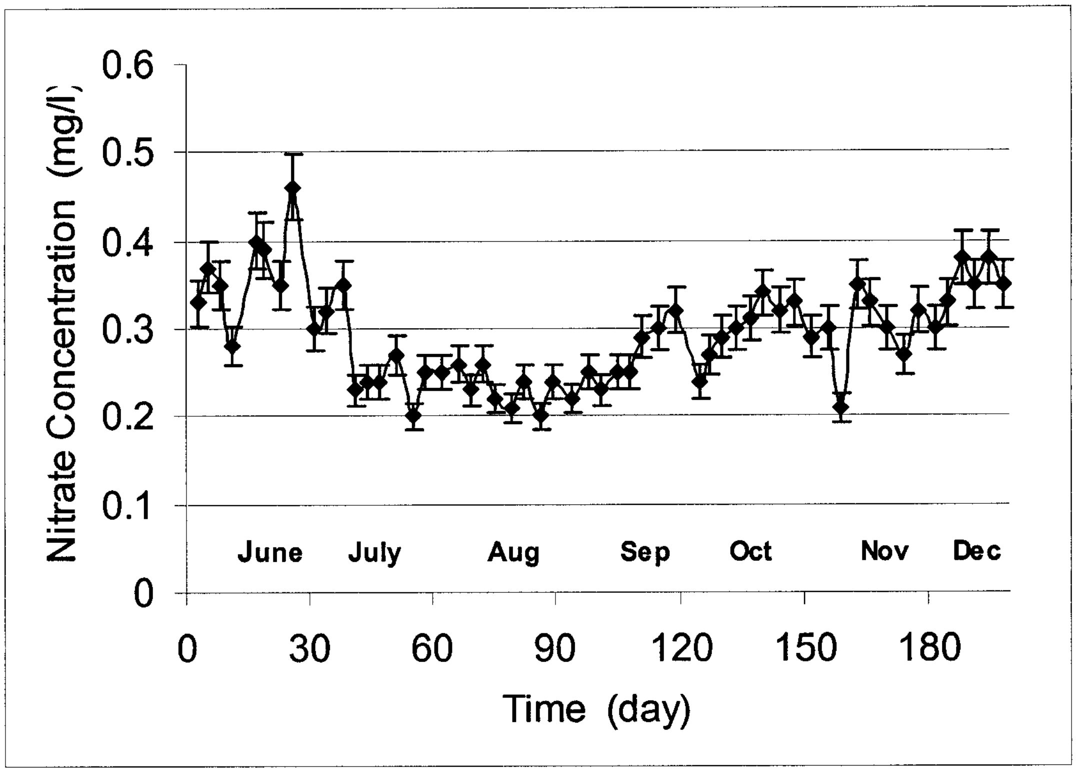


Figure 5.1 Nitrate concentrations for D.B raw water (from June to December)

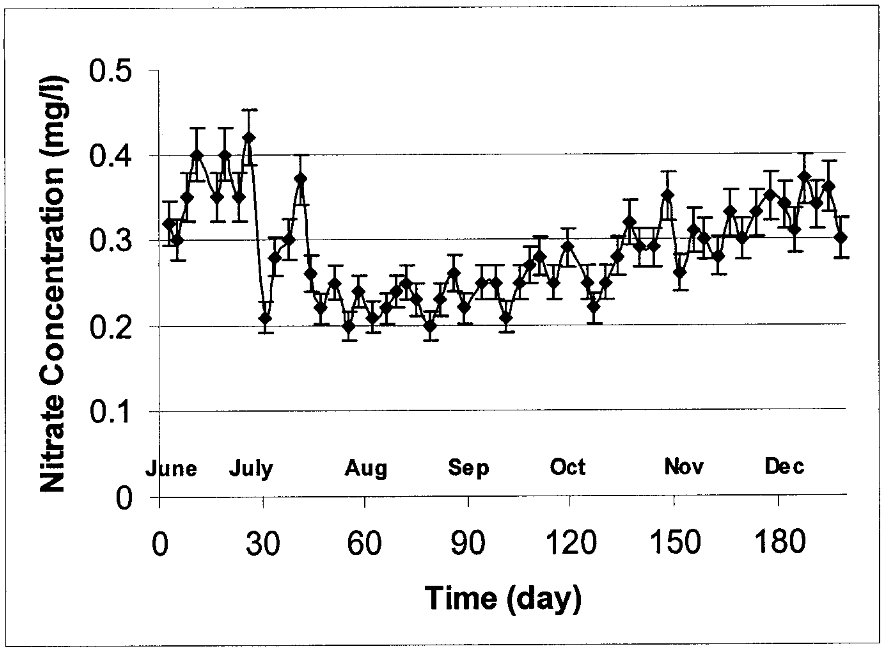


Figure 5.2 Nitrate concentrations for Atwater raw water (from June to December)

The nutrient levels of the raw water from Atwater and D.B plants are less than the Canadian and Quebec guidelines for drinking water. Canadian Guideline for Nitrate as (Nitrate- Nitrogen) is 45 mg/L, whereas Quebec guideline is 10 mg/L (Canadian Drinking Water, 2003).

There is no specific MAC (maximum acceptable concentration) for phosphate, but the acceptable concentration for phosphate is ranging between 0.02 to 0.10 mg/l (Spectrophotometer manual, 1998). The acceptable pH for surface water ranges from 6.5 - 9, where pH for our water samples was slightly change during the whole season (June to December), and pH varied between 8 and 9.

Figures 5.1 and 5.2 show the maximum concentration for NO_3^- was 0.46 mg/L and occurred on June 26, whereas the minimum concentration was 0.2 mg/L and occurred on August 25. Figures 5.2 illustrated the nitrate concentration for the Atwater raw water. The maximum concentration for NO_3^- was 0.42 mg/L and the minimum concentration was 0.2 mg/L. Nitrates started to increase in early March when the runoff was generated. This increase continued until the algae started to grow and we can observe that from Figure 5.1 and 5.2 by noting the nitrate concentration in August because the algae growth has a maximum value in August as we will see. After August, the nitrate started to increase again until September.

The phosphate concentration has the same behavior as nitrate. Figures 5.3 and 5.4 show the phosphate level of raw water for the D.B and Atwater plants.

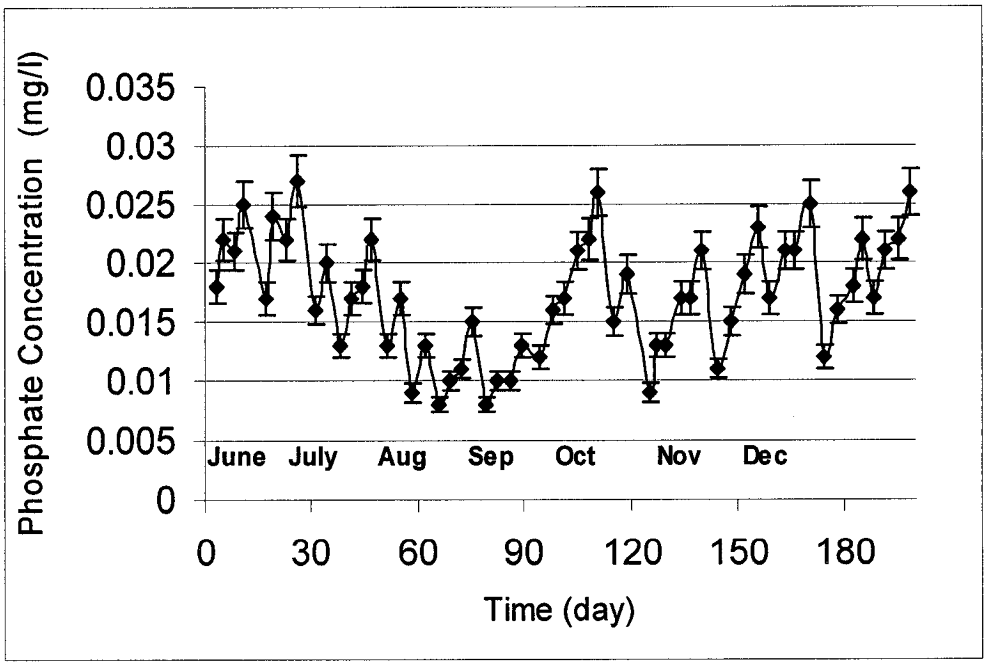


Figure 5.3 Phosphate concentrations for D.B raw water (from June to December)

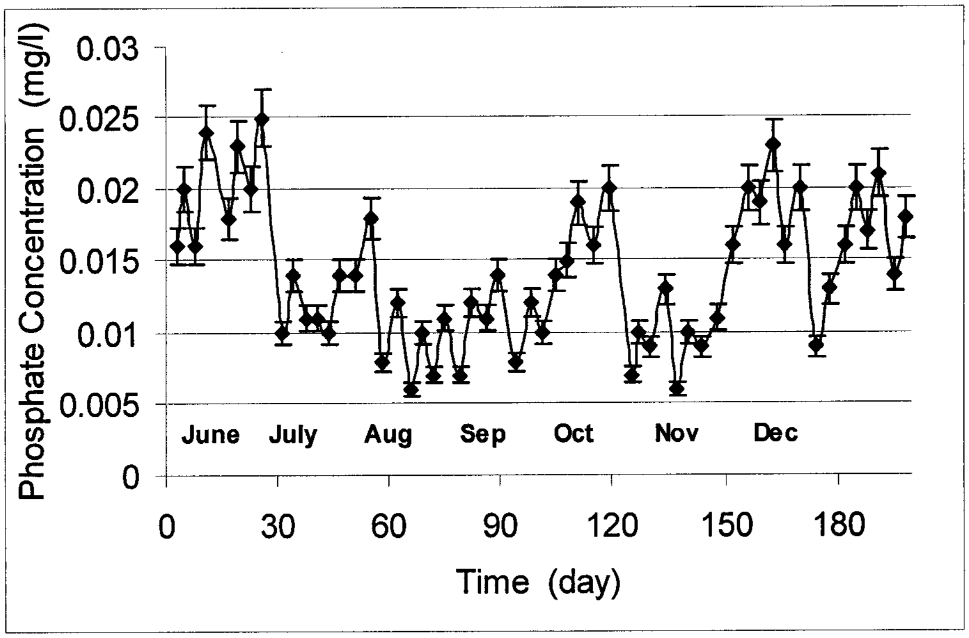


Figure 5.4 Phosphate concentrations for Atwater raw water (from June to December)

Figure 5.3 shows that the maximum phosphate concentration in D.B was 0.027 mg/L in June; whereas the minimum concentration was 0.006 mg/L in August. Figure 5.4 demonstrated that the maximum phosphate concentration in Atwater raw water was 0.027 mg/L and the minimum concentration was 0.008 mg/L. These levels of nutrients enhance algae development in the water. Algae uptake nutrients to grow during the summer season and this is reflected by the decreasing concentration of NO_3^- and PO_4^{-3} in August and September for both plants.

Nitrate and phosphate results for both plants illustrated that there is a slight difference between the two plants. The reasons for this difference are due to the difference in the feeding system for both plants. As seen in Figure 5.1 the Atwater plant receives water through open system (Aqueduct canal). This system keeps water in contact with atmospheric gases such as CO_2 and N_2O, and these gases may influence the quality of water. In constant, the D.B plant receives water through a closed system (closed tunnel), which protects the raw water from atmospheric changes, and this is consider the main cause for the slightly difference in the quality of raw water for the plants.

Treated water samples were collected for three months (June, July, August) for both plants. The results showed that the maximum nitrate concentration for D.B plant was 0.30 mg/L, and the minimum concentration was 0.004 mg/L. For the Atwater plant the maximum nitrate concentration was 0.28 mg/L and the minimum concentration was 0.15 mg/L for the treated sample. Phosphate concentration in treated water for D.B was 0.027 mg/L as maximum values, and 0.004 mg/L as minimum value.

For the Atwater plant, the maximum phosphate for treated water was 0.021 mg/L and minimum concentration was 0.001 mg/L. These levels for nitrates and phosphates emphasize that the treatment efficiency in both plants are very effective, and provide a very good water quality for Montrealers

There is no direct relationship between air temperature and nutrient level. The main source of nutrients is fertilizer. Temperature has an indirect affect on nutrients levels in water, as the temperature enhances the growth of aquatic plants and increases the biochemical reactions which raise the level of nutrients in water (Horn, 2003). To study algal growth in the aqueduct canal which is our objective, it's important to examine the behavior of nitrate and phosphate in the aqueduct canal under the temperature variations. Figures 5.5 and 5.6 demonstrate the nutrient concentration under variations in air temperature in the aqueduct canal.

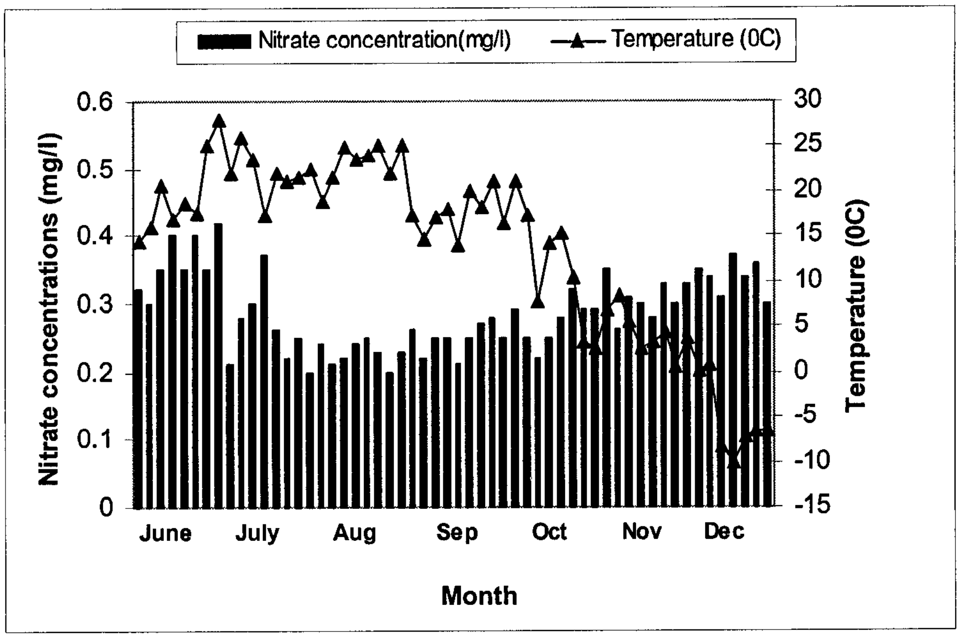


Figure 5.5 Nitrate concentrations under air temperature variation in aqueduct canal.

(from June to December).

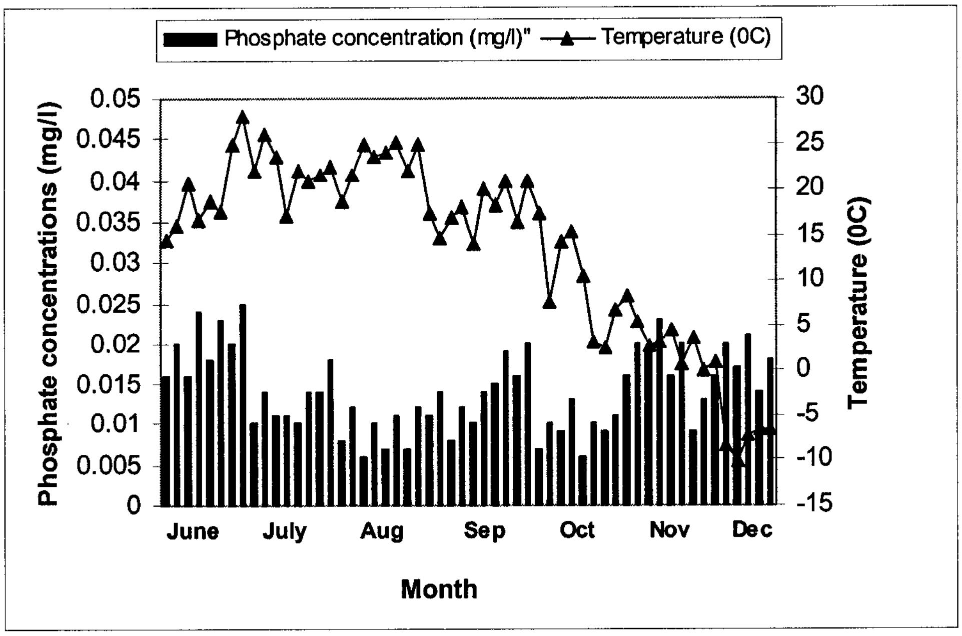


Figure 5.6 Phosphate concentrations under air temperature variation in aqueduct canal

(from June to December)

Figures 5.5 and 5.6 showed that the nitrate and phosphate concentration are independent of temperature fluctuation. For example, nitrate concentration at 22 ^{0}C was 0.26 mg/L , where as the nitrate concentration at 16^{0}C was 0.3 mg/L. Also the phosphate concentration at 20 ^{0}C was 0.016 mg/L whereas the phosphate concentration at 18.6 ^{0}C was mg/L.

Monthly concentrations of nutrients have the same trends as daily data. The pH value of raw water for both plants varied between 8 to 9. Figures 5.7 and 5.8 illustrate these relations.

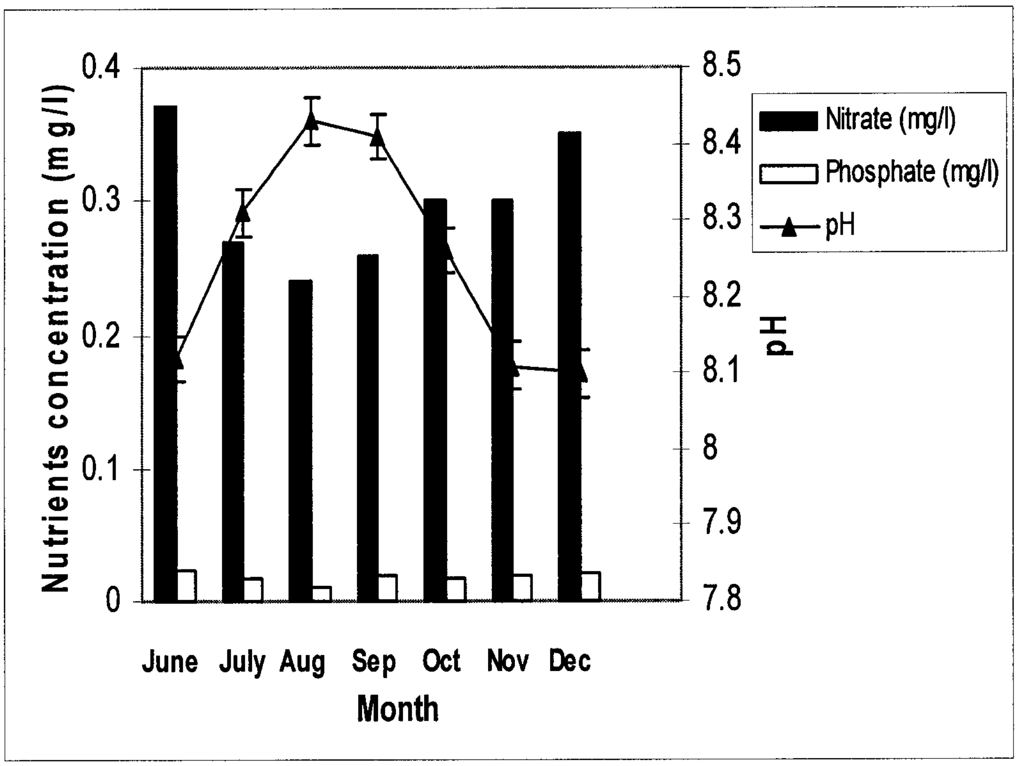


Fig 5.7 Monthly pH and Nutrients measurements for D.B raw water (whole season)

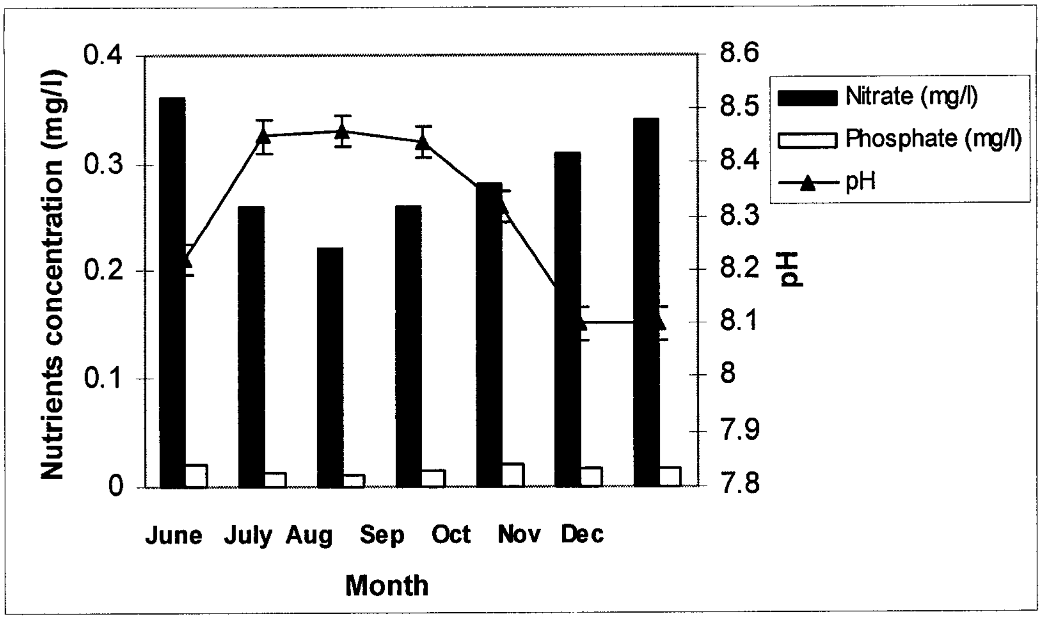


Figure 5.8 Monthly pH and Nutrients for Atwater raw water (whole season)

Figures 5.7 and 5.8 demonstrate that there is little change in the pH values during the season. The maximum pH value is 8.46 in August, whereas the minimum was 8.10 in December. There are two main factors that influence pH in the aqueduct canal. First, there was no heavy fertilizer runoff in the canal area. This maintains pH value slightly changes during the season. The second factor is related to the slight change, variation of pH between 8 and 8.5 is a result to algae growth and atmospheric gases exchange. The highest pH value in August was associated with high phytoplankton (algae) densities (4.2 mg/m^3 in August). Photosynthesis by phytoplankton consumes carbon dioxide at high temperature, and during the growing season. Algae obtain CO_2 from bicarbonate, reducing hardness and usually increasing the pH (Waitf, 1984). In the winter, phytoplankton decay releases carbon dioxide and the pH value returns to 8.1 in December.

When pollution results in higher productivity, for example, from increased temperature or excess nutrients, pH levels increase. Although these small changes in pH are not likely to have a direct impact on aquatic life, they greatly influence the availability and solubility of all chemical forms and may aggravate nutrient problems. (Gesun, 2000).

The pH has no direct effect on nutrients level in aqueduct canal. The general impact is the negative relation between pH and nutrients, as nutrients decrease the pH increases and vice versa. The processes that affect pH are complex, the pH depends on climate conditions, physical, chemical and biological processes that take place in water. To determine the relationship between nutrients and pH for both plants, the mathematical relationship was applied to the data. There is a medium relationship for Atwater raw water between pH and nitrate $N= -0.25pH+ 2.4$ ($R^2 = 0.60$), the relationship between pH and phosphate is medium also and the slope is ($P= -0.017pH+0.15$ and $R^2 = 0.52$). Larger R^2 values were found in the raw water of D.B plant for nitrate, 0.78, and for phosphate, 0.6. Figures 5.9 and 5.10 illustrate this relationship.

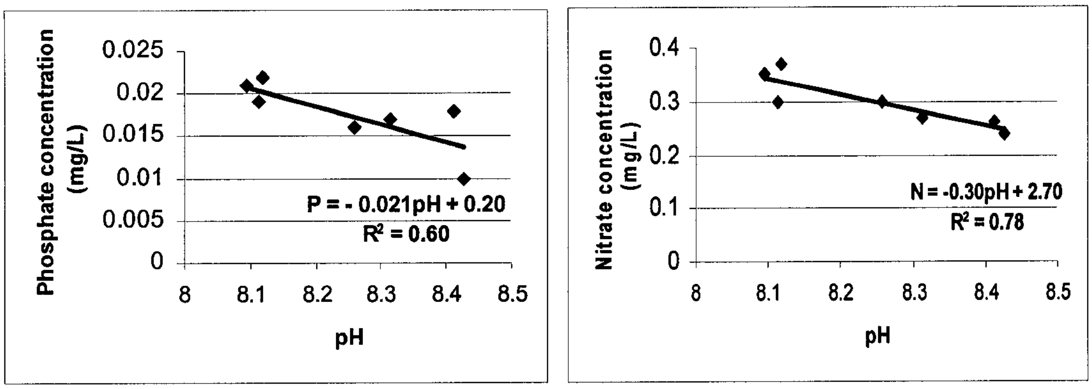


Figure 5.9 Relationship between pH and nutrients in D.B raw water

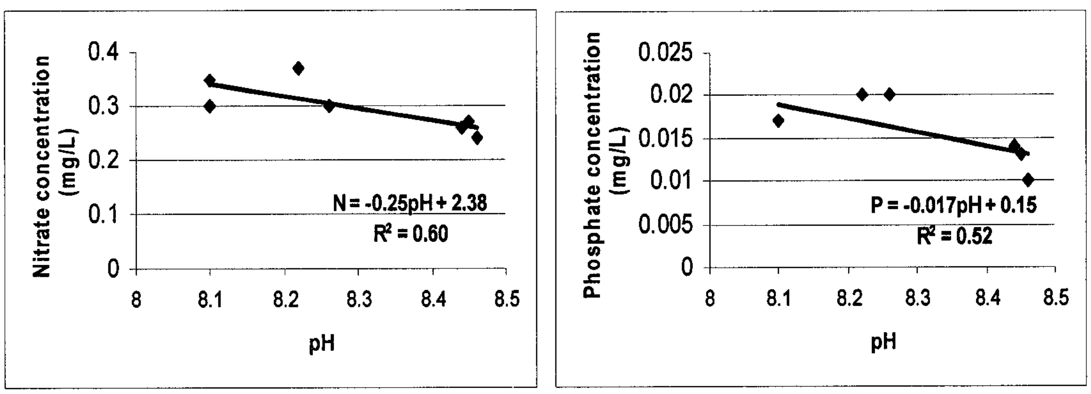


Figure 5.10 Relationship between pH and nutrients in the Atwater raw water

5.1.1 Water quality index for Aqueduct canal

The water quality index (WQI) is a unitless number ranging from 0 to 100. It provides a meaningful indicator of water quality in the water basin and its trend. WQI is considered a description for political decision makers and non technical water managers.

It is a statistical method dependent on water quality parameters in the water body and the water quality guidelines for protection of aquatic life (Water Guidelines for the Protection of Aquatic Life, 2003). WQI is an indication of the water quality in the water basin.

In 1997, the Canadian Council of Ministers of the Environment (CCME) modified the British Columbia index that could be adopted by all provinces and territories. The CCME water quality index ranks surface water by 5 classes as follows.

Table 5.1 Descriptions of Water Quality Categories and Values (CCME, 2001):

Category	Value	Description
Excellent	95-100	Water quality is protected with a virtual absence of Threat or impairment; conditions very close to natural or pristine levels.
Good	80-94	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.
Fair	65-79	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.
Marginal	45-64	Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.
Poor	0-44	Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels

Once the water samples were analyzed, data was used to calculate the WQI for the aqueduct canal. The calculation of the index depends on three factors, (F1, F2, and F3), and the definitions of these factors are:

F1 Scope = Represents the percentage of variables that do not meet their objectives at least once during the time period under consideration (failed variables), relative to the total number of variables measured as:

F1 = (# of failed variables / Total number of variables) * 100 (5.1)

F2 Frequency = Represent the percentage of individual tests that do not meet objectives (Failed tests) measured as:

$$F2 = (\# \text{ of failed tests} / \text{Total number of tests}) * 100 \quad (5.2)$$

F3 Amplitude = Represents the amount by which failed test values do not meet their objective, F3 is calculated by three steps:

1) The number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective is termed an "excursion" and is expressed as follows. When the test value must not exceed the objective:

$$\text{Excursion } i = (\text{failed test value } i / \text{Objective}) - 1 \quad (5.3.a)$$

compliance is calculated by summing the excursions of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those not meeting objectives). This variable, referred to as the normalized sum of excursions, or nse, is calculated as:

$$nse = (\textstyle\sum^{n}_{i=1} \text{excursion} / \# \text{ of tests}) \quad (5.3.b)$$

3) F3 is then calculated by an asymptotic function that scales the normalized sum of the excursions from objectives (nse) to yield a range between 0 and 100.

$$F3 = (nse / (0.01nse+.01)) \quad (5.3.c)$$

Finally the WQI can be calculated using following equation:

$$\mathbf{CCMEWQI=100 - ((F1^2+F2^2+F3^2)^{0.5} / 1.732) \quad (5.4)}$$

Where 0 represents the worst water quality and 100 represents the best water quality. Results were obtained from data analysis, and were used to calculate the water quality index for the aqueduct canal (five parameters index) as shown in Table 5.2 as follows:

Table 5.2 WQI Results for Aqueduct Canal

Month	**pH**	**Air Temperature(^{0}C)**	**NO_3^- (mg/l)**	**PO_4^{-3} (mg/l)**	**BOD**(mg/l)**
June	8.22	**19.64**	0.36	0.02	1.85
July	8.45	**22**	0.26	0.013	1.38
August	8.46	**21.7**	0.22	0.01	1.29
September	8.44	**18.2**	0.26	0.014	1.19
October	8.26	9.7	0.28	0.02	1.28
November	8.10	3.6	0.31	0.017	1.94
December	8.10	-6.3	0.34	0.017	2.05
Objectives*	**< 8.50**	**<15**	**<45.0**	**<0.05**	**<3.0**

* Objectives taken from Canadian water quality guidelines for the protection of aquatic Life (Water Guidelines for the Protection of Aquatic Life, 2003).

** BOD values were taken from the Atwater plant datasheet.

As shown above, all the parameters in the aqueduct canal meet the guidelines except for the temperature. Temperature is the dominant factor for the F2 and F3 calculations, as reflected by the inverse relation between temperature and WQI. Calculation of the WQI gives the following results: (for calculations see the appendix)

F1= 20

F2= 11.4

F3= 3.94 and

WQI= 86.5 Good

We may rewrite the WQI equation in relation to temperature in order to estimate the sensitivity of the index to temperature. For example if X represents the number of failed tests for temperatures above 15^{0}C, then F2= (X/35)*100. By drawing the relationship between frequency (F2) and X, the following relationship was observed (Figure 5.11)

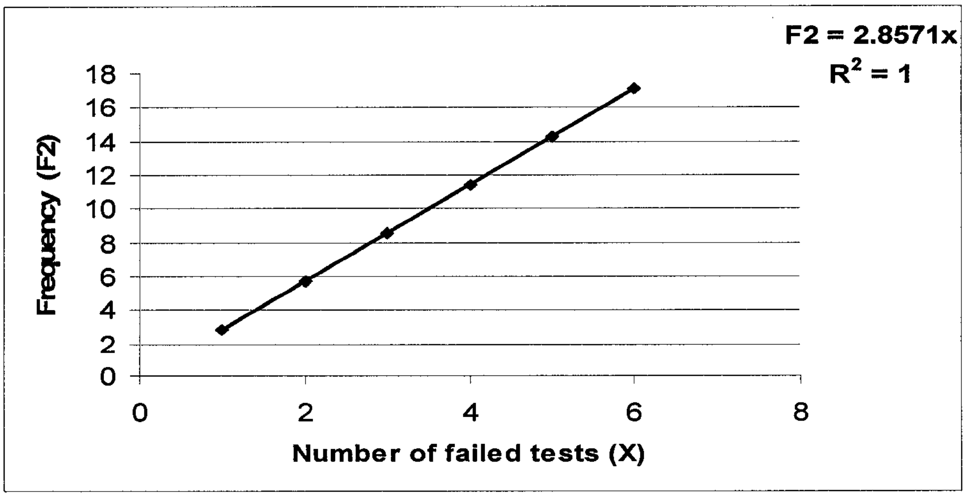


Figure 5.11 Relationship between failed tests and F2

Figure 5.11 shows that there is a strong relationship between X and F2. This relationship affects the value of WQI. As F2 increases, WQI decreases. Any future rise in temperature will reduce the WQI value, this decrease was due to only temperature. It should be noted that the possibility of increasing the other quality parameters may affect the WQI.

The Canadian Centre for Climate Modeling and Analysis (CCCma) predicts that there will be an increase in air temperature in the next decade. This prediction was concluded from the different Canadian Climate Models (Canadian Centre for Climate Modeling and Analysis, 2004). In the summer, the modeled temperature will range between 22 and 30 ^{0}C.

If 30 C^0 is selected as the maximum possible monthly temperature, the WQI will be altered depending on the F3 value. The relationship between the Amplitude (F3) and X and nse is $F3 = (0.043X / (4.3*10^{-4} X + 0.01))$. By drawing this relation the results of a linear regression between X and Amplitude, is shown in Figure 5.12.

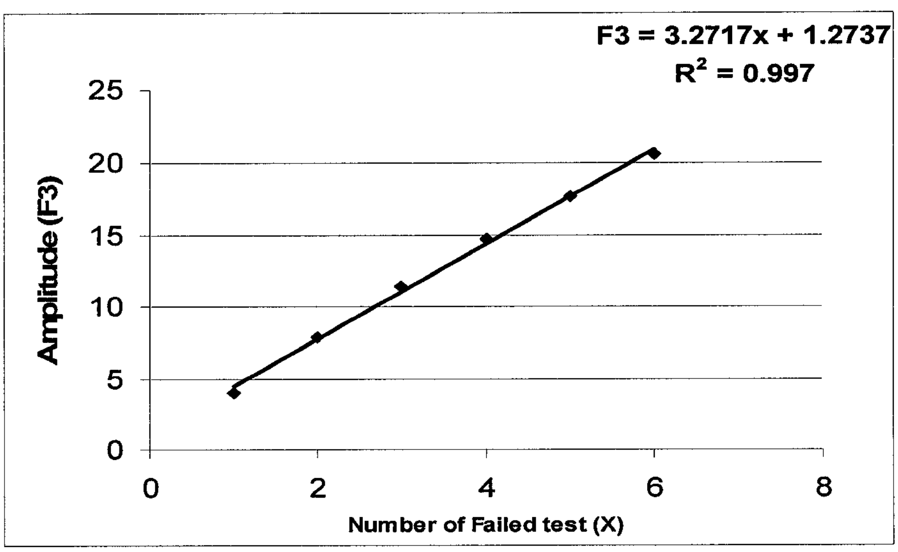


Figure 5.12 Relationship between nse and amplitude

If the previous relationship was used and coupled with the results shown in Figure 5.11 and 5.12, the WQI equation will be :

$$\mathbf{WQI = 100- (((20)^2 + (2.86X)^2 + (3.27X + 1.27)^2)^{0.5} / 1.732)} \quad \mathbf{(5.5)}$$

The above function has a strong inverse relation between X and WQI as shown in Figure 5.13.

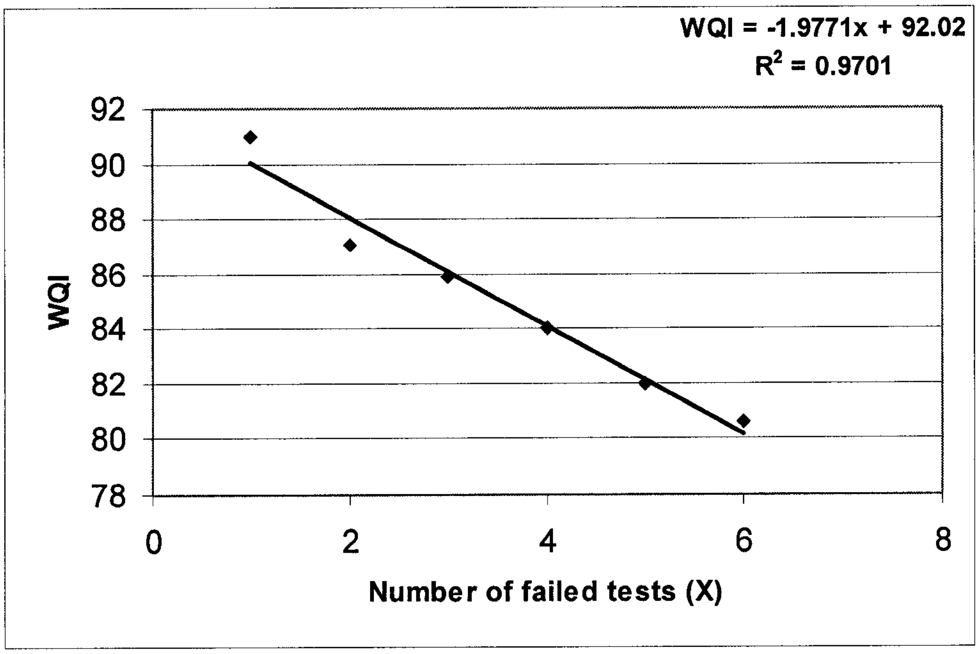


Figure 5.13 Number of failed tests and WQI

The previous statistical method is a simple method and an initial estimation of temperature on water quality. Further effects of temperature on nutrient levels and how temperature affects the growth of algae will be discussed in the next section.

5.2 Algae Results

Green algae growth occurs in both fresh and salt water. All types of algae contain the green pigments "chlorophyll". Estimation of chlorophyll content is considered an indirect method to determine algal level in water (Latif, 1997). Algal levels in aqueduct canal are characterized by high concentrations in the summer relative to the levels in the winter, because of the raw water feeding system (aqueduct canal). Algal growth is considered to be a function of three principle factors (Thomann and Mueller, 1987) :

1) Temperature, G (T)

2) Nutrients, G (N)

3) Solar radiation, G (I)

Growth rate μ, can be expressed as

$$\mu = G_{max} * G(T) * G(N) * G(I) \quad (5.6)$$

G_{max} is the maximum growth rate of the algae at 20 ^{0}C under optimal light and nutrient concentrations and G(T), G(I), and G(N) are factors which influence the growth rate for other temperature, light and nutrient conditions (Oregon Department of Environmental Quality, 2000). The third factor G (I) represents the degree of solar penetration to the water. The depth of the aqueduct canal is 5 m. This low depth and turbidity of the canal (average monthly of 1.4 JTU) (Atwater treatment plant publication, 2003) provide constant light penetration for the canal. In addition, historical data is available for other parameters affecting algal growth, such as nutrient concentration and temperature, but it is not available for light intensity. It is assumed that sufficient solar radiation is available during the entire season. This assumption leads to the conclusion that algae growth in the canal is solely due to the first two factors. Equation 5.6 was used to calculate algal growth in order to compare calculated and observed values.

An exponential relationship was detected between algal growth and time. In addition, the growth and death of phytoplankton represent an important term as shown in the kinetic expression (Thomann and Mueller, 1987)

$$dP/dt = (GP-DP)*t \qquad (5.7)$$

$$P=P_0*\exp(\mu t) \qquad (5.8)$$

Where

P: chlorophyll a concentration (μg/L)

P_0: initial chlorophyll a concentration (μg/L)

t: time (day)

(GP-DP), μ= net algae growth rate (μg/L.day)

By rearranging this kinetic expression, μ for algae in aqueduct canal was determined.

$$P/P_0 = \exp(\mu t) \qquad (5.9)$$

The following results were obtained for an entire season and this rate will be discussed with respect to its variation over the months. Figure 5.14 shows C/C_0 values from August to mid December.

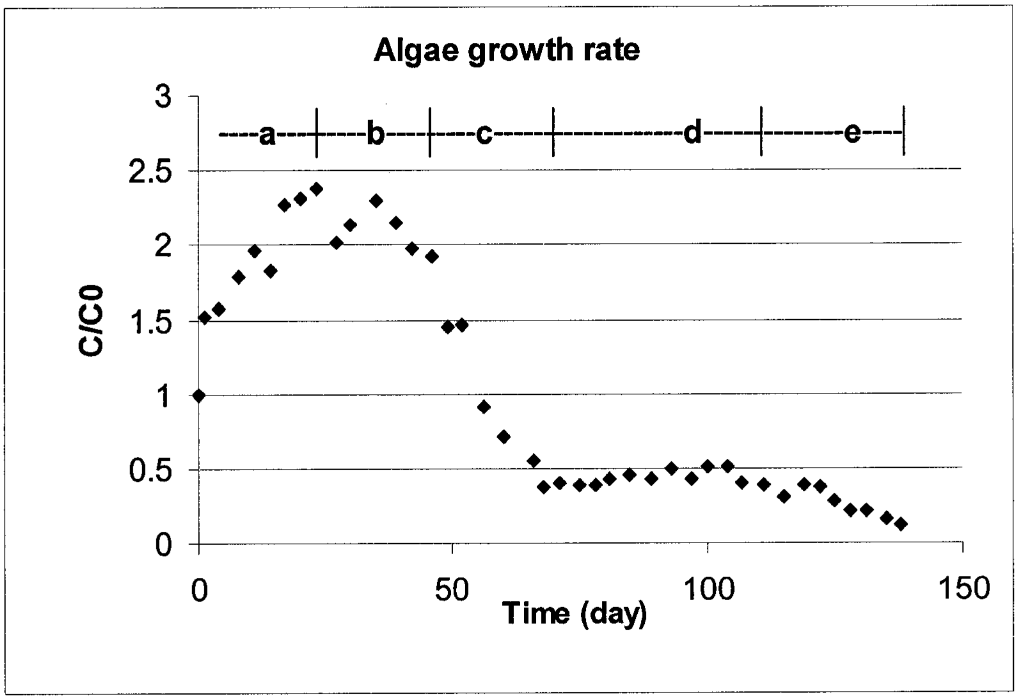
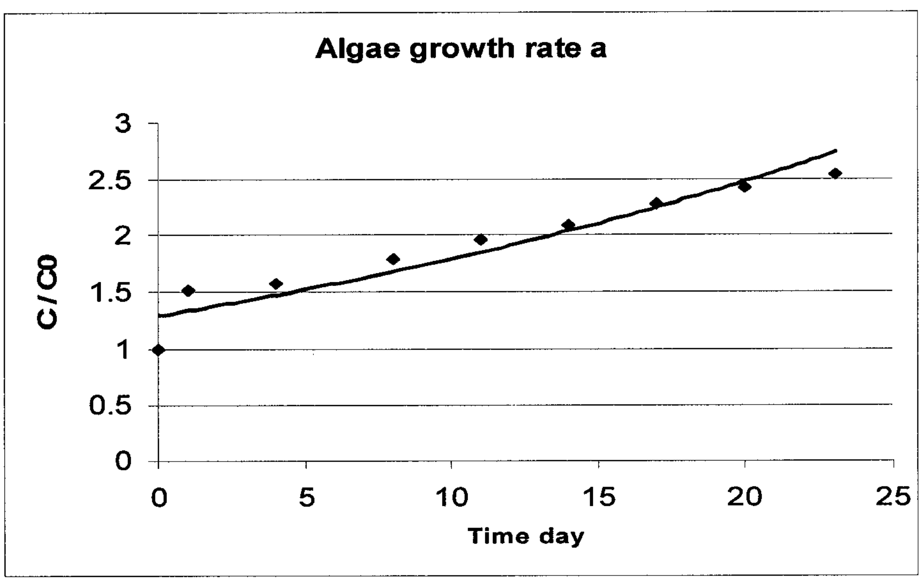
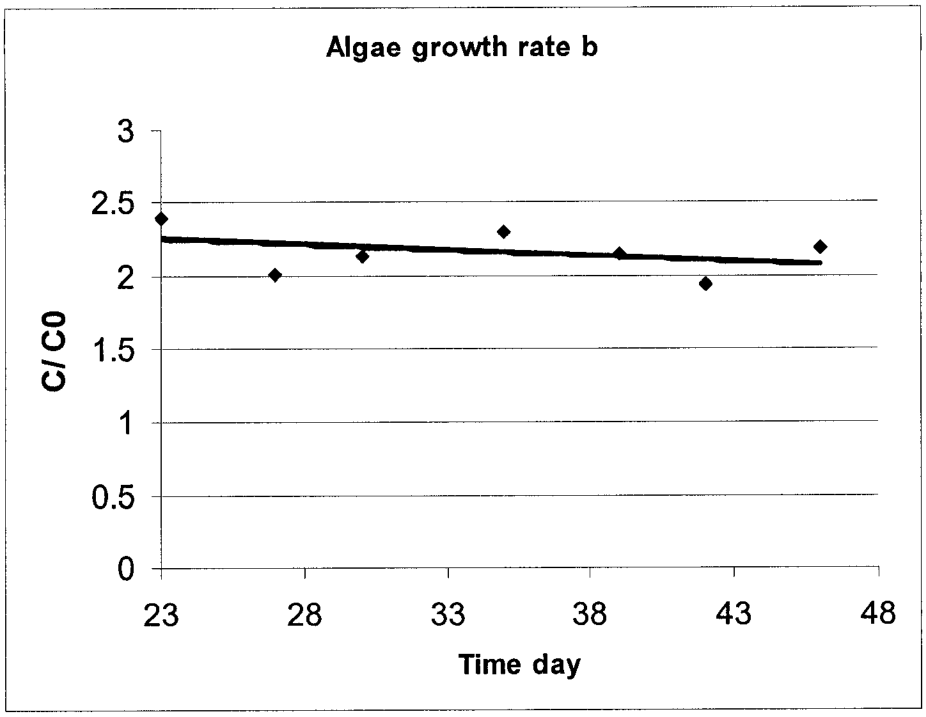


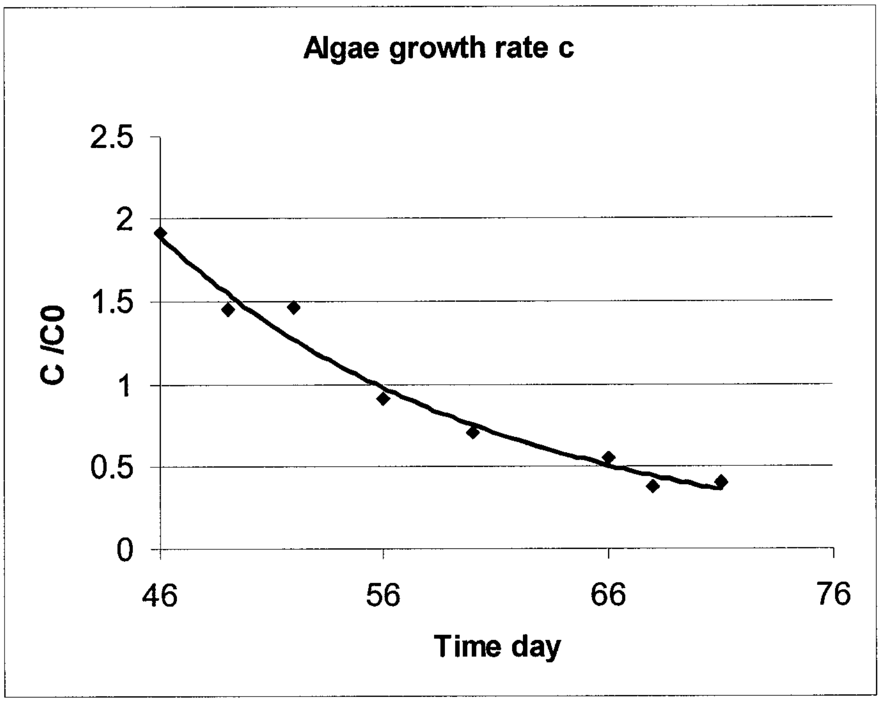
Figure 5.14 Seasonal algae growth (from August to December)



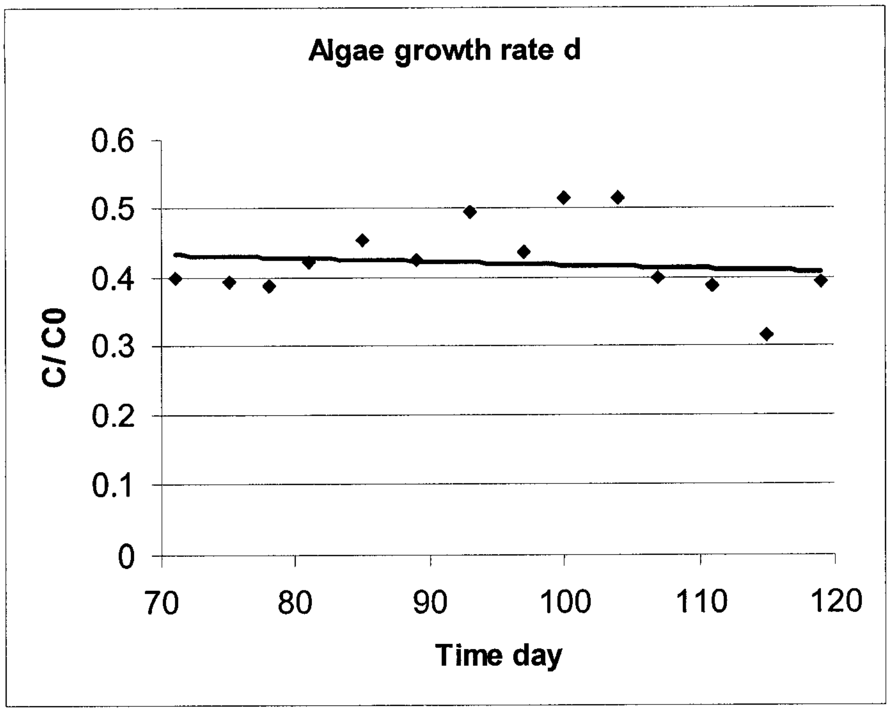
a) $P/P_0 = 1.29e^{0.033*t}$ $R^2 = 0.850$



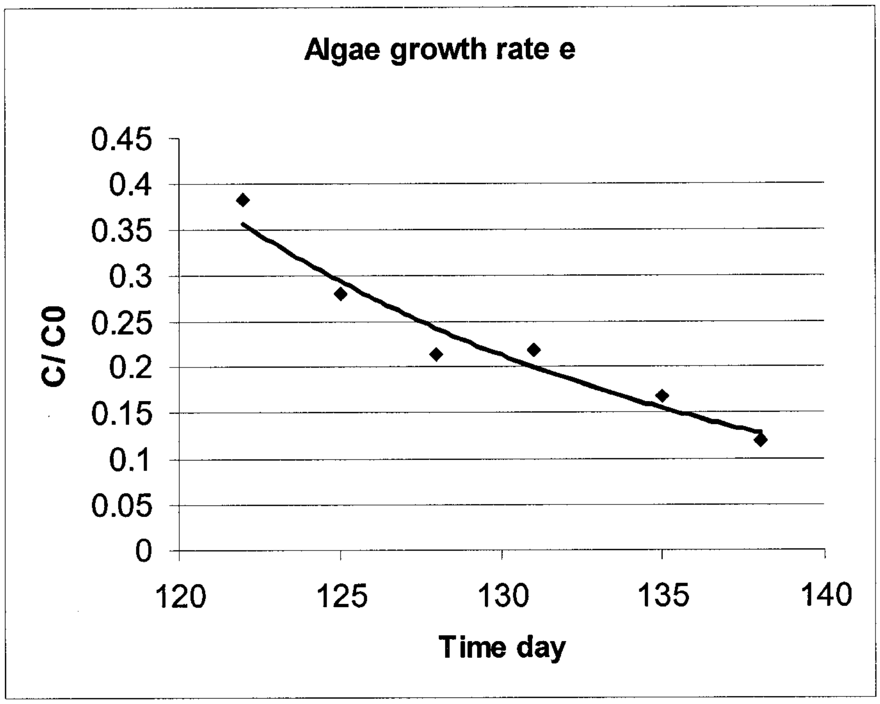
b) $P/P_0 = 2.4e^{-0.0036*t}$ $R^2 = 0.22$



c) $P/P_0 = 40.04e^{-0.063*t}$ $R^2 = 0.97$



d) $P/P_0 = 4.73e^{-0.0012*t}$ $R^2 = 0.02$



e) $P/P_0 = 875e^{-0.064*t}$ $R^2 = 0.95$

Figure 5.15 Algae growth rate phases in Aqueduct canal

Figures 5.14 and 5.15 illustrate that the growth behavior of algae during the experiments period beginning in August and extending until mid December based on initial chlorophyll-a concentration as P_0 for the whole period, which is equal 1.70 μg/l.

The growth phases were divided into five main stages. The first phase as shown in Figure 5.15-a demonstrates that the growth rate is 0.033 day^{-1} in August. An exponential relation for algae give a regression value of 0.85, this high regression value supports the fact that as temperature increases in the summer the growth rate increases (Kowe, 1998). The maximum temperature during the entire season is 25.2 ^{0}C, occurring on August 14. During this period, the production rate GP was greater than the decaying rate DP (μ is positive).

Figures 4.15 b, c, d showed that μ values were -0.0036, -0.063, -0.0021 respectively. This decaying rate can be attributed to a decrease in temperature starting from September to November. Figure 4.15 b shows that a decaying rate of -.00036 is very low and considered as a stationary (GP=DP) phase (Thomann and Mueller, 1987). Figure 4.9c is a declining phase, which started at October with a rate -0.063 day^{-1} with an average monthly temperature of 9.7 ^{0}C.

Figure 4.13 d demonstrated a very low R^2 value = 0.02 This low value is due to the fluctuation in temperature during November. For example in the 13th, 17th, 21st of October the temperature are 4.7, 0.7, 3.7 ^{0}C respectively. This variation in temperature results in μ = -0.0012 day^{-1}.

The last period in the season (December) is shown in Figure 4.15 e, and shows a decaying rate -0.063 day $^{-1}$, which is approximately equal to the decaying rate in C = -0.064 day^{-1} with a low average temperature of -6.3 ^{0}C .

The major monthly changes in phytoplankton development can be seen in the above figures, through the change in μ and chlorophyll-a concentration. For example, the maximum chlorophyll-a in season will be 4.2 μg/l on the 21st of August with μ 0.03 day^{-1}, whereas the minimum chlorophyll-a a value is 0.2 μg/l on the 15th of December with μ= -0.063 day^{-1}. These results illustrate that there will be a risk for a high algae level in August. For this reason, calculation of current and future rates will be established for August only.

Results confirmed that a positive growth rate occurred in August, and all the others months had a negative growth rate (decaying rate). The target of this study is the growth rate, in order to calibrate the model for calculating algae growth in response to future temperature increase.

It is important to determine the growth rate on a daily basis in August in order to estimate the daily growth rate in the growth phase period (Martinez, 1999). The specific growth rate is very important in the determination the nutrients and temperature contribution in growth, because this rate will be used to calculate algae growth. The results of observed daily algal growth rate for the month of August are presented in Table 5.3. These values will be used to compare observed and calculated growth rates.

Table 5.3 Specific Growth Rate Values for August.

Day	Temperature (^{0}C)	Observed Daily Growth Rate (day^{-1})
1	21.6	0.013
5	24.8	0.032
8	23.6	0.030
11	24.0	0.022
14	25.2	0.029
18	22.0	0.015
21	25.0	0.016

Daily growth rate results change from day to day; and are function of temperature, and nutrients. At this point, it is difficult to determine which factor has more influence on the growth rate (G (N) and G (T)) in equation 5.6, and what the contribution of each factor in growth is. For example, algae cells simultaneously use phosphates in the cellular process energy transfer and nucleic acid synthesis (Martinez, 1999), and absorb sunlight as a source for energy.

5.2.1 Determination of Limiting Factor

The concept of the limiting factor was introduced in section 3.10.4. As discussed previously the plant biomass increases by uptaking the available phosphorus and nitrogen in water. There are two major considerations in algal uptakes of nutrients. These considerations are (Thomann and Mueller, 1987):

1) The relative amount of nitrogen and phosphorus required by aquatic plants.

2) The relative amount of nitrogen and phosphorus available for growth initially in the body of water.

Phosphorus normally is the limiting nutrient in the growth of free floating algae in lakes, Florida community scientists believed that water bodies with higher phosphorus levels will have higher levels of algae and water bodies with low phosphorus concentrations will have lower levels of algae (Florida Lake Watch Water Body, 1998).

A simple analysis was used to calculate the limiting factor in the aqueduct canal. If the N/P ratio is 10 or greater, phosphorus is considered the limiting factor, while N/P less than 5, nitrogen is the limiting factor (Thomann and Mueller, 1987). Regarding the above classification, there are three possibilities for the limiting factor:

1) $N/P > 10$. Phosphorus is the limiting factor.
2) $5 < N/P < 10$ .Both are limiting factors.
3) $N/P < 5$. Nitrogen is limited.

For the aqueduct canal, N/P ratios were different from month to month; but the limiting factor for entire season was phosphate, N/P values are shown in Table 5.4.

Table 5.4 Monthly N/P for aqueduct canal

Month	**Temperature (^0C)**	**NO_3^- (mg/l)**	**PO_4^{-3}(mg/l)**	**N/P Ratio**
June	19.64	0.36	0.02	18
July	22	0.26	0.013	20
August	**21.7**	**0.22**	**0.01**	**22**
September	18.2	0.26	0.014	18.6
October	9.7	0.28	0.02	14
November	3.6	0.31	0.017	18.2
December	-6.3	0.34	0.017	20

Table 5.4 confirms that the limiting factor is phosphate. The maximum N/P ratio of 22 in August (maximum algal growth period). This result emphasizes that the phosphate concentration decreases because it was taken up by algae and this fact was reflected by the N/P value. Also it is possible to relate temperature and N/P ratio depending on algae growth period. As the growth increases, the phosphate uptake increase and N/P increases. Table 5.4 showed that phosphate is considered the limiting factor, and phosphate concentration will be used to calculate the nutrient factor G (N) which was introduced in equation 5.6.

Figure 5.16 illustrates the N/P ratio and chlorophyll relationships, the nitrate concentration is more available than phosphate, which indicates that phosphate is less available for algae growth and will limit the growth. Schematic diagram (Figure 5.16) below represents this mechanism. The N/P ratio is a useful measure for understanding the relationship between nitrates, phosphates, and algae.

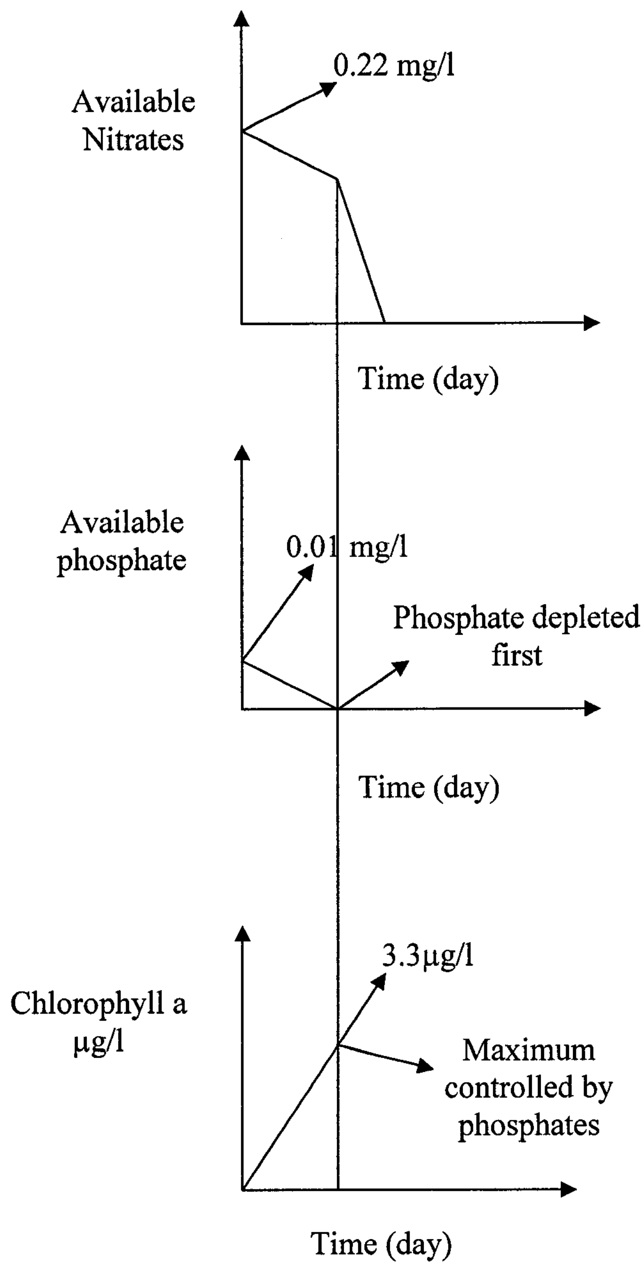


Fig 5.16 Schematic diagram for phosphate uptake by algae in the aqueduct canal

(August)

Phosphate as the limiting factor controls the growth of algae. Chlorophyll-a concentration increases as the available phosphate decreases in the growth phase. Figures 5.17 and 5.18 show a relationship between chlorophyll-a and phosphate concentration and chlorophyll-a and temperature in August.

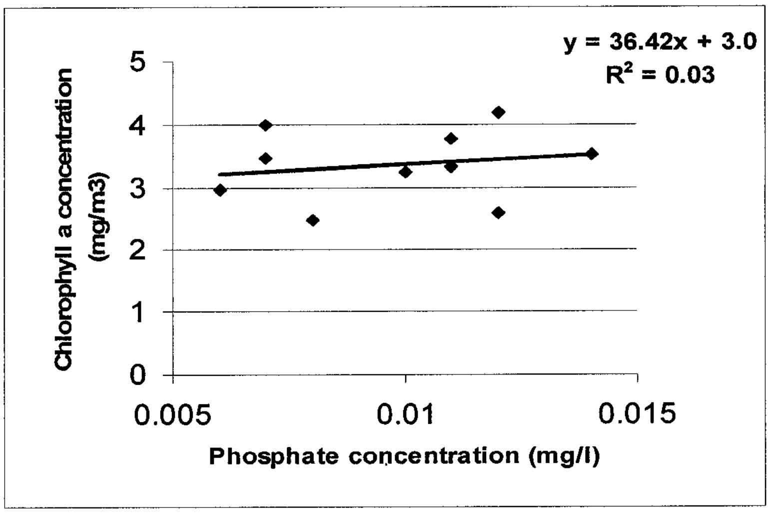


Figure 5.17 Relationship between phosphate and chlorophyll a concentration in August.

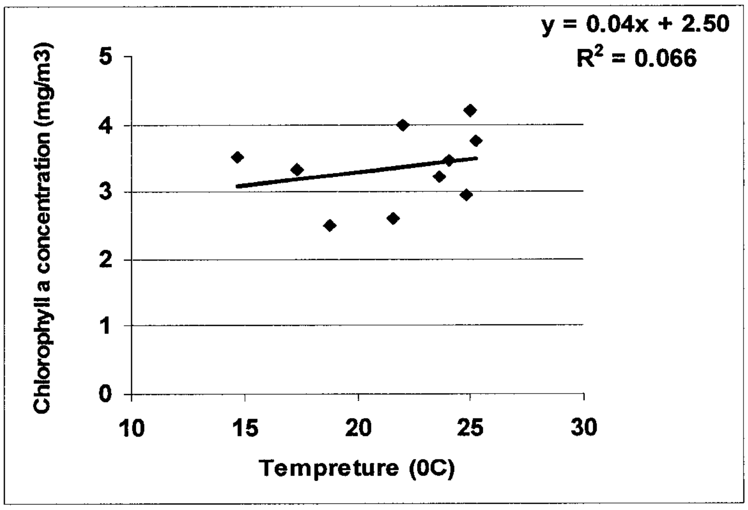


Figure 5.18 Relationship between temperature and chlorophyll a concentration in August

Figures 5.17 and 5.18 show that there is a very low correlation between chlorophyll-a concentration and phosphate R^2= 0.03. Also there is weak correlation between chlorophyll-a concentration and temperature R^2= 0.066. This low correlation emphasize that there is no direct relation between chlorophyll-a and temperature and phosphate, all algal models dealing with alga growth rate. There are two main models used to calculate temperature factor and nutrient factor. These models will be introduced in the next sections.

5.2.2 Algae Growth Models

The two main models are suggested to predict the growth of algae. These models are used to calculate the growth rate of algae in relation to the factors mentioned in section 5.2. These models are:

a) Nutrients model, Michaelis-Menten kinetics

b) Temperature model.

The first model is applied under optimal levels of temperature and light, and the second model is applied under optimal conditions of nutrients and light.

a) Nutrients model G (N)

The prediction of algae growth response can be related to phosphate concentration, and the half saturation constant. These parameters are presented in the Michaelis-Menten model as:

$$G(N) = S / (S+Ks) \quad (5.10)$$

G (N): growth rate factor due to phosphate

S: Phosphate concentration (μg/L)

Ks: half saturation constant (μg P/L)

This model is a very useful method from an engineering point of view, because it aids in the prediction of algae growth for a given nutrient concentration.

The Michaelis-Menten model is the most commonly model used equation correlating microbial growth with substrate utilization, and was applied to relate the algal growth and substrate availability in the system with a single growth limiting substrate (Kayombo, 2003). Inputs in the above equation were taken from phosphate and algal growth results. Typical Ks value for phosphorus range from 1 to 5 μg P/L. A phosphorus half-saturation constant of 5 μg/L was used depending on previous works done by researchers. (Oregon Department of Environmental Quality, 2000).

The relationship between the substrate concentration and growth rate depends on the substrate concentration, until the substrate concentration reaches the maximum value. At this point, growth rate begins to have a constant value. This relationship is shown in Figure 5.19

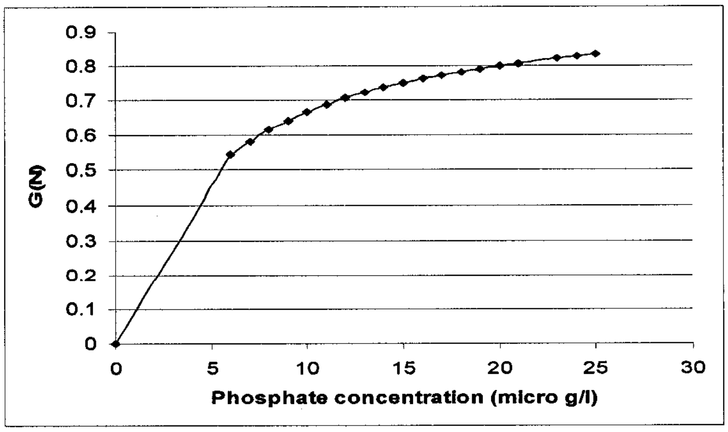


Figure 5.19 Algae Growth in response to phosphate concentration for the aqueduct canal

By applying the nutrient model for phosphate concentration and maximum growth for August in the aqueduct canal, because algae are in the growth phase, the following results are obtained as shown in Table 5.5 .

Table 5.5 G (N) values in the aqueduct canal calculated by Michaelis-Menten model

PO_4^{-3} (μg/L)	Ks (μg/L)	G(N)
12	5	0.71
6	5	0.55
10	5	0.67
7	5	0.58
11	5	0.70
7	5	0.58
12	5	0.71

The nutrient factor due to phosphate and during growth phase showed that the G (N) values will impact the growth rate. This factor is a measure of the contribution of phosphate to algae growth. Phosphate availability ensures the growth of algae; and the results show that the nutrient factor changed slightly during the growth phase; as ranged between 0.55 to 0.71. This is because the availability of minimum amounts of phosphates will guarantee growth (Martinez, 1999).

Increasing the phosphate concentration by 50% between August and October has no effect on G (N). This fact implies that the growth response to phosphate is less related to the growth response to other factors like temperature which will be investigated later. The growth phase as a function of phosphates shows a strong correlation between growth rate and phosphate concentration, as shown in Figure 5.20.

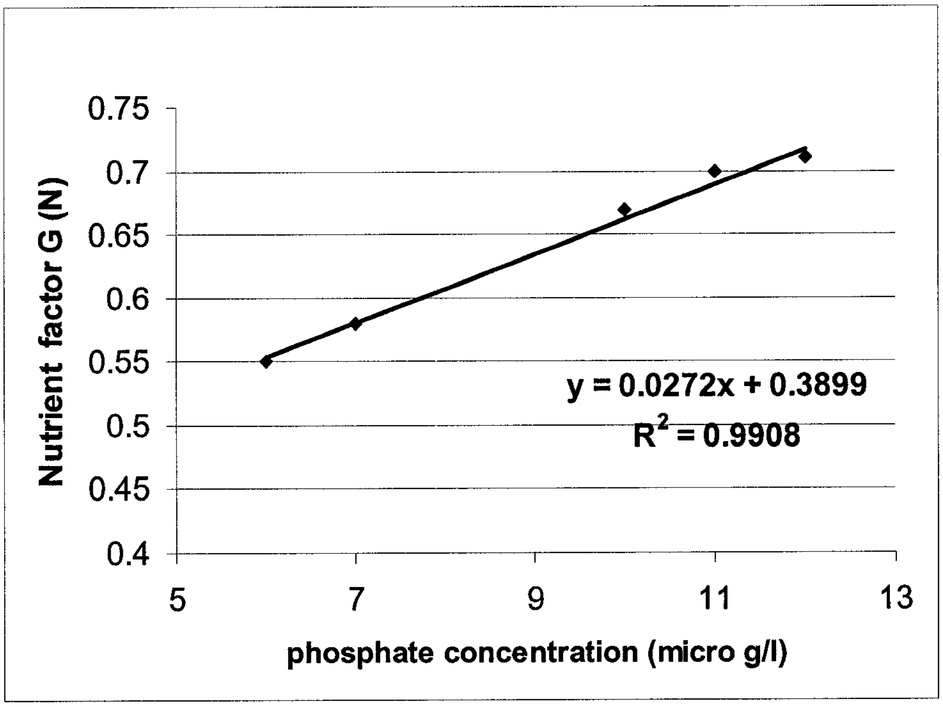


Figure 5.20 Relationship between G (N) and phosphate

During August, the phosphate concentrations reached the lowest value in comparison with other months. An increase in phosphate concentration begins in early September, and the chlorophyll-a concentration decreased concurrently.

There are rapid uptakes of phosphate in August, which results in a very low phosphate concentration. Generally 10 μg/l of phosphate is the limit for preventing excessive phytoplankton growth (Petterson, 2003). A comparison between the observed growth rate and calculated growth rate by using nutrients model and later in a temperature model will be discussed in detail in the following sections.

b) Temperature model G (T)

Relationship between growth rate and temperature as a climate change parameter can be determined from work done by Eppley (Thomann, 1987):

$$G\ (T) = (1.066)^{*(T-20)} \qquad (5.10)$$

Where

G (T) = temperature factor

1.066= temperature activity coefficient

T = temperature in Celsius (^{0}C)

The relationship expresses the growth rate as a function of temperature assuming that there is no inhibitory effect from other growth factors. Temperature has a maximum value in August, and the growth phase also occurs in August, and thus controls the growth more than any other factor. A potential effect of high temperature will increase the value of G (T). Temperature variations in August showed a minimum value of 18.8 ^{0}C and a maximum value of 25.2 ^{0}C, as shown in Figure 5.21.

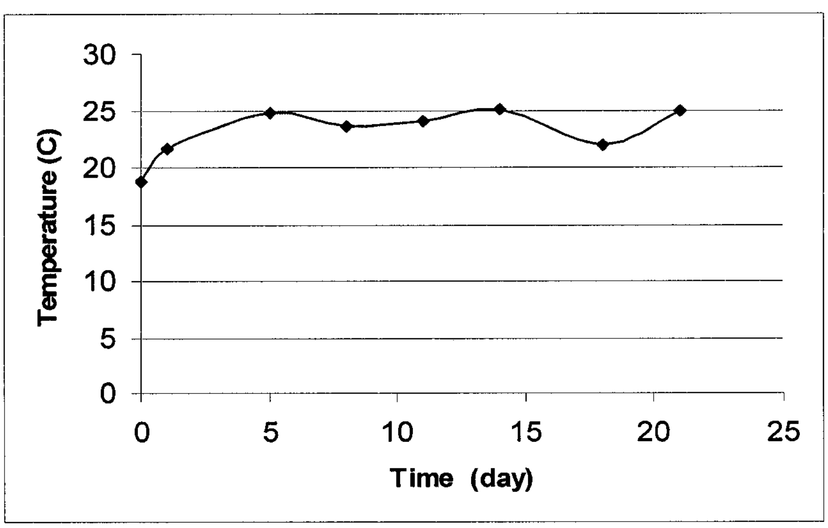


Figure 5.21 Temperature variations in August.

Temperature increases of 5–8 ^{0}C during growth phase seem small, but they can have large effects on the structure and dynamics of in-stream plant and animal communities. The growth and development of algae are in part temperature-dependent and elevated temperature can affect development of algae. In addition, dissolved oxygen concentrations decrease as the temperature increases, limiting plant and animal life and possibly contributing to fish deaths (Kowe, 1998). Increased water temperatures also increase the rates of algae breakdown of organic matter and increase oxygen consumption, and as a result increase the algae level as shown in Table 5.6. In the case of in-stream algae, temperature can set the maximum potential for primary production in watercourses when other factors such as light, nutrients and turbidity are not limiting (Chapra, 1997). The chlorophyll-a concentration has a maximum value of 4.2 μg/l corresponding to a temperature 25 ^{0}C and a maximum G (T) value of 1.39. G (T) values for aqueduct canal are presented in Table 5.6.

Table 5.6 G (T) Value for the Aqueduct Canal (August) calculated by Eppley model

Chlorophyll a (μg/L)	**Temperature (^{0}C)**	**G (T)**
2.60	21.6	1.11
2.95	24.8	1.36
3.23	23.6	1.26
3.45	24	1.30
3.76	25.2	1.39
4.00	22	1.14
4.20	25	1.38

G (T) values are strongly dependent on temperature. The G (T) value has a larger influence than G (N) on algae growth, because all the G (T) values in Table 5.6 have values greater than one where as all G (N) values are less than one. That means G (T) value is the key factor in algae growth. In other words climate change has more potential effect on algae level than nutrients. This turning point emphasizes that temperature is a dominant factor in algae growth and this fact may be used to estimate future values of growth rate.

As the temperature increases, the growth rate increases as shown in Figure 5.22. This figure also shows that the sensitivity of G (T) to temperature can be used to estimate the effect of global warming on algae growth as will be discussed in the next section.

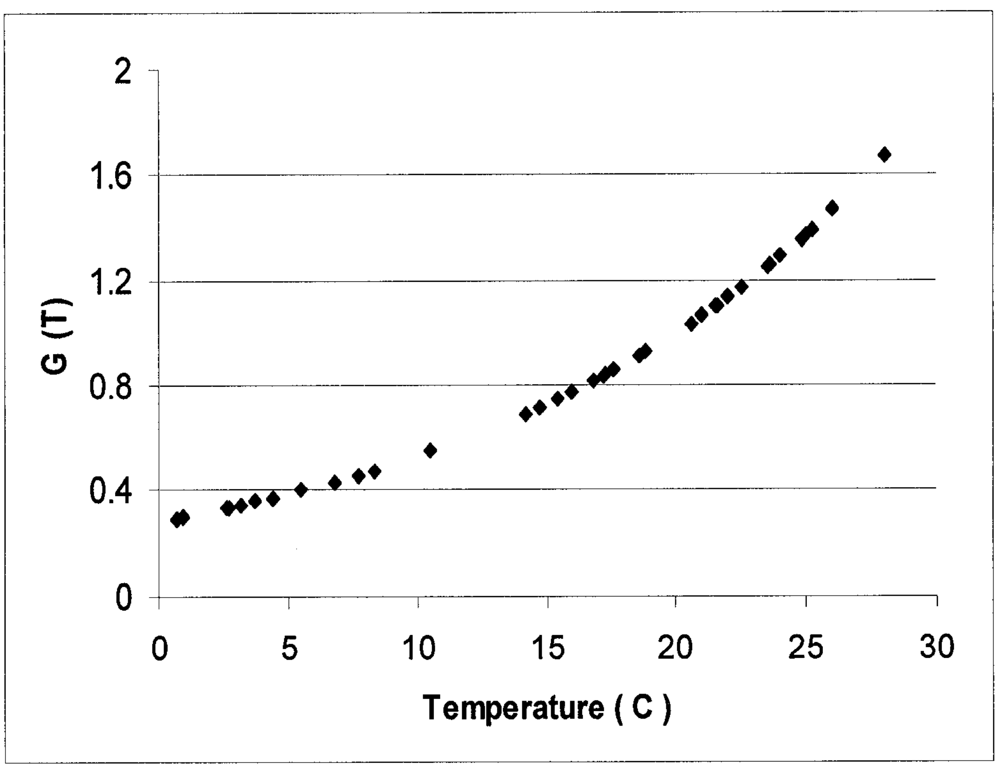


Figure 5.22 Response of G (T) values to temperature (from June to December)

Calculated G (N) and G (T) values were used to estimate the growth rate values, using equation 4.6 and G_{max} at 20 ^{0}C was calculated using equation 5.8 and its value was 0.02 day^{-1}. Table 5.7 presents the calculated and observed growth rate value for August.

Table 5.7 Observed and Calculated Algal Growth in August

Day	Calculated Daily Growth Rate (day^{-1})	Observed Daily Growth Rate (day^{-1})	Relative Error (%)
1	0.016	0.013	23
5	0.015	0.032	53
8	0.017	0.030	44
11	0.015	0.022	32
14	0.200	0.029	33
18	0.013	0.015	12
21	0.020	0.016	25

Table 5.7 shows the difference between observed and calculated growth rate in August. Relative errors between the observed and calculated rate was ranged between 12% and 55%. This error could be due to many factors. Using the empirical equation 5.10 could be a source for error. As well known, all empirical equations are associated with a specific error during the derivation of equation (Kowe, 1998). In addition, the presence of organisms in the water sample could affect the growth rate,

because they consumed a portion of the nutrients that are available in water the sample (Kayombo, 2003). Neglecting the G (I) factor may affect the calculated rate. Finally accuracy of the measurements affects the observed growth rate. These factors together are considered the main source for the error.

5.3 Climate Change Model

Climate change scenarios are a consistent description of climate prediction. Scenarios required in climate change to provide views of future conditions considered likely to influence a given system or activity. There are five main scenarios; these scenarios are (McCarthy, 2001):

1) Socioeconomic scenario
2) Land-use and land-cover scenario
3) Environmental scenario
4) Climate scenario
5) Sea level scenario

The focus of this research is the climate scenario, since all climate models are based on this scenario. The most common model is the general circulation model (GCM), which is used by all climate centers when constructing their models (McCarthy, 2001). Climate change researchers suggest that more research is needed to correct impact results, due to the large uncertainty in GCM predictions. An inherent uncertainty typically occurs in climate change predictions (Ruzicka, 2000).

The Canadian Centre for Climate Modeling and Analysis (CCCma) has developed a number of climate simulation models for climate prediction that study climate change and variability, and aid in the understanding of the various processes which governe climate system. These models are as follows (CCma, 2004):

1) AGCM1: The first generation atmospheric GCM
2) AGCM2: The second generation atmospheric GCM
3) AGCM3: The third generation atmospheric GCM
4) CGCM1: The first generation coupled GCM.
5) CGCM2: The second generation coupled GCM.

Data was obtained from these models in order to compare current and future changes in temperature, and how this future change will impact the algae growth based on previous results. Temperature outputs for August from the CGCM1 (GHG+A) model were used to explore the predicted effect of climate change on algae growth. CGCM1 data from three 201-year simulations with CGCM1 was used in conjunction with an IPCC forcing scenario in which the change in greenhouse gases (GHG) forcing corresponds to that observed from 1900 to 1990 and increases at a rate 1% per year thereafter until year 2100 (CCma, 2004). The direct effect of sulphate aerosols (A) is also included. Daily data from the run labelled GHG+A1 are available for the time period 1961-2100 (CCma, 2004). Temperature outputs in 2003, 2010, 2020, and 2050 and 2099 are presented in Table 5.8.

Table 5.8 Future Temperature Values for August

Day	**Observed[*1] T 2003 (^{0}C)**	**Modeled[*2] T 2003 (^{0}C)**	**Modeled T 2010 (^{0}C)**	**Modeled T 2020 (^{0}C)**	**Modeled T 2050 (^{0}C)**	**Modeled T 2099 (^{0}C)**
1/Aug	21.6	27.7	26.7	25.5	28.0	30.5
5/Aug	24.8	22.2	27.6	23.1	21.7	32.2
8/Aug	23.6	23.8	21.8	27.0	29.0	28.8
11/Aug	24	24.7	24.2	27.7	21.0	34.0
14/Aug	25.2	21.0	23.6	23.7	23.8	28.8
18/Aug	22	22.8	26.7	19.0	24.0	27.4
21/Aug	25	23.4	24.5	17.5	27.0	26.0
Average	**23.7**	**23.7**	**25.0**	**23.4**	**25.0**	**29.7**

[*1] Observed temperature for August 2003

[*2] Obtained from CCma model (CCma, 2004)

The average monthly temperature tends to increase over the years. In August 2010, the monthly temperature will be 25 ^{0}C compared to the observed monthly temperature in August which was 23.7 ^{0}C in 2003. In addition, the results illustrated that the short run (10-15 years) change is less than the long run (50-100 years), which is in agreement with climate change theory by increasing the temperature in future decades (Gleick, 2000).

This variation is due to the uncertainty, which typically accompanies weather forecasting especially for a 100 year prediction. Temperature modeling was used to give a future vision and to determine how a future change in temperature may affect water quality.

5.4 Future Algae Growth

Climate change and its impact on algal growth will be presented in relation to AGCM1 temperature projections in the sections to follow. Modeled temperatures were used to calculate G (T) factors for algae growth in the growth phase period, because it was shown previously that G (T) has potential effect on algae growth. Future growth rate values were calculated in order to compare current and future results (Hassan, 1998).

Using equation 4.6 and the current G (T) and G (N) values, and future G (T) values were estimated using a temperature model (equation 5.10). These values are shown in Table 5.9.

Table 5.9 Future G (T) values.

Day	**Observed G(T) 2003**	**Modeled G(T) 2003**	**Modeled G(T) 2010**	**Modeled G(T) 2020**	**Modeled G(T) 2050**	**Modeled G(T) 2099**
1	1.11	1.64	1.53	1.42	1.67	2.00
5	1.36	1.15	1.63	1.22	1.11	2.20
8	1.26	1.27	1.21	1.56	1.78	1.75
11	1.30	1.35	1.31	1.63	1.11	2.45
14	1.39	1.10	1.26	1.27	1.27	1.75
18	1.14	1.19	1.53	0.94	1.29	1.60
21	1.38	1.24	1.33	0.85	1.56	1.47
Average	**1.27**	**1.27**	**1.38**	**1.27**	**1.40**	**1.88**

It is very clear that there is an increasing trend for G (T) values. Predicted G (T) values may reach 2.45 in 2099, which represents an increase of 55% in comparison to the observed G (T) value. The trend of increasing of G (T) has some exceptional values such as 0.94 and 0.85 in the year 2020 due to uncertainty from prediction errors especially in weather forecasting. Figure 5.23 demonstrates a comparison between observed and predicted G (T) values.

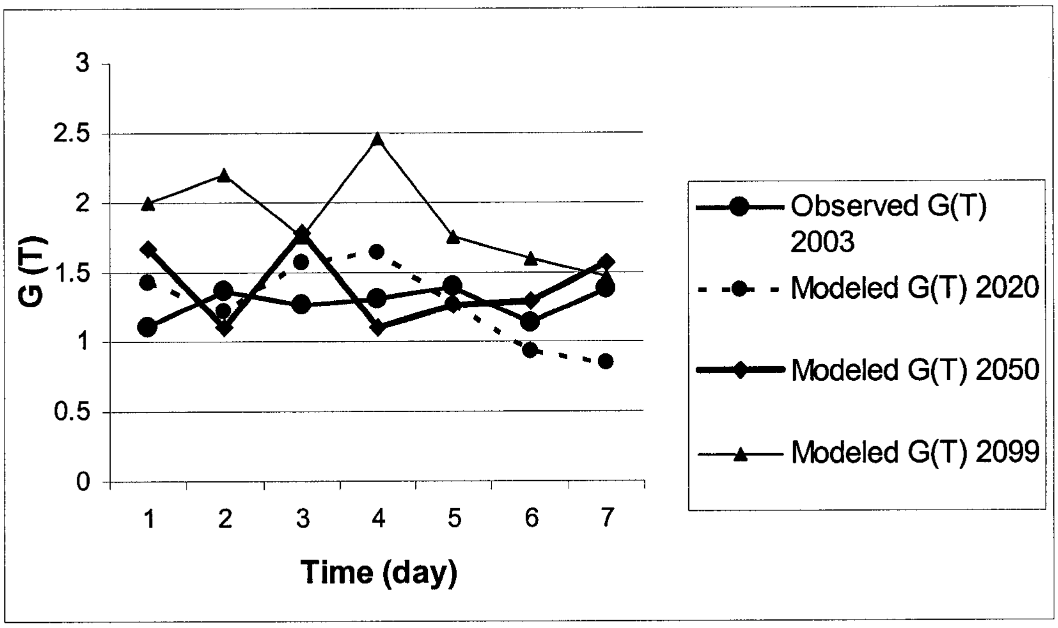


Figure 5.23 Effect of climate change on G (T)

Predicted G (T) values were used to calculate current and predicted growth rate using equation 5.6, $\mu = \mu_{20} * G(N) * G(T)$. Current and predicted μ values are presented in Table 5.10.

Table 5.10 Future growth rate values

Day	Calculated μ 2003 (day^{-1})	Modeled μ 2003 (day^{-1})	Modeled μ 2020 (day^{-1})	Modeled μ 2050 (day^{-1})	Modeled μ 2099 (day^{-1})
1/Aug	0.016	0.023	0.020	0.024	0.029
5/Aug	0.015	0.013	0.013	0.012	0.024
8/Aug	0.017	0.017	0.021	0.024	0.023
11/Aug	0.015	0.016	0.019	0.013	0.028
14/Aug	0.020	0.015	0.018	0.018	0.025
18/Aug	0.013	0.014	0.011	0.015	0.019
21/Aug	0.020	0.018	0.012	0.022	0.021
Average	**0.016**	**0.016**	**0.016**	**0.018**	**0.024**

Table 5.10 presents a comparison of future and current algae growth rates. The calculated growth rate in 11/Aug/2003 is 0.015 day^{-1}, whereas the future rates on the same day in 2020, 2050 and 2099 are 0.019, 0.013 and 0.028 day^{-1}, respectively. There is a strong relation for growth rate between the calculated growth rate in 21/Aug/2003 and future rates for the same day in 2050, 2099; these rates are 0.022, and 0.021 day^{-1} respectively. These results emphasize that the climate change will enhance algae growth.

Focusing on future growth rate values, an increase in growth rate will have an impact on the quality of water, by decreasing the WQI and the trophic state of the aqueduct canal. This increase may create an unexpected load in some days which will affect treatment efficiency. In addition, cyanobacteria species will impact drinking water and causing public health problems. For example, liver damage an associated disease with cyanobacteria species (Federal –Provincial subcommittee on drinking water, 1998). Diseases associated with drinking water also will increase due to exposure to algae, including diarrhea, muscle weakness sore throat and respiratory difficulties. These are examples of the possible health problems related to algae, and the importance of considering climate change as a future source of pollution in order to protect water quality for our children and for the next generations.

Chapter Six

Conclusions and Recommendations

6.1 Conclusions

The aim of this study was to estimate the effect of climate change on the water quality parameters, by studying the algae growth response to present and future increases in temperature.

The results of this study provide the following conclusions

- Studies show that temperature is the dominant factor for algal growth.

- Nutrient levels in the raw waters that feed Atwater and D.B plants are acceptable. Nitrate levels range between 0.24-0.37 mg/l; and this range is less than the Canadian guidelines (45 mg/l). Phosphate levels range between 0.010-0.022 mg/l, which is also within acceptable limits.

- There is a significant correlation between water quality index (WQI) and water temperature in the aqueduct canal. The current class of the aqueduct canal according to the CCME is good, but, as was observed, this class may be violated in the future.

- The algal level in the aqueduct canal will increase when the temperature increases. This variation in temperature will control the growth behavior for algae.

- Phosphate as a limiting factor in algae growth has a larger effect than nitrate in the aqueduct canal; phosphate availability in water will support algae development during the growing season.

- The observed growth rate is larger than the calculated rate, with a relative error ranging between 12% - 55 %.

- A rise in air temperature will occur over time. This is reflected by a temperature of 25 ^{0}C in August 2050, whereas a temperature of 29.7 C^0 is predicted in August 2099.

- Results confirm that the growth rates of algae will increase in response to a temperature increase.

6.2 Recommendations

- Investigate the potential effect of climate change on the other water quality parameters, such as dissolved oxygen (DO), and biological oxygen demand (BOD).

- Determine the production of toxin by algal species such as microcystin production, in order to evaluate the effect of climate change on public health.

- Investigate the effect of climate change on the treatment efficiency for the drinking water treatment plants.

- Investigate the effect of the increase in greenhouse gases level on the water quality and quantity.

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Appendix

1) Spectrophotometer procedure for nitrate

1) Test mode and conditions in spectrophotometer were inserted; these conditions are:

- Number of reference: these references are samples from tube 2, 3, and 4 respectively, as demonstrated in section 3.2.1
- Wave length: 540 nm
- Curve fit: linear

2) The two 1 cm cuvettes were rinsed with blank

3) Cuvettes were inserted into chamber, lid was closed and scan blank was selected. The nitrate concentration in each tube was determined with reference to the blank concentration.

4) Cuvettes were removed from spectro.

5) Cuvettes was rinse with water samples from tubes 2, 3,4,5 and 6 respectively. The spectrometer will detect the nitrate concentration for each sample. Performs duplicates for 5 and 6.

6) Forms the calibration curve as shown in Figure 1.

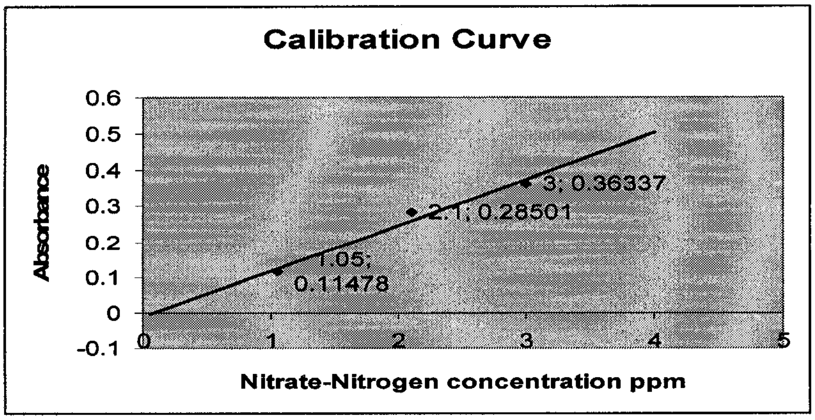

Figure 1 Calibration curve for NO_3^--N concentration

2) Spectrometer procedure for phosphate

1) Test mode and conditions were inserted; these conditions are:

   - Number of reference: 3 (these references are samples from tube 2, 3, and 4 respectively) .

   - Wavelength: 340 nm

2) The two 1 cm cuvettes were rinsed with blank

3) Cuvettes were inserted into chamber, close lid was closed and scan blank was selected. Phosphate Concentration in each tube was determined with reference to the blank

4) Cuvettes were removed from spectrometer

5) Rinse cuvettes with water samples from tube 2, 3,4,5,6 respectively, spectro will detect the nitrate concentration for each sample duplicate for sample 5 and6

6) Constructs the calibration curve and prints out the results. Figure 2 shows the phosphate calibration curve.

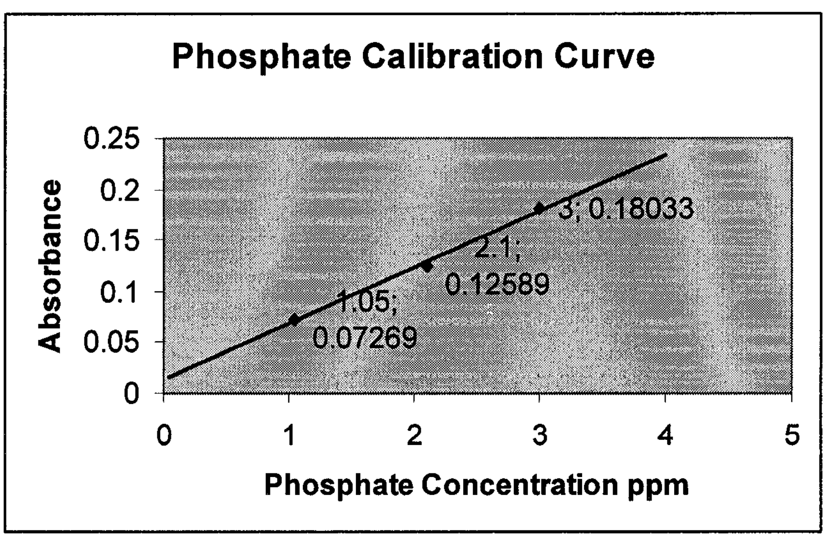

Figure 2 Calibration curve for Phosphate concentration

3) Water Quality Index Calculation

$F1 = (1/5) * 100 = 20$

$F2 = (4/35)*100 = 11.4$

$Excursion = (19.64/15 - 1) + (22/15 - 1) + (21.7/15 - 1) + (18.2/15 - 1) = 1.43$

$nse = (1.43/35) = 0.041$

$F3 = 0.041/(0.01*(0.041)+0.01) = 3.94$

$$WQI = 100 - ((20^2+11.4^2+3.44^2)*0.5) / 1.732) = 86.5$$