MODELING THE IMPACTS OF ATMOSPHERIC DEPOSITION ON WATER QUALITY IN LAKE ONTARIO UNDER CLIMATE CHANGE SCENARIOS

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Abstract

Water quality in urban areas in Canada is a major issue despite the fact that it has excessive resources of freshwater. Current methods of addressing the impacts of atmospheric deposition and climate change on water quality are inadequate. Physical methods are too complex and usually ignore the impacts of atmospheric deposition. Therefore, in this research two categories of data driven models have been developed using artificial neural networks to model the atmospheric deposition and water quality. These models were developed in three regions near Lake Ontario: Toronto, Cobourg, and Grimsby regions which have different characteristics of population and air contamination. The results showed in future, the atmospheric deposition contamination in summers and autumns will become higher than the present situation. However, the precipitation contamination in winters will be lower. Moreover, the atmospheric deposition can not influence the water quality of Lake Ontario considerably.

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List of Acronyms

ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
BRT	Boosted Regression Trees
CAA	Clean Air Act
CAPMoN	Canadian Air and Precipitation Monitoring Network
CanESM	Canadian Earth System Model
CCDP	Climate Change Data Portal
CIT	California Institute of Technology
DDM	Data Driven Model
DEHM	Danish Eulerian Hemispheric Model
DO	Dissolved Oxygen
EC	Electrical Conductivity
EMEP	European Monitoring and Evaluation Programme
GCM	General Climate Models
GLIP	Great Lakes Intake Program
MATCH	Multi-scale Atmospheric Transport and Chemistry
MLP	Multi Layer Perceptron
MLR	Multiple Regression Model
MSC-W	Meteorological Synthesizing Centre-West
PM	Particulate Matter
RMSE	Root mean square error
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
STW	Sewage Treatment Work
TDS	Total Dissolved Solids
TN	Total Nitrogen
TP	Total Phosphorus
TRP	Total Reactive Phosphorus
WQI	Water Quality Index

1. Chapter 1: Introduction

1.1. Background

Water quantity is a challenging subject in Canada (Mckitrick et al. 2018). Even though Canada has abundant freshwater resources (including more lakes than any other country), and has been ranked as the third country which has the largest freshwater supplies in the world, most of the available freshwater resources are draining northward into the Arctic Ocean and Hudson Bay away from the populated areas which are primarily in the south. Thus, these resources are distributed unevenly across the country. This uneven distribution can make challenges in terms of providing clean water for all residents (Mckitrick et al. 2018).

In addition to freshwater quantity issues, the water quality is deteriorating due to point and non-point sources of pollution. The results of water quality measurements have demonstrated that over the period of 2014 to 2016, 82% of the monitoring stations across the country had fair to excellent water quality status. The rest of the stations had poor to the marginal water quality (Mckitrick et al. 2018). In fact, the spatial analysis showed that the stations with good water quality are mainly located in rivers in the Atlantic and Arctic Oceans watersheds. However, on the other hand, poor or marginal ones are more common in rivers and Great Lakes in southern areas especially in Ontario, Quebec, and British Columbia where the majority of the population resides (Mckitrick et al. 2018). Thus, decreasing the water quality of the limited drinking water resources is another potential challenge in Canada.

One of the most important phenomena in terms of water quality is eutrophication. Eutrophication is the enrichment of water by nutrients such as nitrogen and phosphorus. The phenomenon can lead to some major changes in water bodies including increased production of algae (algal bloom)

(Thomas et al. 2018). Eutrophication is a major stressor that can reduce dissolved oxygen (DO), increase algae and even heavy metals (releasing of heavy metals can happen in low concentration of dissolved oxygen in deep layers of a lake). During the 1960s, the algal bloom became a concerning subject in Lakes Erie and Ontario which enforced the governments of Canada and the United States to protect the water quality of these lakes (Munawar and Fitzpatrick 2018). However, by enhancing anthropogenic land use, particularly urban and agricultural activities, the sources of pollution will increase. Therefore, it is still an important subject and needs to be investigated.

One of the sources of nutrients (especially for the nitrogen compounds including nitrate and ammonium) is atmospheric deposition. Atmospheric deposition of nitrate and ammonium has been identified as a major factor in the decline of water quality in watersheds (Jung and Kim 2017). It can increase water and soil acidification, and when nitrogen enters into water resources, it will cause eutrophication and algal blooms. Therefore, the role of atmospheric deposition as a contributor of nitrogen load needs to be systematically investigated (Palani et al. 2011). Hence, an accurate prediction of atmospheric deposition will provide a quantitative understanding of its possible impacts on water quality.

Generally, there are two different types of atmospheric deposition: wet and dry. The wet deposition takes place through precipitation. In this process, the atmospheric chemicals accumulate in the rain or snow and are eventually deposited on earth (Kulshrestha 2017), while dry atmospheric deposition comes from gaseous and particulate transport. In the dry deposition, the pollutants are deposited through such processes as settling, impaction, and adsorption from the air to the earth's surface. Accordingly, it is obvious that the more pollutants in the air, the more atmospheric deposition. In fact, in places which the air quality is poor, the deposition of pollutants through wet and dry processes is more than places with clean air (Kulshrestha 2017).

In addition to pollution sources, another important issue that can impact the atmospheric deposition, as well as water quality, is climate change. As a consequence of anthropogenic changes to atmospheric chemistry, the mean temperature at the earth's surface is expected to increase as much as 6°C by the end of the 21st century (Bates, Kundzewicz, and Wu 2008). Therefore, climate change is expected to result in changes to the global hydrologic cycle, including changes in the amount, and spatial distribution of precipitation, increased storm intensity, and sea level rise (Huntington 2006; Trenberth et al. 2003; USEPA 2008). Climate change affects water bodies directly via atmospheric drivers, e.g. temperature increase, precipitation, wind speed, and radiation, and indirectly through changes to catchment properties (Taner, Carleton, and Wellman 2011). Hence, changes in temperature, precipitation quantity and distribution, and atmospheric carbon dioxide concentration will affect the agricultural land's characteristics through changes in both soil processes and agricultural productivity. Non-agricultural source terms, such as urban areas and atmospheric deposition, are also expected to be affected (Stuart et al. 2011).

Climate change can alter the water quality of water resources through different pathways including changing the flow regime of water, the chemical and bacteriological processes, reservoirs thermal stratification, etc. One of its impacts would be through atmospheric deposition which eventually can change the water quality. Hence, there is a need for an integrated investigation of atmospheric deposition as well as climate change for understanding their impacts on water quality.

1.2. Research motivation

Based on the literature review, developing a model for investigating the impacts of climate change on the atmospheric deposition as well as water quality at the same time is needed although there are lots of studies in the related field. In a few cases of the previous studies, the atmospheric deposition is linked to the quality of water resources. In fact, in most of the previous research studies, the atmospheric deposition impacts on the water quality have been eliminated from the water quality investigations because of its negligible impacts. However, in some regions, atmospheric deposition can be quite an important factor in determining the water quality situation. Moreover, when we are talking about the impacts of climate change on water quality, it is important to consider all of its possible impacts through different pathways (such as atmospheric deposition). In the procedure of developing a physically based water quality simulation model, one of the challenges is the complication of modeling all the different natural processes without enough information about them. Therefore, in most of the studies, modelers make some assumptions that might not reflect the real situation by neglecting some of the natural processes. One of the alternative approaches is using machine learning algorithms in the modeling approach. In this way, regardless of natural processes, the model tries to implement the statistical techniques relying on patterns and inferences to find the relationship between different data series (inputs and the desired outputs). Artificial neural networks (ANNs) is one of the most common methods in machine learning modeling techniques. In this method, a mathematical structure is developed which is capable of providing the linear or non-linear relationship between inputs and outputs. ANN is a useful and efficient method especially in very complicated natural processes modeling (Hsu and Gupta 1995).

ANN has a number of advantages over physically based approaches. The variety of required information for the ANN is less than physically based models. The data gathering in physically based models usually is both times consuming and costly. In addition to data requirements, applying the physically based models for forecasting the longer time periods become problematic as these models require forecasts of each of the input variables. Also, due to the great complexity of natural systems, physically based models provide a simple approximation of reality and as a result, ANN is more suited to complex problems (Maier and Dandy 1996).

With respect to all the mentioned facts and considering the complications related to modeling of water quality in a physically based approach, in this study, a data driven modeling technique is established in order to develop a model to predict the water quality of Lake Ontario considering the impacts of atmospheric deposition under climate change scenarios.

1.3.Research objectives

The main objective of this study is:

- Modeling the atmospheric deposition quality
- Modeling the impacts of atmospheric deposition on water quality
- Using data driven modeling approach
- Evaluating the impacts of climate change on atmospheric deposition and water quality

By developed method, it is possible to evaluate the impacts of air quality and climate change at the same time on the precipitation quality as well as water quality. In this way, the decision makers will have an insight into the necessary mitigation plans for air contamination. In addition to air quality, it will be revealed whether the atmospheric deposition has enough strength to alter the quality of water resources or not. In addition, it will be clear that is the atmospheric deposition should be considered in water quality modeling or not. In conclusion, the research impacts would be:

- Evaluating the application of DDMs in atmospheric deposition and water quality simulation
- Evaluating the importance of atmospheric deposition impacts on water quality
- Investigating the climate change impacts on both atmospheric deposition and water quality

1.4.Research approach and thesis layout

The first step of this research is to conduct a comprehensive literature review which is presented in chapter 2. In this chapter, the different methods of modeling of the atmospheric deposition as well as the water quality are introduced. These methods are categorized into two main sections: physically based and data driven based modeling approaches. In addition, the relevant studies with respect to considering the climate change impacts on atmospheric deposition and also the quality of water resources is introduced and eventually the gaps of existing studies are presented.

Chapter 3 represents the study area of this research which are 3 regions near Lake Ontario. In this chapter, the different characteristics of the study area and their current temporal and spatial trends are introduced and analyzed.

Following this, the ANN method will be developed in detail in chapter 4. In this chapter, the function of ANN and the different steps of input variable selection, as well as the different scenarios of the future will be explained. After applying the proposed method in the study area, all the results of the simulation of atmospheric deposition and water quality in Lake Ontario are provided in chapter 5. Having the results of modeling, chapter 5 also will present the interpretation, analysis and discussion of these results.

To conclude, the thesis includes in total six chapters; an introduction and justification chapter (Chapter 1), literature review (Chapter 2), study area (Chapter 3), the modeling methodology (Chapter 4), the modeling results and discussion (Chapter 5), and a final concluding chapter (Chapter 6).

2. Chapter 2: Literature review

2.1. Atmospheric deposition modeling

The burning of fossil fuels including oil, coal, and gas is the main contributor to the increase in global nitrogen, in the form of nitrogen oxides (NO_x) in air. In addition to the production of pollutants in a certain area, the weather conditions, as well as the physical-chemical characteristics of the pollutants, can cause transporting them to a new place. One of the important types of deposition is nitrogen compounds deposition. It can vary in different places based on local emissions as well as meteorology. Generally, nitrogen compounds deposition is dominated by inorganic reduced nitrogen (NH_3 and NH_4^+) and oxidized nitrogen (NO_x, HNO_3 and NO_3^-) (Wright et al. 2018). Exposure to nitrogen can cause a wide variety of impacts on aquatic ecosystems. Also, the high concentrations of nitrogen can cause toxicity to some species, eutrophication, and acidification.

Focusing on the amount of nitrogen compounds deposition, it should be mentioned that it will be influenced significantly by air concentrations of the various nitrogen species as well as the surface exchange of these compounds (Zhang et al. 2005). Technically, as mentioned in Chapter 1, for simulating this process we can use two different types of modeling approaches which are physically or data driven based models.

2.1.1. Physically based models for atmospheric deposition simulation

Most of the previous studies applied physically based models to simulate atmospheric deposition. In this method, the model is trying to mimic the most important natural processes and simulate them in a defined temporal and spatial framework. For instance, Langner et al. (2009) developed a model to have an estimation of the present and future deposition of atmospheric nitrogen into the

Baltic Sea basin using the Eulerian chemical transport model (MATCH) which is a three dimensional model. This model includes modules for emissions, advection, turbulent mixing, dry and wet depositions. In addition, chemistry or aerosol dynamics can be added to this model. In this study, the results showed an increase in total nitrogen deposition by ~5% by the end of the 21st century as a result of climate change. In similar research, the impacts of climate change and emission changes on the deposition of reactive nitrogen over Europe were evaluated by Simpson et al. (2014). They used four regional chemistry transport models over the period of 2000– 2050. These models were DEHM, EMEP MSC-W, MATCH and SILAM which are complex models. In these models, it is necessary to focus on a number of complicated natural processes. For example, the physical-chemical modules of SILAM include several tropospheric chemistry schemes, description of primary anthropogenic and natural aerosols, and radioactive processes. The results demonstrated that the impact of emission changes is much greater than the impact of climate change alone.

Hole and Engardt (2008) used a high-resolution chemical transport model to explore the effects of possible future changes in climate on nitrogen deposition in northwestern Europe. The results revealed a considerable rise (30% or more) in nitrogen deposition load over western Norway as a consequence of increasing precipitation but more moderate changes for other areas. A regional model of atmospheric chemistry and transport has been developed by Engardt and Langner (2013) to analyze the spatial and temporal variation of sulfur and nitrogen deposition in Europe during the first half of the 21st century. In order to address the uncertainties in the climate change scenarios, they applied the output from three different climate models. The modeling efficiency was evaluated by comparing average modeled precipitation, deposition, and concentrations over a 20-year period with observations. The predictions proved that by controlling the emissions of sulfur and nitrogen containing species, the deposition of these species will mainly decrease comparing the present situation and climate change does not affect it considerably. In a similar study aiming to develop a model for simulating nitrogen deposition, St-Laurent et al. (2017) used a biogeochemical ocean model forced with a regional atmospheric chemistry model (Community Multiscale Air Quality). This model links the models of atmospheric chemistry, transport, meteorology, and emission to predict fate and transport of atmospheric constituents. They focused on NO_3^- because of its importance in the total atmospheric flux and the simulation results showed the deposition can cause a significant increase in surface NO_3^- concentrations during the summer.

Regarding the studies that have been done in Canada, Zhang et al. (2005) modeled the amounts of dry deposition of NO_3^- at seven stations in eastern Canada. They used the results of deposition in some monitoring stations and modeled the dry deposition. They verified that there is a strong relationship between the concentrations of NO and NO_2 in air and the deposition of NO_3^-. Ro, Reid, and Lusis (1988) focused on the analysis of the temporal and spatial variation of sulfur and nitrogen compounds in precipitation across Canada between 1980 to 1985. The results showed that the concentration of these pollutants in the air is higher in southern Ontario than northern Ontario and as a result, the corresponding distribution pattern for deposition is similar to that. Consequently, the deposition amounts showed different seasonal trends in concentration reflecting a dependence on meteorological factors. In the same research, Zhang et al. (2009) developed a model to estimate the amount of nitrogen deposition (wet and dry) based on air quality parameters. The analysis was conducted for the data between 2001 to 2005 at 8 selected rural sites across eastern Canada using a big-leaf model with on-site meteorological inputs. Nitrogen dry deposition was estimated to be 0.8–4.0 kg N ha^{-1} a^{-1}, depending on location with 60–75% from NO_x and 25–40% from NH_y. Nitrogen dry and wet deposition from $NO_x + NH_y$ was estimated at 4.3–11 kg N ha^{-1} a^{-1}, with dry deposition accounting for 10–50%.

In conclusion, most of the previous studies used the physically based models to develop their simulations. Also, in most cases, the impacts of the atmospheric deposition on the water quality were not investigated. Generally, the physically based models of atmospheric deposition are quite complicated. However, another approach for developing a model is using the data driven models (DDMs).

2.1.2. Data driven models for atmospheric deposition simulation

On the other hand, in some research studies, DDMs have been used to simulate atmospheric deposition. This method involves mathematical equations that are not related to the complicated natural processes but derived from time series data and their correlation (Solomatine, See, and Abrahart 2008). Commonly, there are different methods of DDMs that can be used in hydrological modelings such as ANNs, fuzzy rule-based systems, multiple linear regression, and genetic algorithms.

Ma (2005) applied an ANN approach for simulation of acid deposition (focusing on both SO_2 and NO_X emissions) in the USA. In this study, acid deposition data from various monitoring sites in the USA were collected and a feedforward backpropagation ANN model was developed. The feedforward neural network is one type of ANNs which the information moves only forward and there are no cycles or loops in the ANNs. This study demonstrated the potential of ANN as an accurate modeling approach especially for complicated systems under uncertainties. The results showed that even though there will be a significant drop in the average wet deposition ion concentration level, it is not likely that sulfate or nitric ion concentrations can be reduced to safe levels everywhere in the United States.

Oulehle et al. (2016) used the data from 32 monitoring sites to assess the spatial and temporal variability of sulfur and inorganic nitrogen concentrations in precipitation. They developed a linear regression model to extrapolate site characteristics and estimate the concentration of nitrogen deposition for the individual sites. The results disclosed an overall decay of NO_3^- and NH_4^+ concentrations in precipitation. In addition, they used a multiple regression model to extrapolate the atmospheric deposition from monitored to unmonitored sites. This method is applicable for providing spatio-temporal estimation of acid deposition. But it needs an extensive monitoring history of precipitation chemistry. Pascaud et al. (2016) presented the temporal and spatial variation of atmospheric deposition in France based on the 37 monitoring stations with available measurements between 1995 to 2007. They focused on different parameters including pH, NO_3^-, SO_4^{-2}, Ca^{+2}, and NH_4^+. The temporal trends were different depending on the parameters and site location. Many stations showed an increase in annual pH (+0.3 on average) which is mostly due to the reduction in SO_2 emissions in Europe since the 1980s. However, despite the reduction in NO_x emissions, the concentration of NO_3^- in precipitation remained mostly unchanged. In contrast, NH_4^+ concentrations in precipitation declined while the emission of NH_3 did not change. This reduction is generally due to more dilution process.

Hember (2018) developed a database containing the estimation of annual total nitrogen compounds deposition in North America. This database would be helpful for developing ecosystem models. In this study, the estimates were produced by interpolation of monthly ammonium and nitrate concentration in the period of 1860 to 2013. Fig 1 represents an estimation of nitrogen deposition in different years. As it can be seen in this figure, the amount of nitrogen deposition has declined between 2000 and 2013 while the increasing trend from 1861 to 2000 is evident.

In a similar evaluation of existing data, Zbieranowski and Aherne (2011) conducted a study in the period of 1988 to 2007 at 12 different stations across Canada. They showed that the concentration of NH_4^+ in precipitation had no significant or consistent trend.

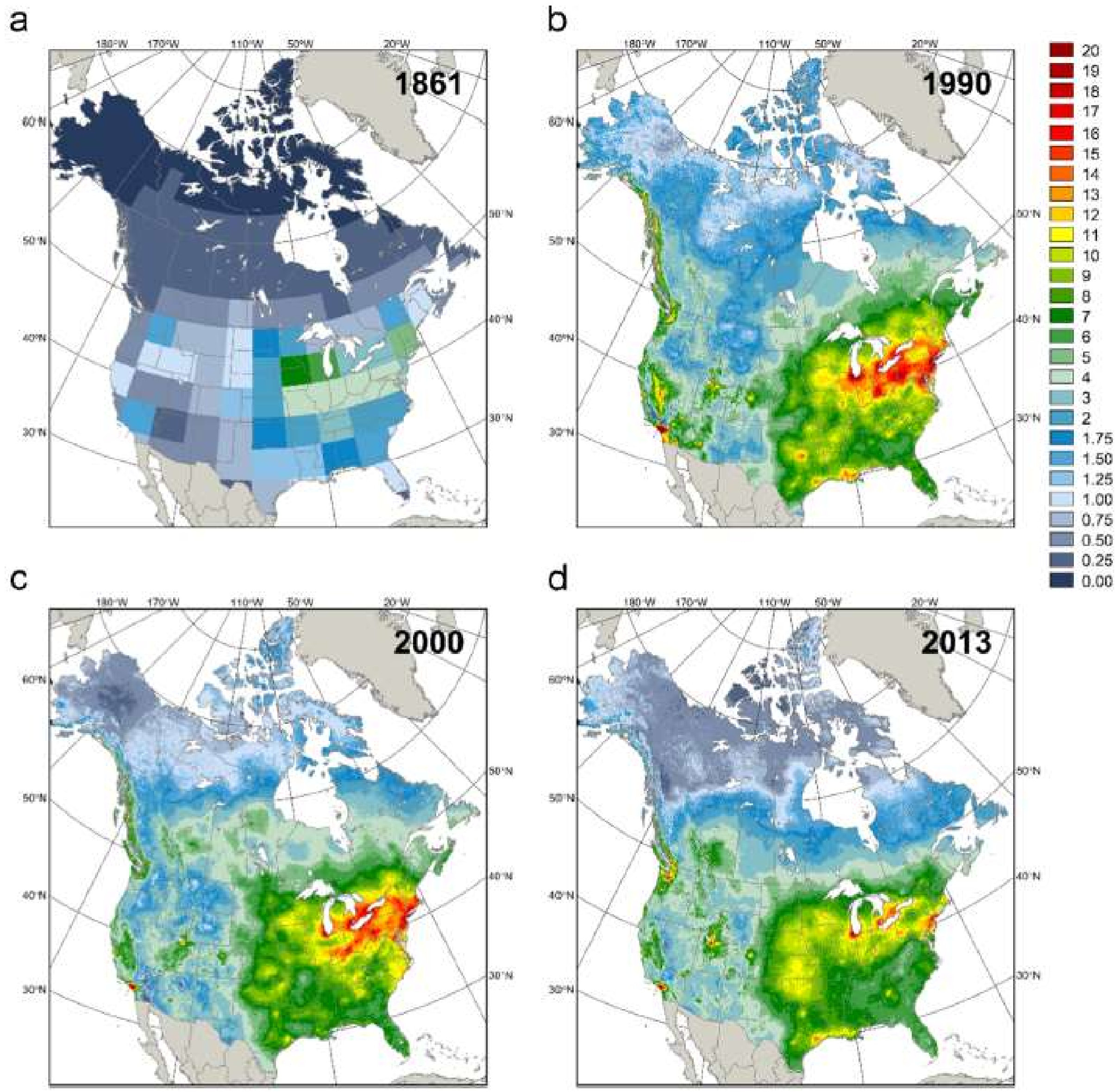


Fig 1. Estimates of annual total N deposition at different times across North America (Hember 2018)

In terms of NO_3^- concentration, it significantly decreased which was due to lower NO_x emissions. In another related research, Zbieranowski and Aherne (2012) analyzed the spatial and temporal variation of air pollutants (NO_2 and NH_3) and nitrogen deposition at four sites across southern Ontario. They proved that NH_3 and NO_2 contamination in air will determine the majority of (50 to 60%) total nitrogen deposition.

Most of the studies in Ontario, Canada just focused on the statistical assessment of the monitoring measurements of atmospheric deposition rather than developing a simulation model to evaluate the future condition of atmospheric deposition.

2.2.Water quality modeling considering the atmospheric deposition

Having a simulation tool can help us to evaluate the water quality situation considering different natural processes including atmospheric deposition. In addition, it can be used to evaluate the possible impacts of climate change, which causes changes in trends of precipitation during different seasons as well as increasing the air temperature. Therefore, it is possible to develop a simulation model for the water quality using physically based models or data driven models.

2.2.1. Physically based models for water quality simulation

There are a number of different aspects that contribute to water quality such as air temperature, hydrology, hydro-morphology, ecology, nutrients and eutrophication, toxic substances and etc. By applying the physically based models for the water quality simulation, it is necessary to consider all the introduced processes. After developing a calibrated model, it is possible to apply different scenarios of climate change or sensitivity analysis of the model. The potential impacts of climate change on the water have been studied extensively, in previous research studies but, each one of these studies concentrated on different aspects. For instance, Whitehead et al. (2009) reviewed the potential impacts of climate change on surface water quality in the UK. This study showed the increase in winter floods as well as the frequency of extreme events and even experiencing drier summer may take place because of climate change. Additionally, less precipitation in summer, increasing the temperature and residence time and also decreasing the concentration of DO can provide a satisfactory condition for eutrophication and algal bloom. Fowler et al. (2015) studied the effects of climate change during the 21st century on another important aspect which can alter the water quality called the nitrogen cycle. According to their findings, changes in climate and land use during the 21st century will increase both biological and anthropogenic nitrogen fixation, bringing the total to approximately 2.5 times by the year 2100. It can have a sizeable impact on the water resources eutrophication. Pesce (2017) by developing the integration of climate scenarios and environmental models, tried to predict the phytoplankton ecosystem dynamics in water under climate change conditions. The case study was Zero River basin in Italy. He applied an integrated modeling approach made of an ensemble of global climate models, regional climate models, the Soil and Water Assessment Tool (SWAT), and the ecological model AQUATOX. The results illustrated that by changing the climate, an increase of precipitation in the winter and a decrease in the summer months will happen, while temperature shows a significant increase over the whole year. By using SWAT modeling tool, the water discharge and nutrient load were simulated which showed a tendency to increase in the winter, and a reduction during the summer months. On the other side, AQUATOX predicted the changes in the concentration of nutrients in the water and variations in the biomass and species of the phytoplankton community.

In terms of climate change impacts on lakes and reservoirs, Missaghi et al. (2017) applied a three dimensional lake water quality model to investigate the influence of local meteorological conditions on fish habitat under one historical and two future climate change scenarios. The simulation results demonstrated that the stratification periods expand up to 23%, the thermocline depths increase 49%, and the onset of anoxia occurs 4 weeks earlier under the future climate scenarios. In similar research, Chapra et al. (2017) developed a modeling framework that predicts the effects of climate change on algae concentration in large reservoirs in the USA. Their study indicated that algal concentrations are likely to increase due to higher water temperature as well as increased available nutrients resulting from changing demographics and climatic impacts on hydrology that drive nutrient transport. They assessed the impacts of climate change in terms of temperature, precipitation, nutrient loadings, water demands, and vertical stratification.

The modeling procedure started with projections from general climate models (GCMs) for alternative future climates. GCM projections of precipitation, mean temperature and daily temperature range were inputs into a rainfall-runoff model which was used to simulate a monthly water demand model. In the next step, they used a modified version of the QUALIDAD water quality model to simulate a number of water quality characteristics, including algal concentrations in water bodies.

None of the mentioned studies considered the atmospheric deposition as an important source of nutrients in their modeling although, it has been shown that atmospheric deposition can influence the water quality. In terms of physically based models, SWAT has the ability to simulate atmospheric nitrogen deposition and fixation and evaluate its impact on water quality. In an application of SWAT, Jung and Kim (2017) assessed the impacts of atmospheric and agricultural nitrogen loads on Chungju dam watershed (with 6642 km^2 area). The model was calibrated for 4 years (2003-2006) and validated for another 4 years (2007-2010) using daily anthropogenic nitrogen data. The coefficient of determination (R^2) of total nitrogen modeling was 0.69 considering atmospheric deposition, while it was 0.33 when removing the deposition effect which is a demonstration of atmospheric deposition important role in water quality modeling.

Gabriel et al. (2018) used the SWAT model to estimate the combined effects of changing the land cover, climate and atmospheric nitrogen deposition on the concentration of total nitrogen in the watersheds of North Carolina, the USA between 2020 and 2070. It showed that by implementing the Clean Air Act (CAA), the overall decreasing trends for nitrogen between 2010 and 2070 are obvious while, by including climate and land cover changes in the simulation process, it may offset the benefits provided by the CAA regulations. The SWAT is not the only model that can be used for modeling the atmospheric deposition and water quality at the same time. Burian et al. (2001) used a deterministic physically based model (by coupling the CIT airshed and SWMM models) to contribute the atmospheric deposition as a source of nutrients onto urban stormwater (in the city of Los Angles, USA) or in another study, Poor et al. (2013) applied a watershed deposition tool (developed by U.S. Environmental Protection Agency) to estimate the atmospheric deposition of reactive nitrogen to Tampa Bay, USA and its watershed. This study showed that atmospheric deposition of reactive nitrogen has a significant role in Tampa Bay's total nitrogen loading. Decreasing the nitrogen oxide emissions from different sources such as power plants and motor vehicles are vital to the bay's water quality management.

2.2.1.1. Water quality of Lake Ontario

Focusing on the water quality of Lake Ontario, which is the study area of this research, many different studies have been conducted. In these studies, different aspects of the water quality of Lake Ontario were investigated. For example, Munawar and Fitzpatrick (2018) tried to characterize the eutrophication situation in the Bay of Quinte, Hamilton Harbour and Toronto Harbour that are all coastal regions of Lake Ontario. They assessed the phytoplankton communities as well as nutrients concentration during 2015 and 2016. The results showed that usually the amounts of nutrients (nitrogen, phosphorus, and silica) are quite high and the management of pollution sources is necessary. Regarding the microbial pollution of Lake Ontario, Staley et al. (2018) focused on the concentration of Escherichia coli (*E. coli*) as well as phosphorus on Sunnyside and Rouge Beaches in the City of Toronto and stormwater outfall in the adjacent Humber and Rouge Rivers within their beach sheds. They found that because of the contamination of stormwater with sewage, the concentrations of total phosphorus and *E. coli* in both beach sheds are quite high and usually correlated to each other. As a result, high phosphorus pollution load could contribute to changes in microbial communities and also eutrophication along beach shorelines in Lake Ontario. Howell et al. (2018) examined the water quality of Lake Ontario at Toronto Harbour. This place receives water from storm sewers, combined sewer overflows, and urban runoff. They used on-site and lab-based measurements of different water quality parameters including turbidity, conductivity, chlorophyll-a, nitrogen, total phosphorus, dissolved organic carbon, major ions, and *E. coli.* Using the results of the monitoring program, the temporal and spatial analysis of water quality parameters was conducted. The results showed a moderate situation of eutrophication (oligotrophic) in that area.

In terms of modeling the water quality, Chapra et al. (2016) developed a mass balance model in order to model total phosphorus (TP) concentrations in both Lake Erie and Lake Ontario. The results illustrated that decreasing the concentration of TP in Lake Erie (by controlling the pollution sources) has a direct impact on Lake Ontario water quality improvement. Focusing on algal bloom which is a result of eutrophication, Leon et al. (2012) applied a three dimensional hydrodynamic-ecological model to a coastal segment of Lake Ontario to investigate the role of different parameters like dynamics and external inputs on algae growth. The modeling showed that the average values of chlorophyll-a were well simulated while there was an unrecognized sink (or error) for estimated nitrate load.

Even though the presence of nutrients is the main factor of eutrophication, the importance of water temperature in this process is undeniable. Technically, propagation, flow circulation, and mixing coefficients are some variables that correlated to water thermal characteristics. The thermal behavior of Lake Ontario was investigated by Arifin et al. (2016) by using the three dimensional thermo-hydrodynamic model, Environmental Fluid Dynamics Code (EFDC). The results showed an accurate model for predicting the temperature profile. The value of root mean square error (RMSE) for the surface temperature was between 1 and 2 °C while for the vertical temperature profiles it was about 0.5 °C which is showing a good agreement between the model predictions and observed data.

The overall situation of great lakes, streams and groundwater resources across Ontario is being evaluated by the Ontario Ministry of Environment annually. In the provided analysis of the great lakes water quality, the index of water quality (WQI) has been used in their reports. In order to calculate the WQI which is a value between 0 to 100, the results of water quality monitoring for multiple samples and parameters have been used. The results showed 39% of sites were categorized as having Good water quality, 48% were Fair and 13% were Poor (Fig 2). In this assessment, the tributaries to Lake Ontario had Fair water quality. Theses analysis demonstrated that the watersheds with the less human developments had lower water contamination.

Regarding the temporal variation of nutrients in Lake Ontario, based on Eimers and Watmough (2016) research, the concentrations of nitrate (NO_3^-) in offshore waters of Lake Ontario increased by approximately 60% between the 1970s and 2000s. It should be noted that the agricultural lands have been expanded during the mentioned time period and this change is the main cause of the nutrients load enhancement in water. All of the mentioned studies used the physically based models in their simulations even though using the DDMs is another alternative to develop a simulation tool for climate change impacts on water quality.

DDMs have been widely used in terms of water quality simulation. The target is to find the correlation between inputs and output data series. Lin (2017) developed a framework to evaluate the sensitivity of algal biomass to climate change in the USA. He applied machine learning algorithms including boosted regression trees (BRT) and the results showed that mean annual algal biomass, which is the output of the model, generally increased with annual temperature (as one of the inputs). The greater increase was found in lakes with more nutrients.

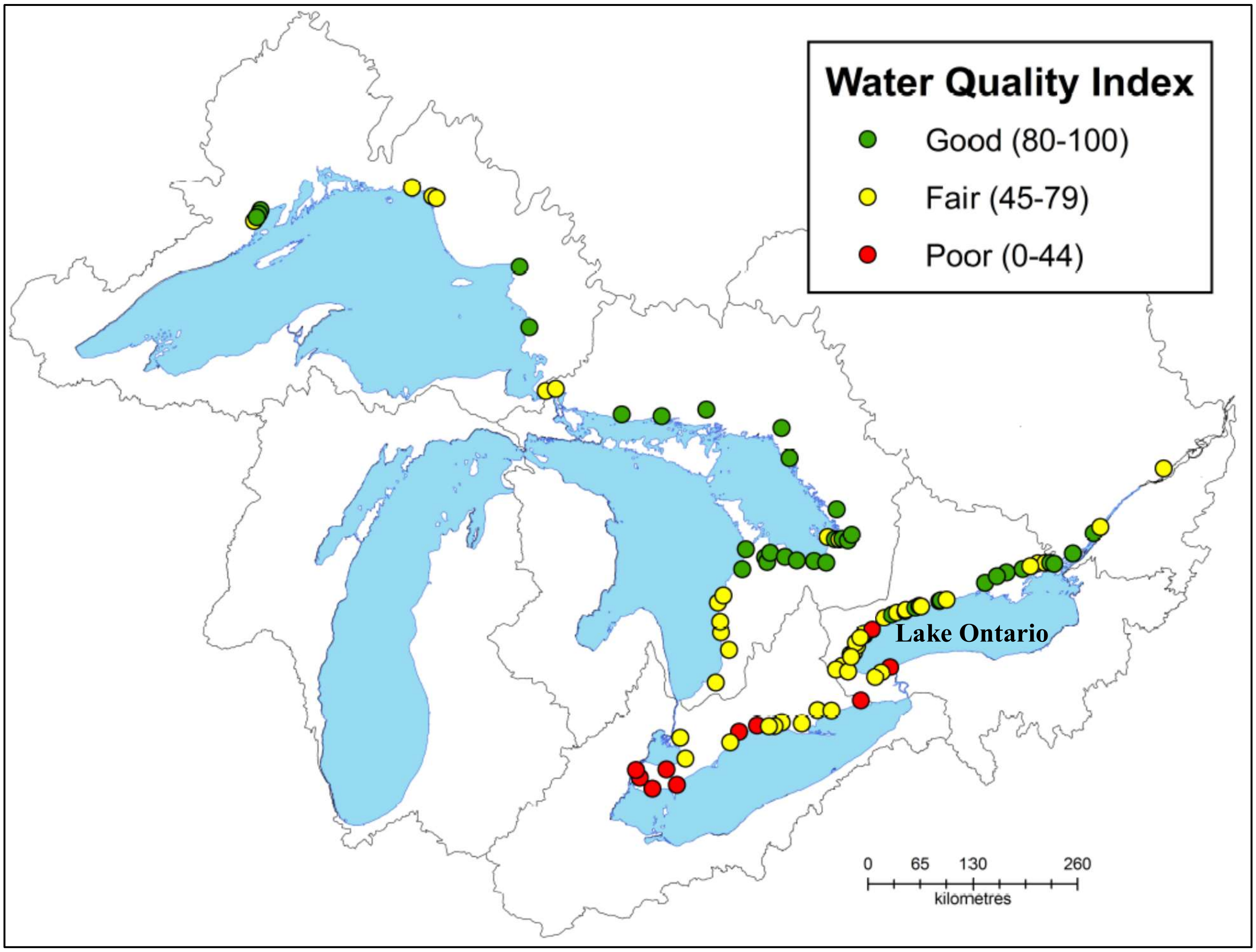


Fig 2. Water Quality Index values for tributaries to the Great Lakes (Ontario Ministry of Environment (2014))

2.2.2. Data driven models for water quality simulation

Also, the mean annual algal biomass generally decreased with annual total precipitation. Eventually, the mean annual algal biomass in lakes increased with climate change. Al-Mukhtar and Al-Yaseen (2019) assessed the performance of using three different models of DDMs: Adaptive neural based fuzzy inference system (ANFIS), artificial neural networks (ANNs) and multiple regression model (MLR) to predict and estimate TDS and EC in Abu-Ziriq marsh south of Iraq from 2008 to 2019. The inputs of the models were nitrate (NO_3^-), calcium (Ca^{+2}), magnesium (Mg^{+2}), total hardness (TH), sulfate (SO_4^{-2}) and chloride (Cl^-). The comparison of the models demonstrated that the ANFIS model outperformed the ANN and MLR models considering their performances. In a similar study, Mulia et al. (2013) developed a data driven model for forecasting turbidity and chlorophyll-a. They used the ANN and genetic algorithm combination. The hydrodynamic parameters were used as inputs of the model. The proposed method presented an accurate prediction of outputs.

Huo et al. (2013) used ANNs to predict the eutrophication indicators such as dissolved oxygen, total nitrogen, chlorophyll-a, and Secchi Disk in the Lake Fuxian in southwest China based on several different physio-chemical water quality parameters such as pH, temperature, etc. The correlation coefficient between predicted values and measured data was about 0.7. This research illustrated the good performance of ANN for simulation of complex processes such as lake's eutrophication. In the same research, Charlton et al. (2018) estimated the total reactive phosphorus (TRP) concentrations for the 2050s under 11 climate change driven scenarios of future river flows and under scenarios of both current and higher levels of sewage treatment at 115 river sites across England. The produced maps showed a small but inconsistent increase in annual average TRP concentrations with a greater change in summer. In this study, a load apportionment model was used to describe the current relationship between flow and TRP. The approach is based on the observation that rivers that receive the majority of their phosphorus inputs from sewage treatment works (STW) always have their highest phosphorus concentrations at lowest flows, and this rapidly decreases with increasing flows. Once the river flow increases due to rainfall, these dominant STW inputs will be diluted.

In some research studies, it has been tried to investigate the impacts of atmospheric deposition on water quality using DDMs. For example, Kothawala et al. (2011), by implementing the statistical analysis and hypothesis tests, demonstrated a rapid response in stream NO_3^- to declining atmospheric inputs in south-central Ontario, Canada. These results revealed the importance of atmospheric deposition as a source of nutrients in river water quality. In similar research, Eshleman et al. (2013) evaluated the statistical relationship between nitrate and atmospheric deposition in a group of nine predominantly forested Appalachian Mountain watersheds from 1986 to 2009. The statistical analysis showed a surprising linear decline in both annual surface water nitrate concentration and annual wet nitrogen deposition in the study area. The main reason for this reduction was the U.S. NO_x emission control programs during the same time period. Palani et al. (2011) used an ANN model to estimate atmospheric deposition of total nitrogen and organic nitrogen concentrations to coastal aquatic ecosystems. The selected input variables were nitrogen species from atmospheric deposition, total suspended particulates, pollutant standards index and meteorological parameters. The results demonstrated that the ANN modeling provides acceptable predictions for high concentration events. None of the previous studies in Lake Ontario water quality considered the impacts of atmospheric deposition. Also, the impact of climate change is another missing subject in this area.

2.3.Gaps and limitations

There are many studies that have been conducted in terms of atmospheric deposition and water quality modeling. In some of them, the impacts of climate change have been evaluated as a scenario of future conditions. Most of these research studies used physically based models while the number of DDMs is quite a few. However, the interaction of atmospheric deposition and water quality is not investigated comprehensively. In a few studies, the relationship between the air quality and atmospheric deposition was introduced but, the following impact, which is the changes in the water quality, was not pursued.

In terms of the gaps of previous research studies in Lake Ontario, none have considered the impacts of atmospheric deposition on the water quality of the lake. Moreover, there is not a comprehensive study regarding the impacts of climate change on the water quality of Lake Ontario. Also, in most cases, the physically based models have been used and the efficiency of DDMs was not examined. Therefore, there is a need to develop a DDM to be able to evaluate the impacts of the atmospheric deposition and climate change on the water quality of Lake Ontario in the future.

3. Chapter 3: Study area

The study area is the Lake Ontario which is located in the southern part of Ontario, Canada (Fig 3). The main objective of this research is to predict the water quality (focusing on nutrients) considering the atmospheric deposition. As a result, the water quality of Lake Ontario, as well as the atmospheric deposition, will be investigated in three different regions: Toronto, Cobourg, and Grimsby. In this way, it is necessary to focus on different aspects of the study area in each region including:

- Atmospheric deposition
- Water quality
- Air quality
- Meteorological characteristics (air temperature and precipitation amount)
- Land use

In terms of atmospheric deposition, there is a comprehensive monitoring program in Canada which is the Canadian Air and Precipitation Monitoring Network (CAPMoN). This monitoring program is designed to study the regional patterns and trends of atmospheric pollutants such as acid rain, smog, particulate matter, and mercury, in every precipitation event. The network began operating in 1983. In this research, the data of 3 stations of this monitoring program (Fig 3) have been used. These stations are the closest ones to the study area. More detail of these stations will be presented in the following sections.

In terms of water quality of Lake Ontario, the Great Lakes Intake Program (GLIP) monitors nearshore water quality in the great lakes across Ontario. GLIP is a joint program between the Ministry of the Environment and municipal water treatment plants to monitor the water quality of Great Lakes. The samples are collected weekly or bi-weekly at water treatment plant intakes. In the current study, the results of water quality monitoring in 3 different stations will be used (Fig 3).

Since the atmospheric deposition has a considerable correlation to air quality, it is necessary to have an insight about the air quality of the study area as well. The Ministry of Environment of Ontario, Canada has a network of 38 ambient air monitoring stations across the province. These monitoring stations measure the air pollution data parameters (starting from the year 2000). In this study, the information of 7 close stations to the water quality monitoring stations have been used to characterize the air quality situation of the study area (Fig 3).

Additionally, with respect to the meteorological characteristics of the study area, the air temperature and total precipitation were considered in this research. Therefore, the available data from 5 close meteorological stations have extracted and used for different study regions.

In the next sections, all of these different monitoring programs will be introduced and a preliminary analysis of the temporal and spatial variation of the available data will be provided.

3.1.Atmospheric deposition monitoring results

There are 33 CAPMoN stations across Canada which are located in central and eastern Canada, but new sites are being developed in the west. In this study, three of them which are close to the study area will be used. The location of these stations is presented in Table 1 and Fig 3.

In this monitoring program, the major ions in precipitation including Cl^-, NO_3^-, SO_4^{-2}, NH_4^+, Na^+, K^+, Ca^{+2}, Mg^{+2} are monitored in each precipitation event. In addition, the program includes the pH and depth of the precipitation sample.

Table 1. The atmospheric deposition monitoring stations coordination

Station Name	Latitude (North)	Longitude (West)
Egbert	44°:13′:52′′	79°:46′:59′′
Longwoods	42°:53′:05′′	81°:28′:50′′
Warsaw	44°:27′:50′′	78°:07′:50′′

In this study, the final target is the evaluation of air quality on atmospheric deposition as well as water quality, focusing on nitrogen compounds in all these three different aspects. The data was available until the year 2012, all the current situation investigations have been conducted until this year. Fig 4 and Fig 5 show the historical trends of the average concentration of nitrate and ammonium in the precipitation events.

Based on Fig 4 and Fig 5, the concentration of ammonium and nitrate in precipitation has not changed considerably during the time. However, it seems that the concentration of pollutants in the Longwood station is slightly higher than the other stations. In addition, focusing on the time period after the year of 2000, it seems that the quality of precipitation (especially in terms of nitrate) is lower which might be because of the air quality situation.

3.1.Air pollution monitoring results

As mentioned earlier, there are 33 air quality monitoring stations across Ontario, Canada. However, aiming to simulate the nitrate and ammonium in atmospheric deposition and water quality of Lake Ontario in Toronto, Grimsby and Cobourg regions, seven air quality monitoring stations that were close to these points where selected. Table 2 is presenting the location of these monitoring points.

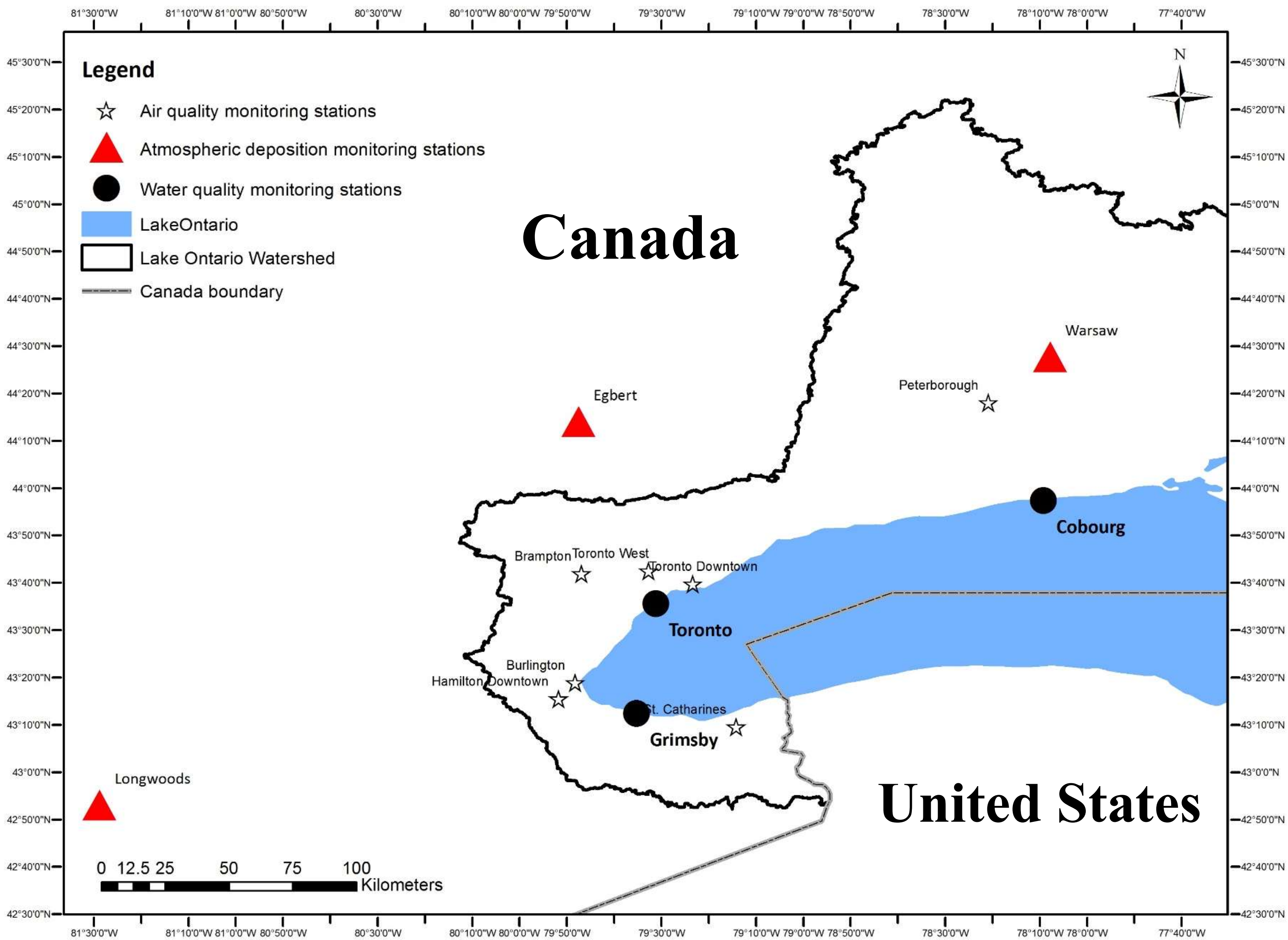


Fig 3. **The study area that shows Toronto, Cobourg and Grimsby regions**

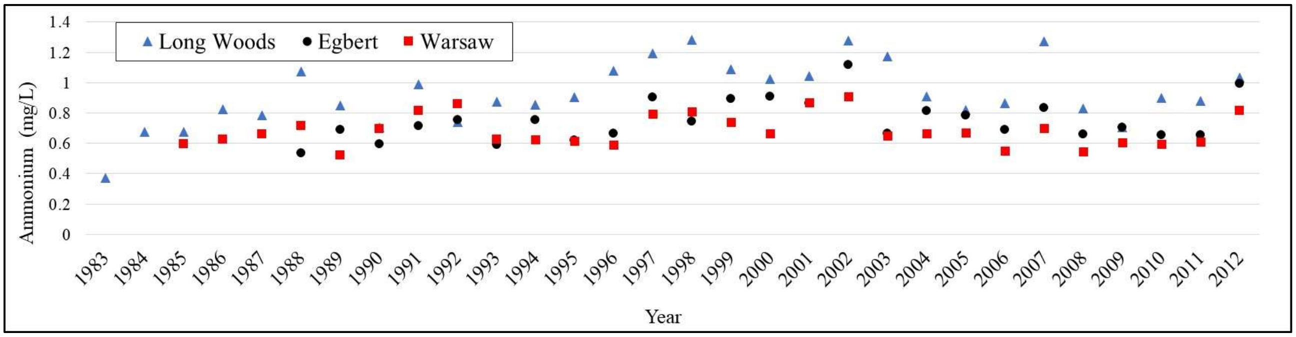


Fig 4. The concentration of ammonium (mg/L) in different atmospheric deposition stations

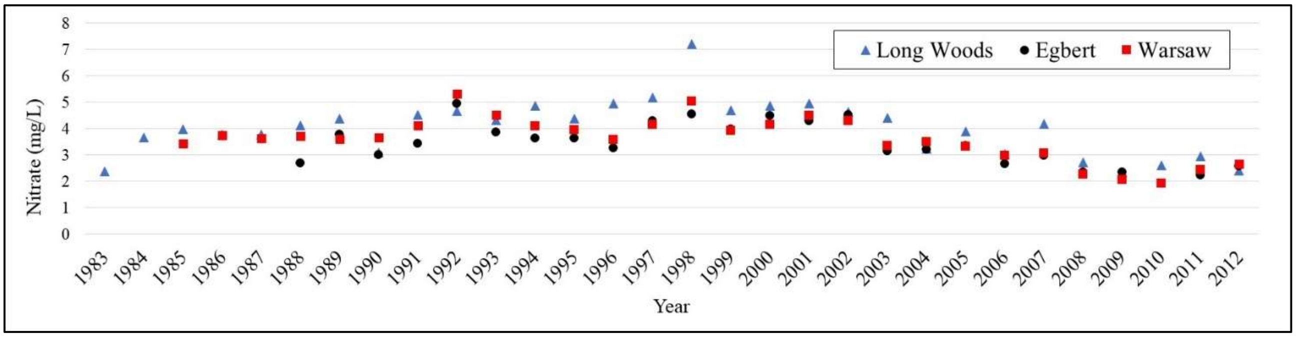


Fig 5. The concentration of nitrate (mg/L) in different atmospheric deposition stations

Table 2. The air quality monitoring stations coordination

Station Name	Latitude (North)	Longitude (West)
Brampton	43°:40´:12´´	-79°:45´:59´´
Toronto West	43°:42´:34´´	-79°:32´:37´´
Toronto Downtown	43°:39´:46´´	-79°:23´:17´´
Peterborough	44°:18´:07´´	-78°:20´:46´´
Burlington	43°:18´:54´´	-79°:48´:10´´
St. Catharines	43°:09´:36´´	-79°:14´:05´´
Hamilton Downtown	43°:15´:28´´	-79°:51´:42´´

All of these monitoring stations have started their monitoring program since the year 2000. Regarding that the simulation parameters are nitrogen compounds, the information of Nitrogen Oxide (NO) and Nitrogen Dioxide (NO_2) which are two related parameters measuring in the air monitoring stations are considered in this study.

In Fig 6 and Fig 7, it is obvious that the overall trend of the pollution in the different stations is declining from 2000 to 2012 which confirms the trend of precipitation chemistry (Fig 4 and Fig 5). Also, the air quality in the city of Peterborough is cleaner than the other cities. On the other hand, Toronto region has the most polluted air comparing Peterborough and Grimsby regions.

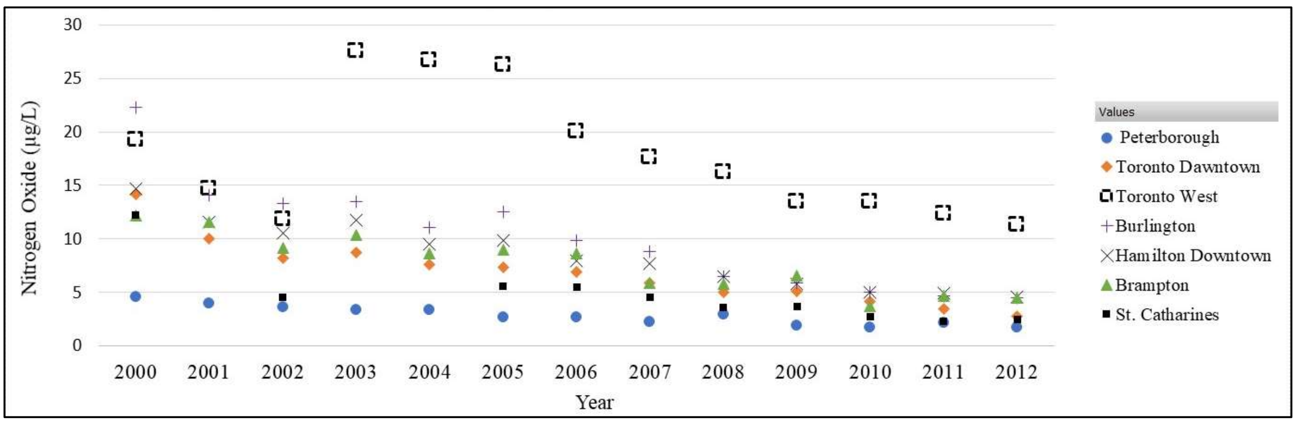


Fig 6. The concentration of Nitrogen Oxide (µg/L) in different air quality stations

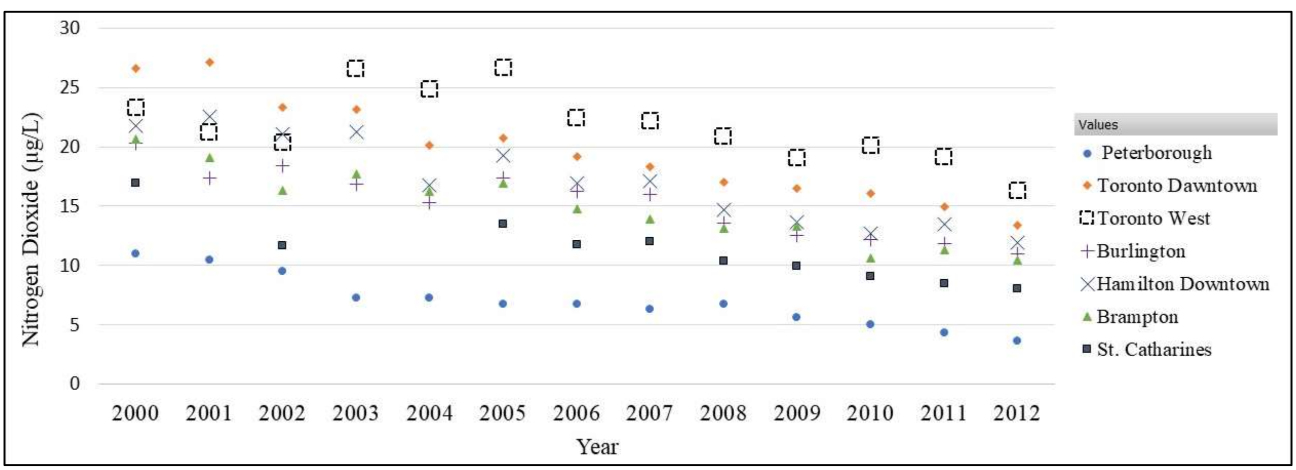


Fig 7. The concentration of Nitrogen Dioxide (µg/L) in different air quality stations

3.2.Water quality monitoring results

As mentioned earlier, in this study, the water quality of Lake Ontario in different regions are modeled: Toronto, Cobourg and Grimsby (Fig 3). As a result, the available data in water quality monitoring stations in these cities which are belonged to GLIP have been used in this study (Table 3 and Fig 3).

Table 3. The water quality monitoring stations coordination

Station Name	Latitude (North)	Longitude (West)
Toronto	43°:35´:36´´	-79°:31´:10´´
Cobourg	43°:57´:22´´	-78°:09´:11´´
Grimsby	43°:12´:22´´	-79°:35´:12´´

In the same way, as other monitoring programs, the nitrogen compounds in water (ammonium and nitrate) are considered in this research. Fig 8 and Fig 9 show the temporal variation of these water quality parameters in Lake Ontario. The water contamination in Cobourg Station is lower than Grimsby and Toronto Stations. Until the year 2000, the water quality in Grimsby and Toronto Stations was quite similar, However, after this year, the water contamination in Toronto Station became higher. But generally, there is not a considerable declining or increasing trend in terms of water quality during the monitoring period.

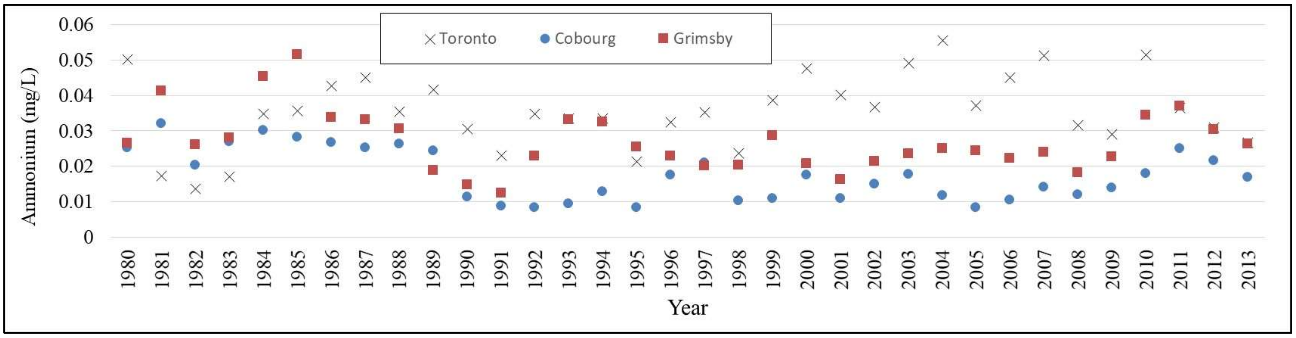


Fig 8. The concentration of ammonium (mg/L) in different water quality monitoring stations

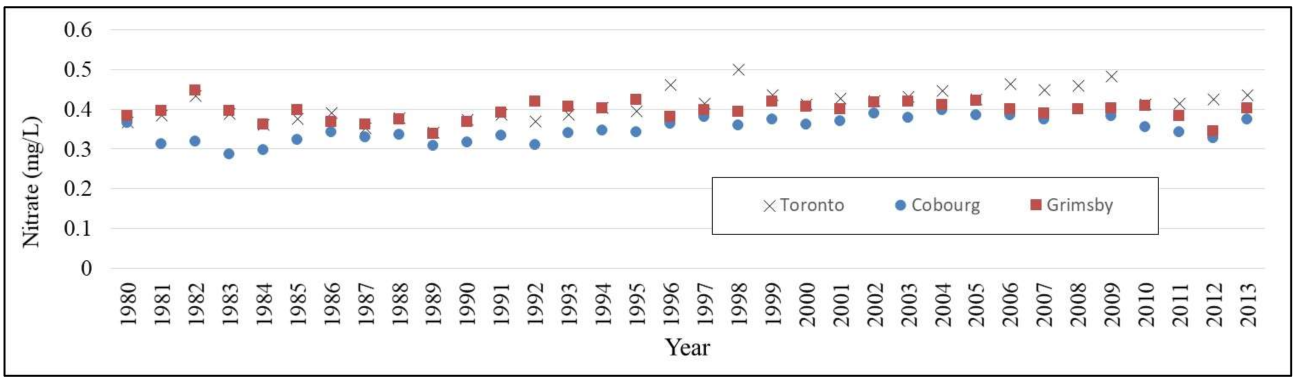


Fig 9. The concentration of nitrate (mg/L) in different water quality monitoring stations

3.3.Meteorological data

In order to have an estimation of the meteorological situation in the location of each water quality monitoring station, different meteorological stations have been selected (Table 4). Since the available air quality data is starting the year of 2000, Fig 10 and Fig 11 are presenting the variation of average air temperature and total precipitation amount in each water quality monitoring station between 2000 until 2012.

As it can be seen in Fig 10, there is no considerable difference between the average air temperature between 3 different locations inside the study area. However, focusing on monthly and daily variations, there might be some differences. On the other hand, the total amount of precipitation is showing a sizable difference between the stations especially after the year 2006 (Fig 11). It is obvious that the amount of precipitation in the Cobourg area has declined.

Table 4. The meteorological stations as well as their related water quality monitoring station

Related water quality station	Meteorological station name	Latitude (North)	Longitude (West)
Toronto	Toronto Lester b. Pearson airport	43°:40′:00′′	-79°:24′:00′′
Cobourg	Cobourg stp	43°:58′:00′′	-78°:11′:00′′
	Peterborough-a	44°:13′:48′′	-78°:21′:48′′
Grimsby	Grimsby mountain	43°:11′:01′′	-79°:33′:30′′
	Burlington piers (aut)	43°:18′:00′′	-79°:48′:00′′

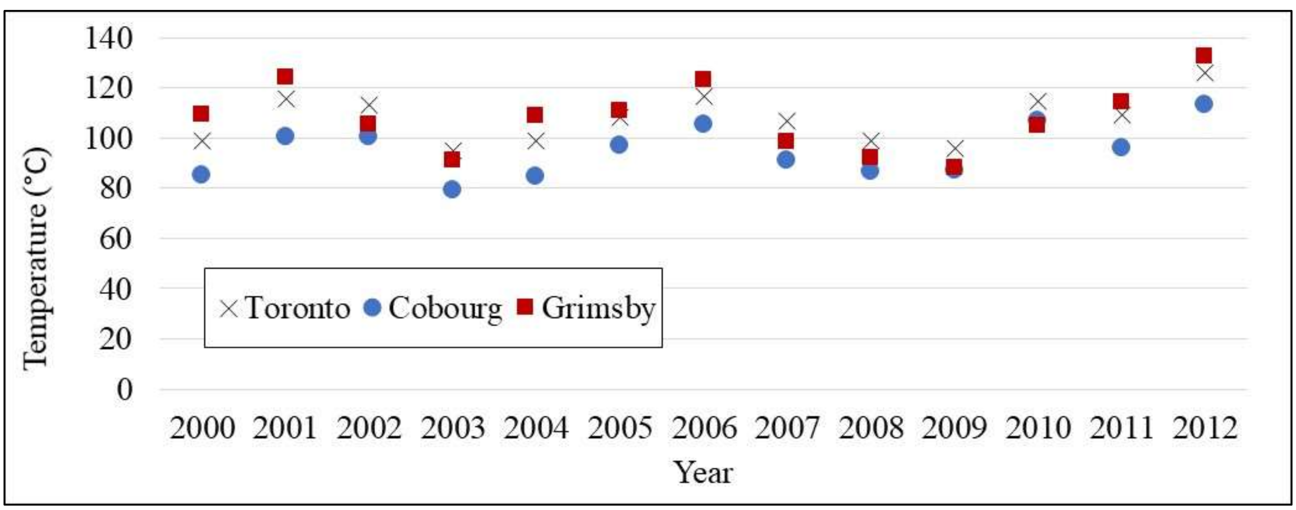


Fig 10. The average air temperature in different regions

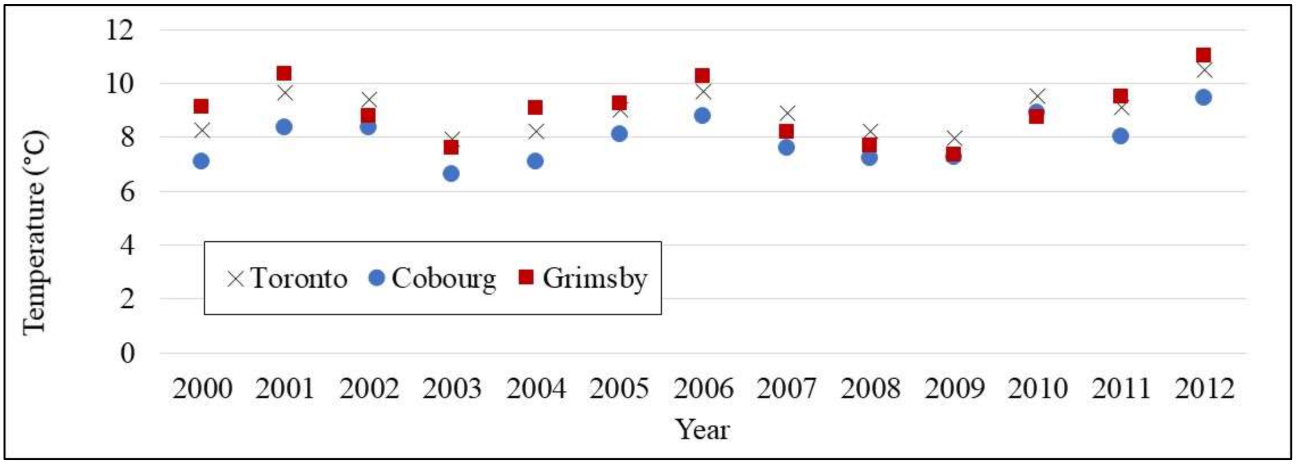


Fig 11. The amount of total precipitation in different regions

3.4.Land use data

As mentioned in Chapter 2, the intensity emissions of pollutants to the air has a direct impact on atmospheric deposition as well as water quality. Therefore, in order to have an insight into the emission rates of pollutants in all 3 different regions of the study area, it would be useful to have the land use maps of these areas (Fig 12 to Fig 14). Considering the different land types in different zones, it is recognizable that the dominant land use in the Toronto region is community/ infrastructure (Fig 12) which is a residential area. In addition, there are a lot of agricultural lands the nearby while in Cobourg region, the concentration of urbanized lands is the lowest although there are some agricultural lands in that area (Fig 14). Grimsby area shows a moderate situation in terms of residential areas while the concentration of agricultural lands in this area is quite high.

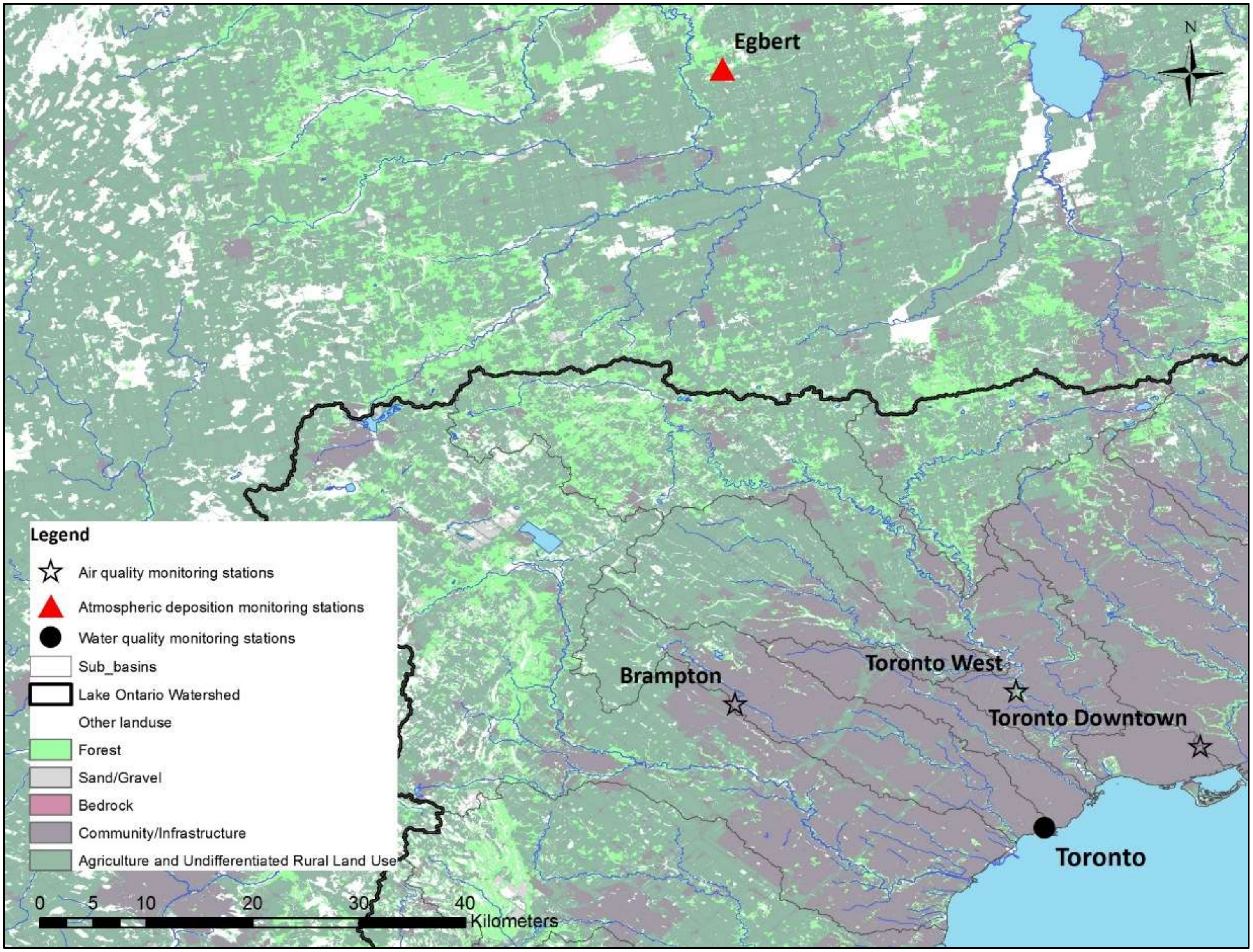


Fig 12. The land use map near the Toronto region

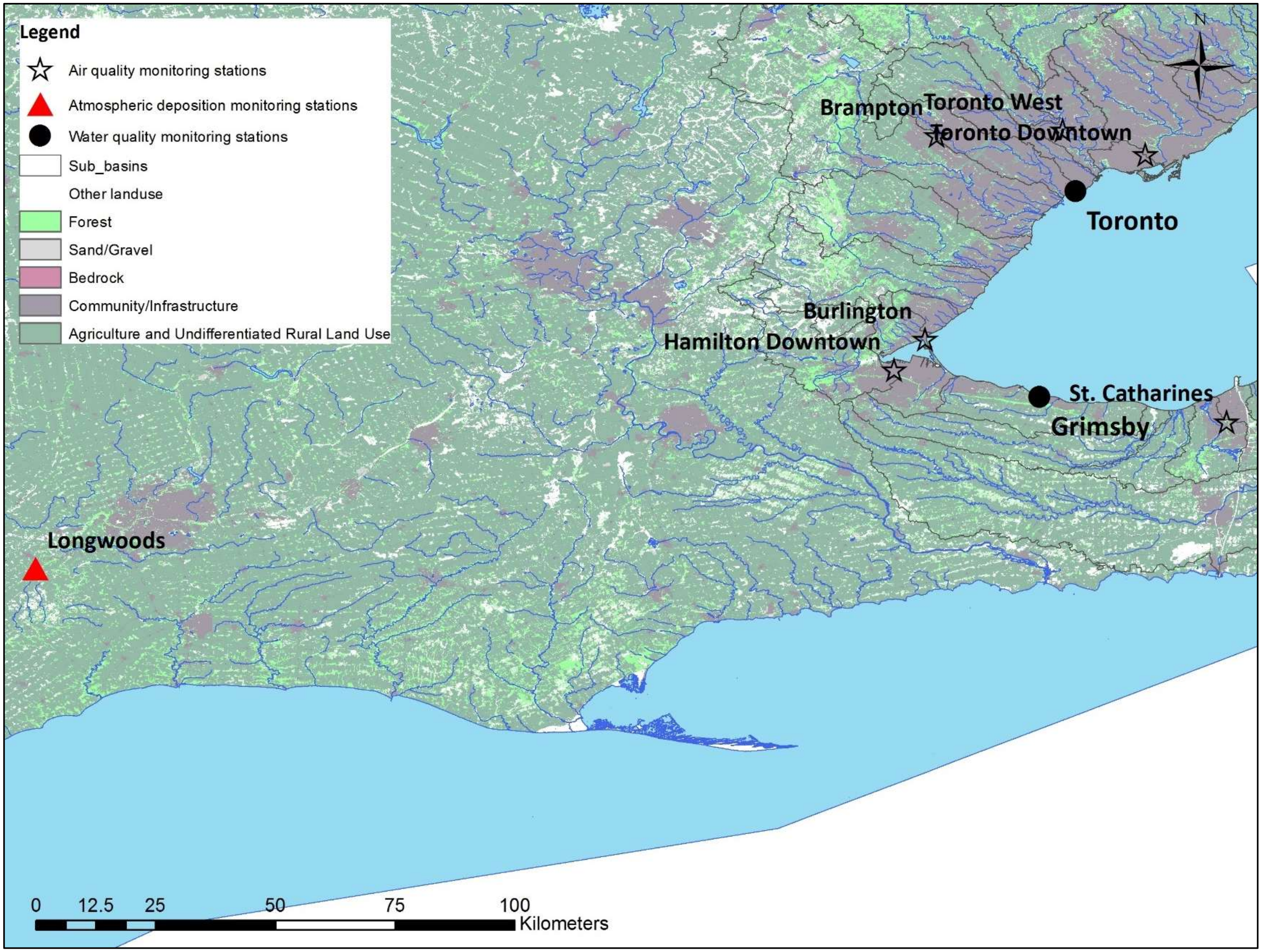


Fig 13. The land use map near the Grimsby region

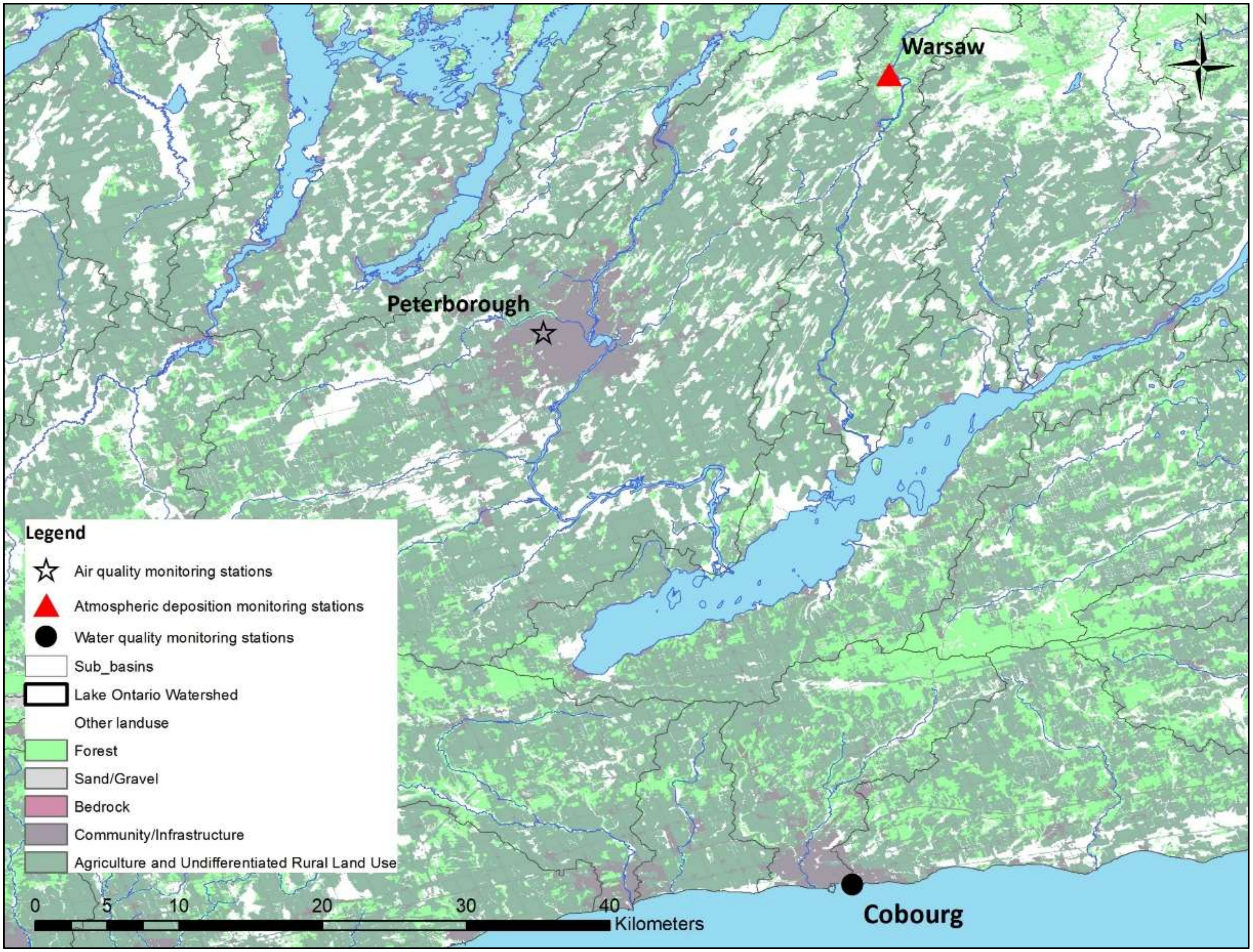


Fig 14. The land use map near the Cobourg region

3.5.Conclusion

In this chapter, some of the important specifications of the study area including water quality, atmospheric deposition, air quality, meteorological data, and the current land use were introduced and evaluated. Comparing three regions showed that Toronto has more air contamination and as a result, the atmospheric deposition contamination is higher than the other regions. Also, the water contamination of Lake Ontario in the Toronto region is higher than Cobourg and Grimsby.

In the next chapters, with respect to the modeling requirements, some of them will be used in the modeling processes.

4. Chapter 4: Modeling methodology

Physically based models have been used widely in water quality simulation. However, one of the challenges in developing a physically based model is the lack of enough data and the complication of all the involved processes. These are including physical processes such as wind speed and direction, evaporation, heating, cooling, mixing, stratification, settling, aeration, and atmospheric deposition quantity. Also, the biochemical processes such as oxidation, respiration, the decay of organics, anaerobic releases, atmospheric deposition quality, etc are another type of involved process. As a result, in many cases, modelers try to simplify the whole water quality procedure by making some assumptions and omitting some of the processes. Hence, the uncertainty of the modeling would be increased and the robustness of the model would be decreased. Regarding the complexity of the physically based modeling approach, using DDM method is an alternative.

4.1. Artificial neural networks principles

ANNs are developed based on the way in which the human brain functions. In this method, the network will be trained by the relationship between inputs and outputs. Data enters the network through the input layer. An ANN consists of nodes in different layers; input layer, intermediate hidden layer(s) and the output layer. The important variables that contribute to the determination of the output can be considered as inputs. The inputs also can be any combination of different parameters.

The feedforward neural network is one type of ANNs which the information moves only forward. Also, the layers are fully connected. It means that all input units are connected to all the units in the hidden units, and all the units in the hidden layer are connected to all the output units. Multi-

Layer Perceptron (MLP) is a type of feedforward network which has one or more hidden layers (Fig 15).

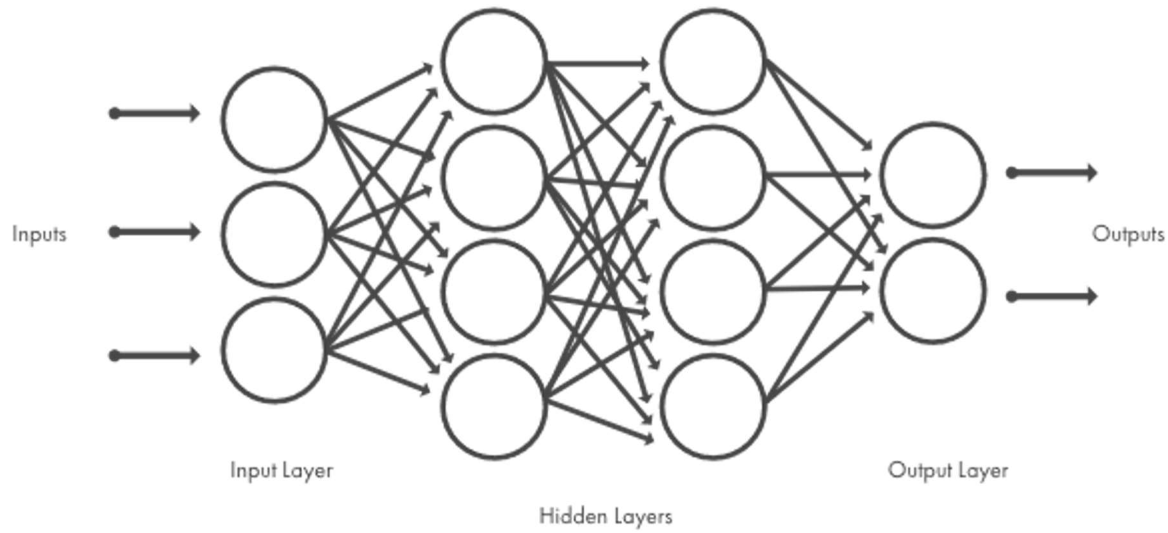


Fig 15. Typical feedforward MLP neural network architecture[1]

Basically, the hidden layers are the processing layers. The number of hidden layers, as well as the number of neurons in each, are important as they have direct impacts on the modeling performance. Usually, determining the best number of hidden units requires experimentation. Too few hidden units will prevent the network from being able to learn the required function. On the other hand, too many hidden units may cause the network to tend to overfit the training data, thus reducing generalization accuracy. Overfitting means the model fits the training data accurately, however, it loses its strength on new data. In fact, If the model isn't complex enough, it may not be powerful enough to capture all of the useful information necessary to solve a problem. However, if the model is very complex, the risk of overfitting is high.

[1] https://www.mathworks.com/discovery/neural-network.html

Generally, in a certain number of hidden units, the modeling process will work accurately while extra hidden units above that do not affect the performance of the model considerably. In the ANN structure, each connection between nodes has a weight. Also, another important item is bias. It is a special weight that feeds into every node at the hidden and output layer. In addition to the ANN structure, the transfer function is another important characteristic of an ANN. In the ANN, each node has an input, a transfer function, and an output. A transfer function can be a linear or a nonlinear function. The transfer functions usually have a sigmoid shape, but they may also take the form of other non-linear functions. One of the most commonly used functions is sigmoid. This function maps the input to a value between 0 and 1 (but not equal to 0 or 1). The sigmoid function curve looks like a S-shape. This means the output from the node will be a high signal (if the input is positive) or a low one (if the input is negative).

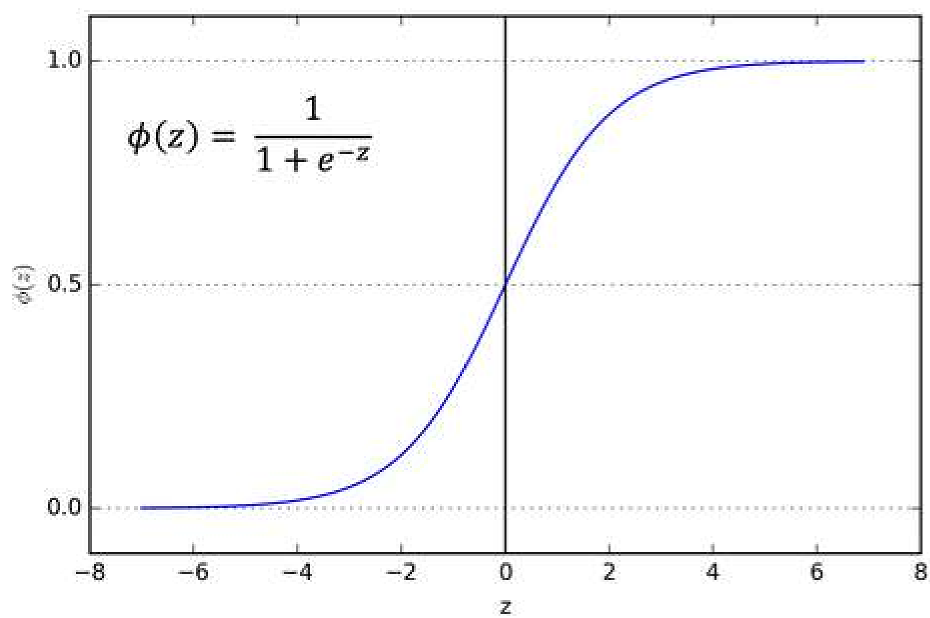


Fig 16. The sigmoid function[2]

[2] https://towardsdatascience.com/activation-functions-neural-networks-1cbd9f8d91d6

After the construction of an ANN, that network is ready to be trained. The training function is a training algorithm that can be applied to the set of input data patterns. In the training process, the ANN tries to develop the correct outputs for the given inputs in an iterative process. In this approach, the network will develop the first outputs based on the predefined amounts of weights and biases and the training function. In this mechanism, firstly, a certain input is multiplied by the weight. Second, the weighted input is added to the bias to form the net input and finally, the net input is passed through the training function, which produces the related output. It should be mentioned that there are many types of transfer functions including:

- Levenberg-Marquardt
- Bayesian Regularization
- Resilient Backpropagation
- Scaled Conjugate Gradient
- Conjugate Gradient with Powell/Beale Restarts
- Fletcher-Powell Conjugate Gradient

At the next step, the network tries to adjust the weight and bias to generate better output. By repeating the network training, the network will learn to produce a better answer. Technically, these answers are not just the right answer for the data that has been used to train the network. Training the network once on each try is called an epoch. Usually, a number of epochs are needed before the results converge. The algorithm of training the network is the backpropagation algorithm. In this method, the main idea is to use gradient descent to update the weights and biases based on their contribution to minimizing the squared error between the network outputs (which is called cost function) and the actual outputs. This process occurs iteratively for each layer of the network, starting with the last set of weights, and working back towards the input layer.

In order to determine whether the ANN has reached the best set of weights and biases in the training process, it is required to validate the performance of the model using a new set of data that has not been used for training. At the time of using the validation set, it is necessary to save the weights and biases of the network when the validation error is decreasing and once the validation errors begin going up, the best amounts of weights and biases are recognized for the best performance. Basically, in the modeling by ANNs, it is necessary to divide the dataset into three parts: training, validating and testing datasets. The training data set is the dataset that is used to train the model. The validation set is used to evaluate a given model, but this is for frequent evaluation. the model occasionally checks this data, but never use it to learn the network. In fact, the validation set in a way affects a model, but indirectly.

Test dataset is used to evaluate the model. It is only used once a model is completely trained (using the train and validation sets). Fig 17 shows a schematic of training, validating and testing datasets in ANNs. In this research, 70%, 15% and 15% of the data have been used for training, validating and testing the models respectively. Using less percentage of the data for training affected the performance of the modeling for the testing data series. On the other hand, using more percentage of the data for the training can cause overfitting which provides less generalized model.

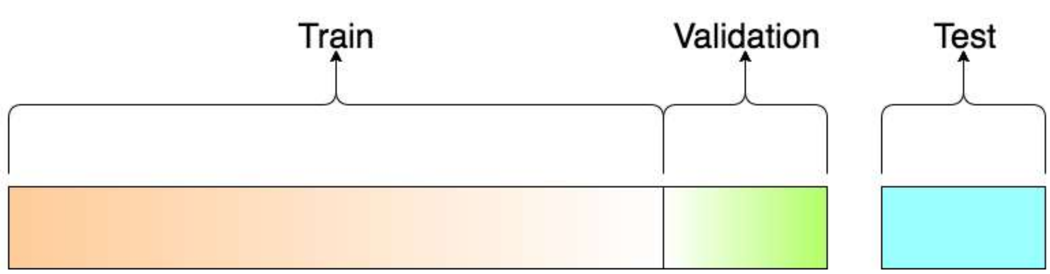


Fig 17. A visualization of training, validating and testing datasets in ANNs[3]

[3] https://towardsdatascience.com/train-validation-and-test-sets-72cb40cba9e7

4.2.The application of ANN in this research

With respect to the complicated natural processes (physical, chemical and biological) in water quality simulation processes (especially considering the air-water interactions), in this research, the ANN has been used for developing the models. This method showed a great ability to simulate the complex systems but never has been used to simulate the atmospheric deposition and climate change impacts on water quality.

In order to evaluate the impacts of climate change in water quality and atmospheric deposition, it is necessary to have separate models for each of them. Since this study is focusing on three different regions across Lake Ontario, three different water quality models (for Toronto, Cobourg, and Grimsby water quality monitoring stations) in Lake Ontario are needed. These models are focusing on the nitrogen compounds concentration in water which is nitrate and ammonium because the aim of this study is to evaluate the impacts of atmospheric deposition on the water quality focusing on the eutrophication of Lake Ontario. Nitrogen can be transferred from the atmosphere to the water bodies. As a result, it has been selected as the modeling parameter in this research. In addition to water quality models, it is inevitable to have the atmospheric deposition models for the 3 different regions (using the data of Warsaw, Egbert and Longwoods stations). By having these models, the future impacts of climate change on atmospheric deposition and water quality in the 3 different areas are available separately. Ultimately, the required models in this research are as below:

1) **<u>Toronto water quality model:</u>** the water quality model for Lake Ontario near the City of Toronto
2) **<u>Cobourg water quality model:</u>** the water quality model for Lake Ontario near the Town of Cobourg

3) **Grimsby water quality model:** the water quality model for Lake Ontario near the Town of Grimsby

4) **Toronto atmospheric deposition model:** The model of atmospheric deposition near the City of Toronto using Egbers atmospheric deposition station data

5) **Cobourg atmospheric deposition model:** The model of atmospheric deposition near the Town of Cobourg using Warsaw atmospheric deposition station data

6) **Grimsby atmospheric deposition model:** The model of atmospheric deposition near the Town of Grimsby using Longwoods atmospheric deposition station data

All of the mentioned models have been developed by similar codes in the MATLAB software (Appendix 2).

4.3. Modeling performance criteria

There are several methods to evaluate the modeling performance. However, in this research, two techniques have been used as follow:

1) R-value: this value is an indicator of the linear correlation between the modeling results (predicted values) and the observed values. It is a statistical technique that can show whether and how strongly they are related. It has a range from -1.0 to +1.0. The closer R-value to +1.0 or -1.0, the more correlation between two variables and as a result the better performance of the model. The formula for calculating the R-value is:

$$R = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}} \qquad Eq.1$$

where x and y are representing the predicted and observed outputs and the n is the number of predicted values.

2) Root mean square error (RMSE): this parameter measures the average magnitude of the error. It is the square root of the mean of squared differences between predicted and observed outputs. the formula is:

$$RMSE = \sqrt{\frac{1}{n}\sum(x-y)^2} \qquad Eq.2$$

where x, y and n are the same as $Eq.1$.

4.4.Models inputs selection

The selection of input variables of a neural network is a very important step for developing a robust model. Even though the model is just based on the mathematical relationship between inputs and outputs, it is important to know which inputs have an impact on the output in reality. With respect to the objectives of this research, in order to develop a model for predicting the concentration of nitrate and ammonium in the precipitation and water, the important air quality parameters would be NO and NO_2. It should be mentioned that the importance of the other air quality parameters including Ozone, PM2.5, and PM10 have been evaluated by using them as extra inputs to the model. Therefore, these parameters have been omitted from the inputs since the did not show any impacts on the performance of the models.

As mentioned in Chapter 3, air quality monitoring results are available between 2000 to 2012. Although the other variables including the meteorological, atmospheric deposition and water quality monitoring data are available in a longer period, the models are created based on the data between 2000 to 2012.

In terms of the meteorological data, while the most important impacts of climate change are on the air temperature and total precipitation, these two meteorological parameters have been selected as other inputs of the neural network models. As a result, the input variable of all the neural network models would be:

- Air quality including NO and NO_2
- Air temperature
- Total precipitation

Table 5 shows the inputs and output of different neural network models.

Table 5. The inputs and output of the neural network models

Neural network model	Output	inputs
Toronto water quality model	Water quality in Toronto station	1) NO, and NO_2 concentrations in Brampton, Toronto west and Toronto Downtown air quality stations
Toronto atmospheric deposition model	Atmospheric deposition in Egbert station	2) Air temperature and total precipitation in Toronto Lester b. Pearson international airport meteorological stations
Cobourg water quality model	Water quality in Cobourg station	1) NO, and NO_2 concentrations in Peterborough air quality stations
Cobourg atmospheric deposition model	Atmospheric deposition in Warsaw station	2) Air temperature and total precipitation in Cobourg stp and Peterborough-a meteorological stations
Grimsby water quality model	Water quality in Grimsby station	1) NO, and NO_2 concentrations in St. Catherine, Hamilton Downtown and Burlington air quality stations
Grimsby atmospheric deposition model	Atmospheric deposition in Longwoods station	2) Air temperature and total precipitation in Grimsby mountain and Burlington piers (aut) meteorological stations

In addition to the type of input variables, it is important to use them in an appropriate form. For example, either the raw data or the logarithm can be used as input to the neural network. Also, the temporal basis of the modeling should be determined. For instance, the models can be created based on daily information or even weekly, monthly, seasonally or annually basis.

Regarding this issue, in order to determine the best input time and form combination, a number of different combinations were evaluated in one of the models (Cobourg atmospheric deposition model) to see which one is showing the better performance of modeling as below:

1) The data of inputs and output on the same day
2) The data of 1 day before the output day
3) The average of 3 days before the output day (excluding the output day)
4) The average of 3 days before the output day (including the output day)
5) The average of 7 days before the output day (excluding the output day)
6) The average of 7 days before the output day (including the output day)
7) The Log of the average of 3 days before the output day (excluding the output day)
8) The average of 3 days before the output day (excluding the output day) to the power of 2
9) The average of 3 days before the output day (excluding the output day) to the power of 3
10) Applying all the options 1 to 9 for the concentration of NO_3^- larger than 1 mg/L in atmospheric deposition
11) Applying all the options 1 to 9 for the concentration of NO_3^- larger than 3 mg/L in atmospheric deposition

None of the daily basis combinations of the inputs showed an acceptable result. The R-values for these models were around 0.5 in the best cases (Fig 18 is an example of applying option 1 in the above list as inputs in the Cobourg station).

Therefore, the same procedure was applied for monthly basis data. In the step, the average air pollution, an average of air temperature and the total amount of precipitation has been applied as inputs. The performance of the modeling became better than the daily basis results (R-values were around 0.65 in the best cases) but still not acceptable. Consequently, developing the models on a seasonal basis has been considered at the next step. Even though in some cases the results of the modeling predictions were not quite high, the average of the model's performances was much better than daily and monthly models and thus, the seasonal basis of the inputs has been selected for all the models of atmospheric deposition and water quality. As specified earlier, the time period of modeling is between 2000 to 2012 (13 years) and as a result, by considering the seasonal basis, there are 52 data points for inputs and outputs. The raw data series of inputs and outputs of models are available in appendix 1.

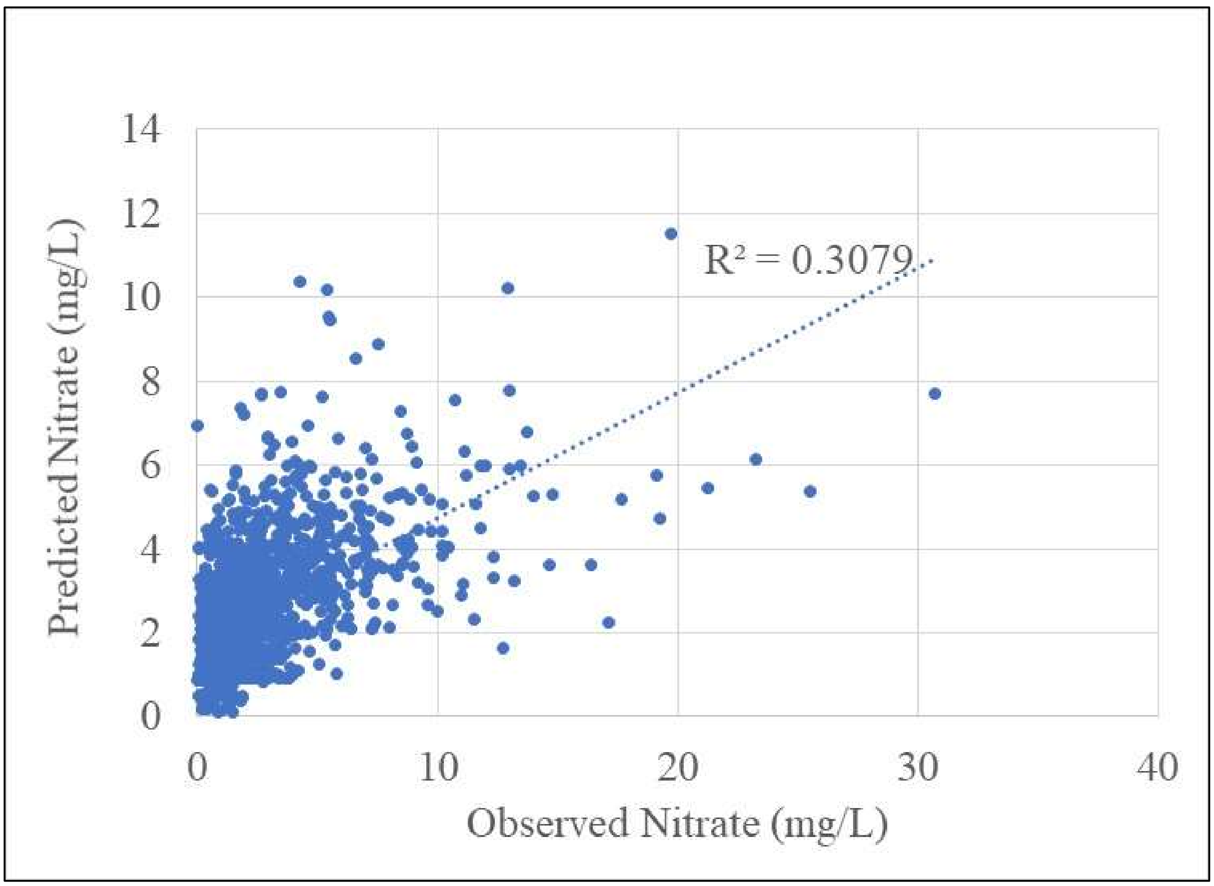


Fig 18. The predicted versus observed concentration of NO_3^- in precipitation using the daily basis neural network model in Cobourg Station

4.5.Models architecture

The objective of this section is to combine all neural networks building blocks in the best way to obtain the highest performance. As specified in previous sections, apart from the input and output layers, the neural network has the hidden layer(s) consisting of units that transform the information from the input to the output. Therefore, choosing architectures of the hidden layer which consists of the number of them as well as the number of neurons in each hidden layer is an important part of developing a neural network model. The neural network should be large enough to approximate the function of interest, but not too large that it takes a long time to train. In this research, different combinations of hidden layers number, as well as the number of neurons in them, have been examined by comparing the performance of the modeling. The different options were:

- 1 hidden layer with 4, 8 and 16 neurons
- 2 hidden layers with 4, 8 and 16 neurons in each
- 3 hidden layers with 4, 8 and 16 neurons in each

The comparisons of the models showed that by increasing the numbers of hidden layers from 1 to 2 and the number of neurons from 4 to 8 in each layer, higher performance (R-value>0.8) can be reached. However, more numbers of hidden layers and the number of neurons did not change the results anymore. Hence, for all the models, 2 hidden layers containing 8 neurons in each have been selected as their final architecture.

4.6.Future scenarios

The future scenarios are mostly focused on climate change impacts. As discussed in Chapter 2, climate change mostly is happening via changes in air temperature and precipitation trends. In this research, for collecting, the climate change data, the predictions of the Ontario Climate Change Data Portal (Ontario CCDP) have been used[4] (Wang et al. 2013).

Ontario CCDP has established the high resolution (25 km x 25 km) climate projections developed at the University of Regina. There are different scenarios of emissions including RCP4.5, RCP8.5, and SRES A1B which can lead to different results. While in this research the target is just to examine the possible impacts of climate change on atmospheric deposition and water quality, only one of the emission scenarios (RCP8.5) has been selected. Comparing the results of the other emission scenarios with RCP8.5 can be considered as the future opportunities for extending this research. Therefore, the downscaled climate projections (with a resolution of 25 km) under RCP8.5 emissions and using the second generation Canadian Earth System Model (CanESM2) has been used. Further information about the models and the emission scenarios can be obtained on the related website.

Nevertheless, by using the available downscaled prediction of the air temperature and precipitation amounts, the seasonal data of these parameters in the period of 2030 to 2099 has been collected to implement as the new inputs of the models for future predictions of water quality and atmospheric deposition.

4.7.Sensitivity analysis

In addition to meteorological data (air temperature and precipitation amounts), the other two inputs of the models (NO and NO_2) which are related to air quality has their importance and should be determined for future scenarios. As mentioned before, the baseline modeling is according to data between 2000 to 2012. In order to examine the sensitivity of the models to the air quality and also

[4] http://www.ontarioccdp.ca.

have an insight about what is going on if the air quality changes, some air quality conditions as below have been considered in future climate change scenarios:

- Keeping the current concentrations of NO and NO_2
- 50% increase in the concentrations of NO and NO_2
- 100% increase in the concentrations of NO and NO_2
- 50% decrease in the concentrations of NO and NO_2

The previous trend in the air quality of three regions (Fig 6 and Fig 7) shows that the air contamination had considerable changes (more than 50% of its concentration). As a result, selecting the introduced scenarios for air contamination sensitivity analysis is reasonable. In order to create the inputs of the models for the sensitivity analysis, by using the current mean and standard deviation of NO and NO_2 data series, two new random data series with same mean and standard deviation for NO and NO_2 have been developed using the MATLAB software. Each data series has 280 data (seasonal data for 70 years) which is another input (in addition to meteorological data) of the models.

5. Chapter 5: Results and discussion

In this chapter, the results of the modeling of atmospheric deposition and water quality of Lake Ontario are presented. Also, the temporal and spatial trends are evaluated. Since there are 3 different regions of study (Toronto, Cobourg, and Grimsby), and in each region, there are separate models for atmospheric deposition and water quality, the results are categorized in a similar approach. Following the results, the discussion about the possible reasons for the predicted trends and variations will be presented in each section.

As mentioned in Section 4.4 and Table 5, the models can reach higher performances by selecting the appropriate input variables. In some cases of modeling runs, the performance of modeling was not quite high. Therefore, in order to accomplish the investigations based on robust models, a number of high efficiency models which is an ensemble of 100 models with the R-value greater than 0.8 for each training, validating and testing dataset have been selected and then the future scenarios were examined using these models. It should be mentioned that all the R-values were positive values and as a result the negative R-values have not been considered. The main reasons for selecting 100 runs for each model were to have a range of future predictions rather than just relying on one output. It should be mentioned that there is a possibility to have some identical results between these 100 runs which can be considered as one of the weaknesses of this research.

5.1.Modeling results in Toronto region

Fig 19 and Fig 20 show the variation of annual mean temperature and total precipitation between 2000 to 2012 (baseline period) and future period (2030 to 2099) in the Toronto region. In addition to annual variations, the seasonal amounts of total precipitation have been shown in Fig 21. The temperature has a clear increasing trend due to climate change while precipitation did not show a considerable increasing or decreasing trend. The important fact about the precipitation is its low value in summer. Also, winter and fall will have more precipitation comparing to the baseline.

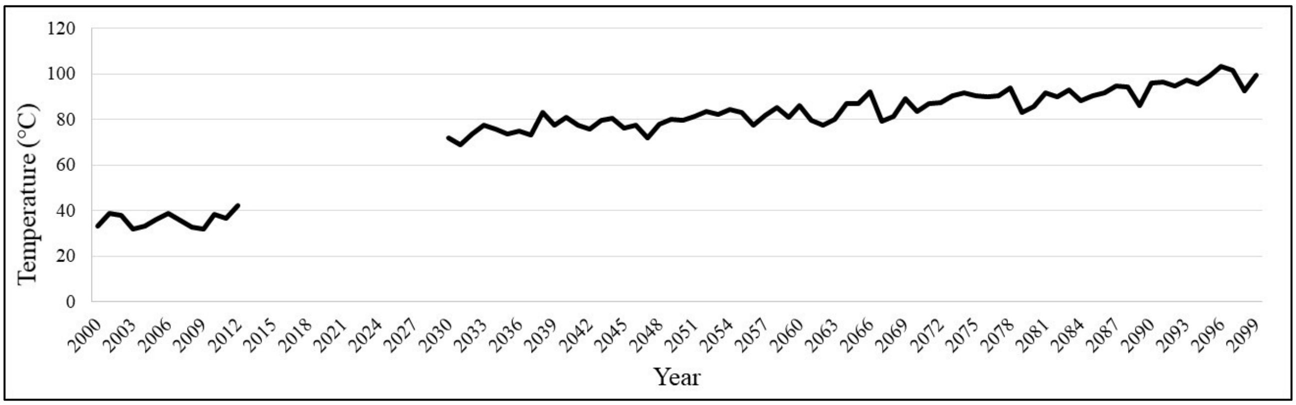


Fig 19. Annual mean temperature during the baseline (2000-2012) and future time (2030-2099) period in Toronto region

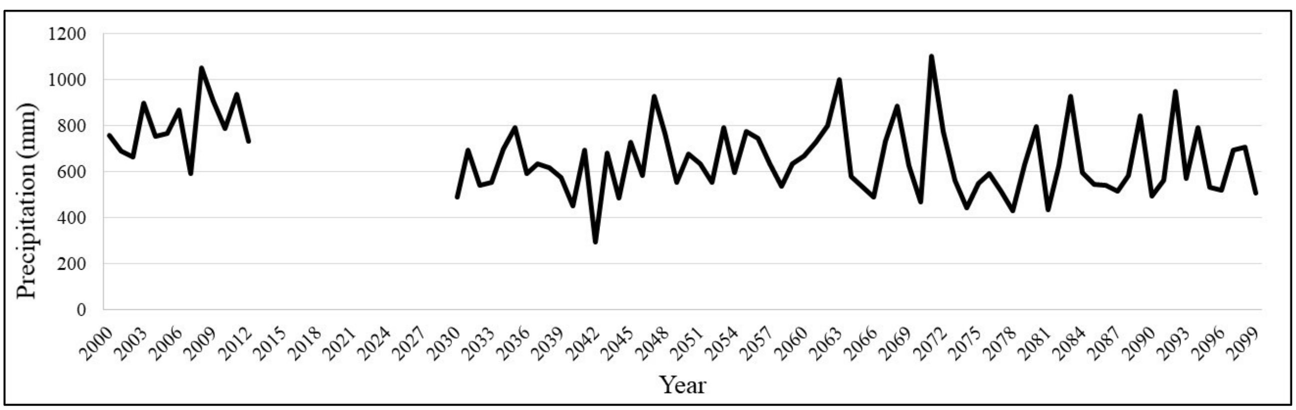


Fig 20. Annual total precipitation during the baseline (2000-2012) and future time (2030-2099) period in Toronto region

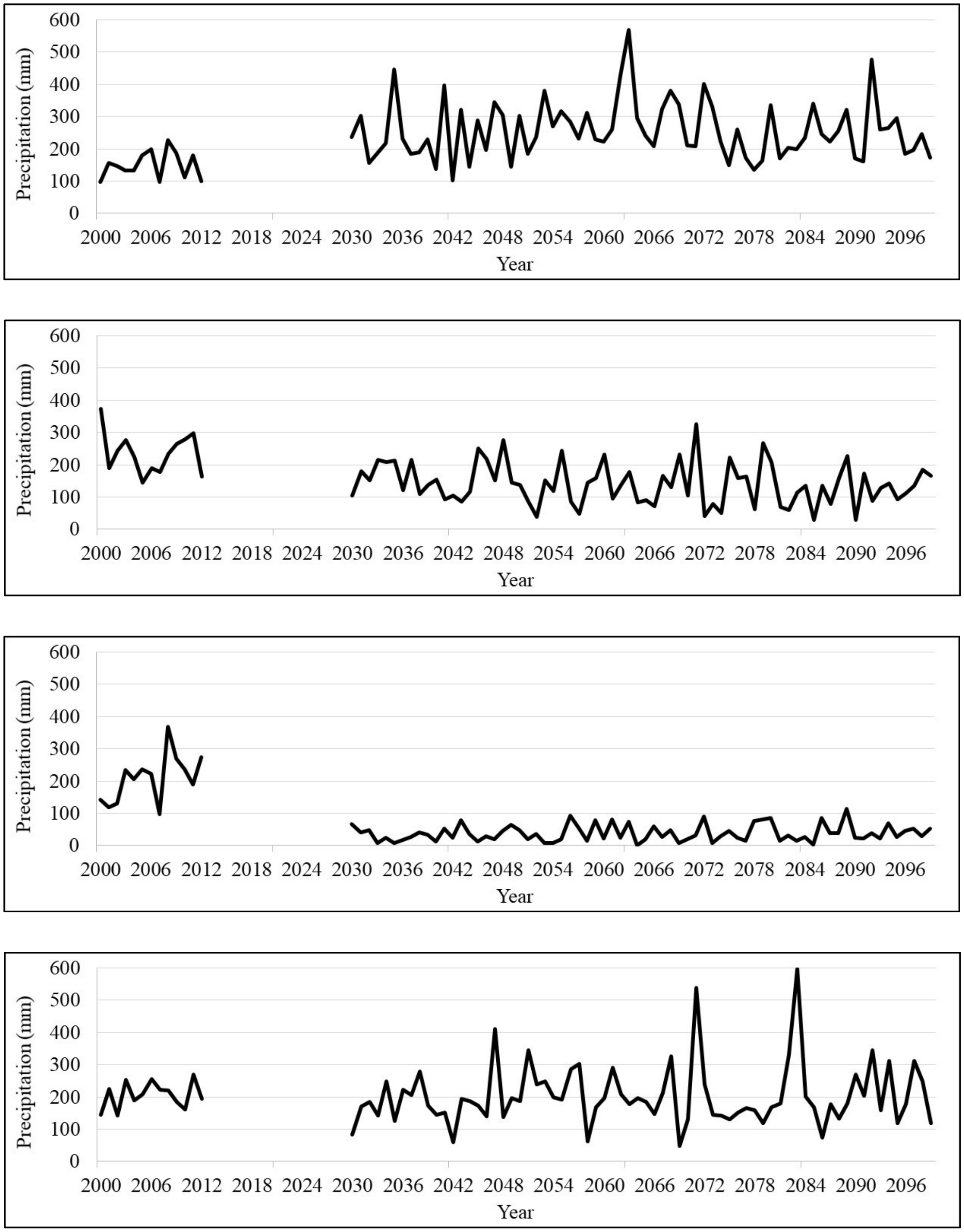


Fig 21. Seasonal total precipitation during the baseline and future time period in Toronto region a) Winter b) Spring c) Summer d) Fall

5.1.1. Atmospheric deposition modeling in Toronto region

In order to extract 100 high performance models for atmospheric deposition in Toronto region, 21533 trials were executed. Fig 22 and Fig 23 show the performances of the 100 models in terms of R-value and RMSE. As it can be seen in these figures, the R-value is always greater than 0.8 for training, validating and testing datasets. Also, the values of RMSE are between 0.2 and 0.4 mg/L.

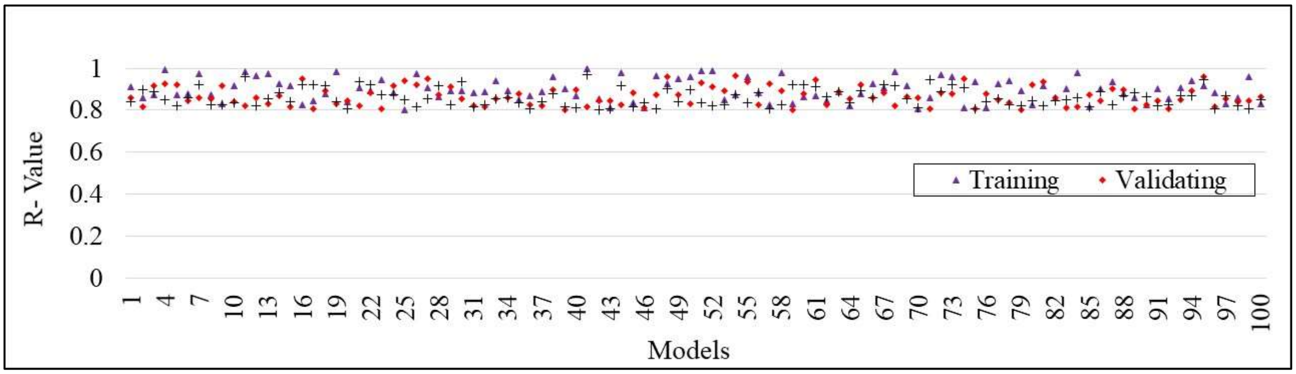


Fig 22. R-value of 100 atmospheric deposition models of Toronto region

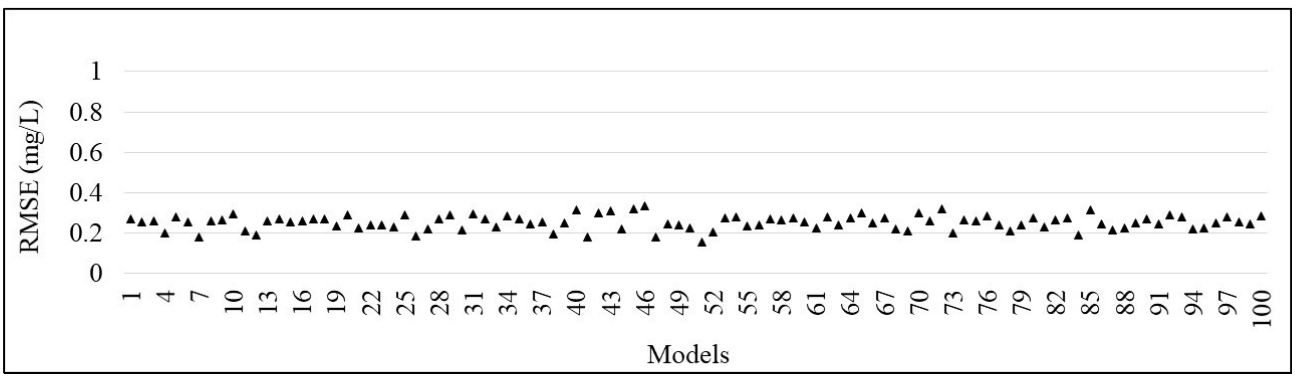


Fig 23. RMSE of 100 atmospheric deposition models of Toronto region

5.1.1.1 Climate change impacts on atmospheric deposition in Toronto region

In terms of the results of the modeling under future scenarios, Fig 24 is representing the future predictions of the atmospheric deposition of Nitrate-N + Ammonium-N. These results have been shown by two different values: 50% range and the average of the predicted data. In addition, this figure includes the current average concentration of Nitrate-N + Ammonium-N for the period of 2000 to 2012 (the baseline). Based on the predictions for the future situation, in 64% of the cases, the concentration of Nitrate-N + Ammonium-N in precipitation will be higher than the baseline average concentration (the average concentration in the future will be 5% higher than baseline average). In addition, the average amounts in different time periods have been shown in **Error! Reference source not found.**Table 6. It shows that in most the time increments the concentration is higher than the baseline. The main reason for increasing the contamination in atmospheric deposition is lower precipitation and as a result lower dilution process in the future.

Table 6. The average of Nitrate-N + Ammonium-N concentration in atmospheric deposition near Toronto region in different time periods

	Time period	**Average of Nitrate-N + Ammonium-N (mg/L)**
Baseline	2000-2012	1.446
	2030-2039	1.529
	2040-2049	1.549
	2050-2059	1.443
Future scenario	2060-2069	1.507
	2070-2079	1.517
	2080-2089	1.521
	2090-2099	1.493

However, the impacts of climate change can be quite different regarding different seasons. For example, in summer higher temperature and lower precipitation are expected, and in winter, the value of precipitation would be higher considerably. Thus, the data of Fig 24, has been categorized based on different seasons adding the current trend of concentrations (between 2000 to 2012) in Fig 25.

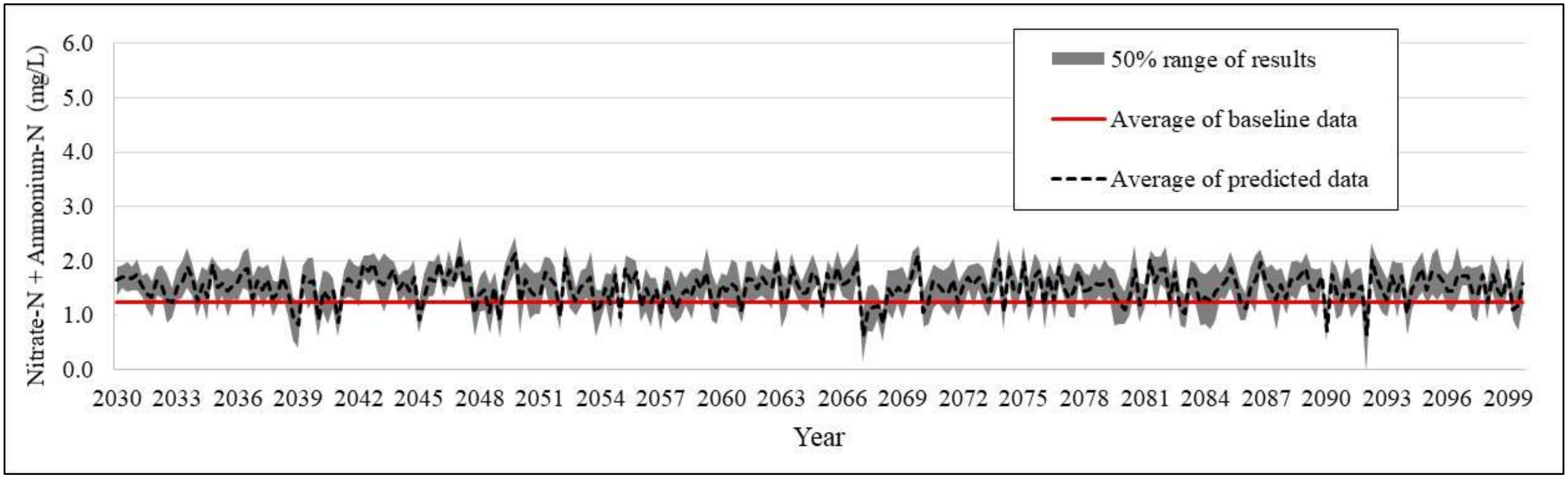
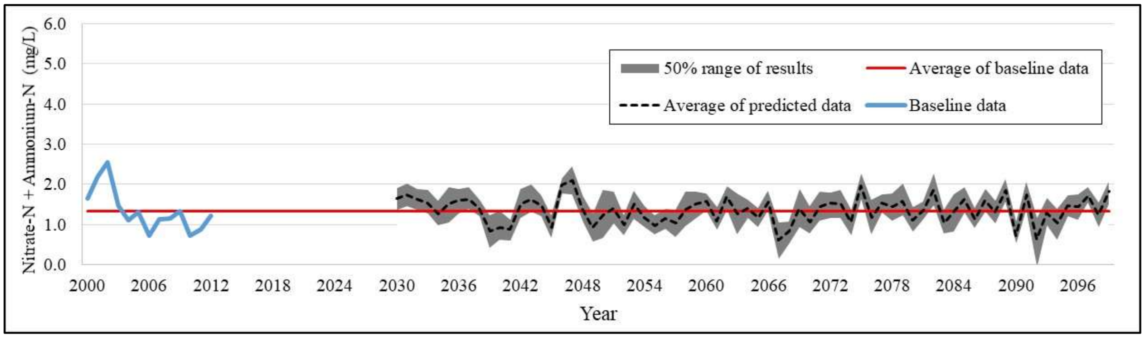
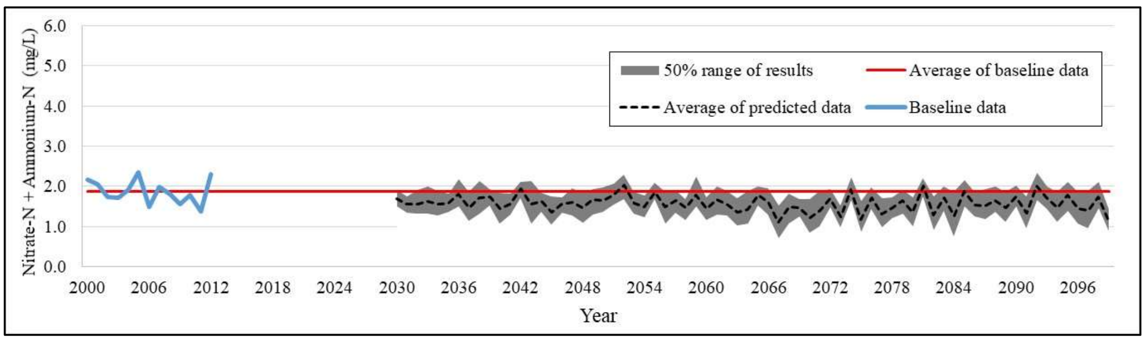


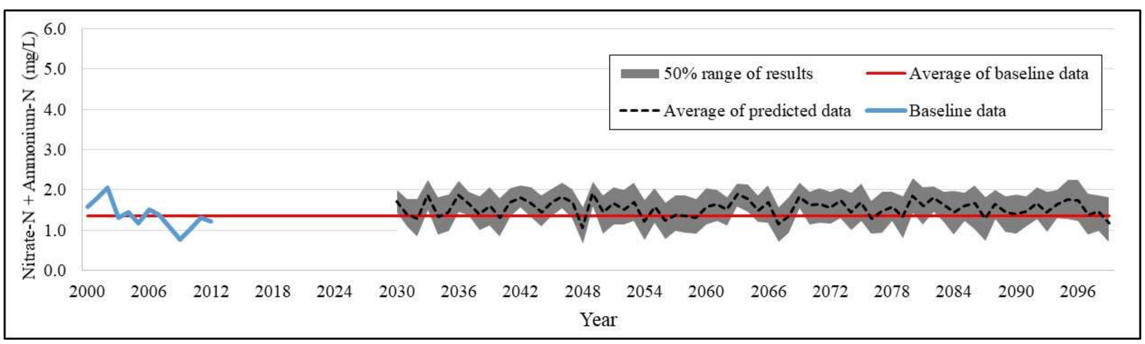
Fig 24. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition near Toronto region under the future scenario of climate change



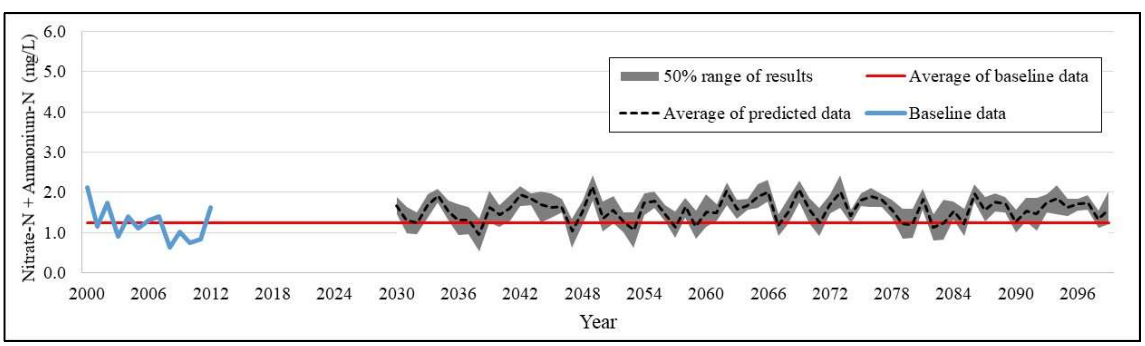
a)



b)



c)



d)

Fig 25. The concentration of Nitrate-N + Ammonium-N (mg/L) in atmospheric deposition near Toronto region under future scenario of climate change for different seasons a) Winter b) Spring c) Summer d) Fall

These results show that in winter, summer, and fall the concentration of the pollutant will be higher than the baseline situation (in 57%, 80% and 86% of the cases respectively). The pollutant concentration in spring in 91% of the cases will be lower than the current average concentration. It seems that the precipitation of late winter and spring has the strength to dilute the air contamination and as a result, the atmospheric deposition contamination in spring and partly in winter is not increased compared to the present level.

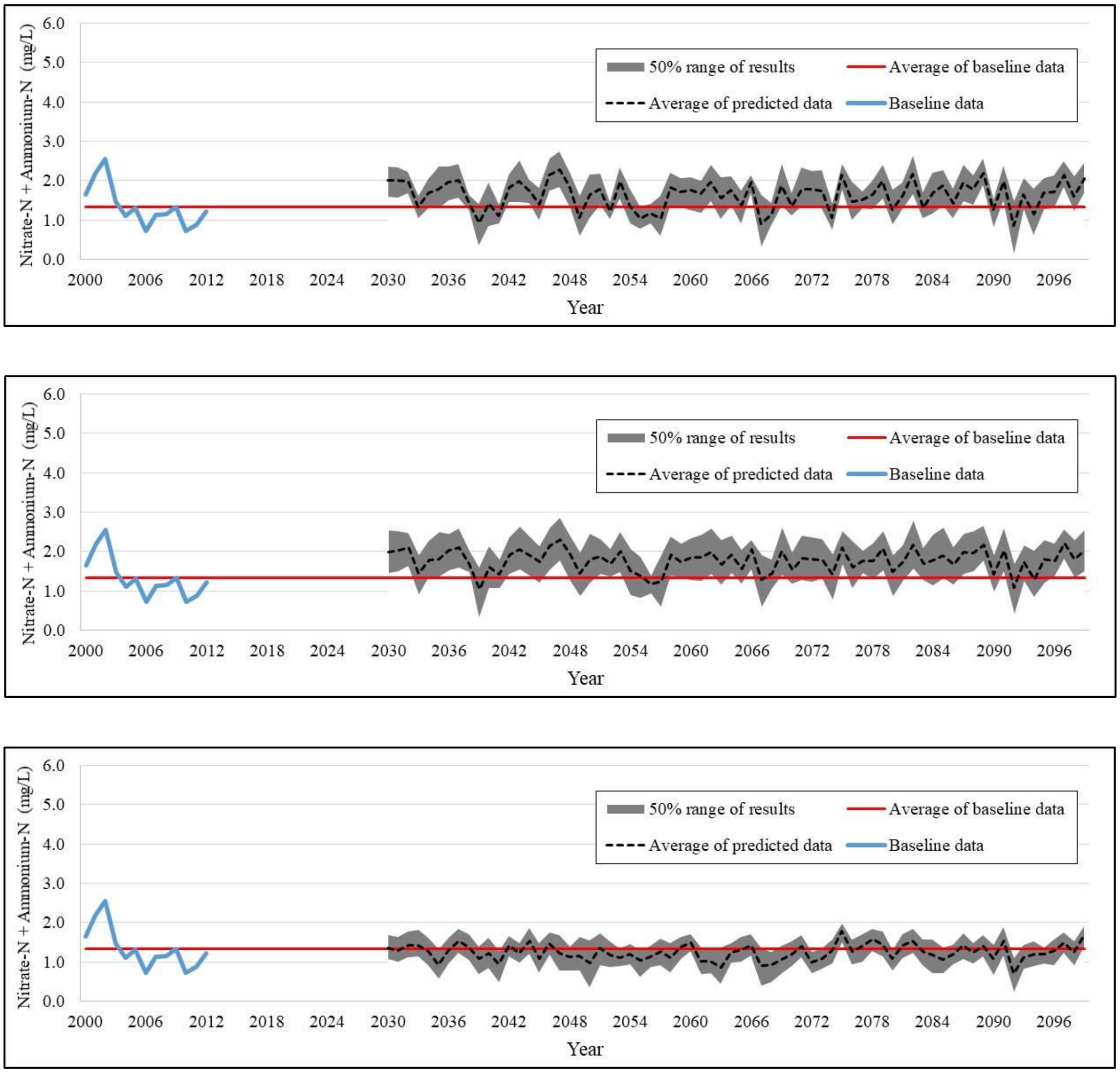
5.1.1.2 Sensitivity analysis of air pollution under climate change situation on atmospheric deposition in Toronto region

As mentioned in section 4.7, in order to evaluate the impacts of the air quality on the modeling results, different scenarios of increasing or decreasing the air quality concentrations (regarding NO and NO_2) were applied under climate change data. The different scenarios of changing air quality are:

- 50% increase in NO and NO_2 concentrations in air
- 100% increase in NO and NO_2 concentrations in air
- 50% decrease in NO and NO_2 concentrations in air

In this section, the sensitivity analysis is presented based on different seasons. Fig 26 to Fig 29 show the concentration of Nitrate-N + Ammonium-N in the precipitation in winter, spring, summer, and fall under different scenarios of air pollution.

The results presented in Fig 26 demonstrated that by increasing the air pollution by 50% and 100% (comparing to baseline concentrations), the concentration of pollutants in precipitation in 77% and 93% of the cases in winter will be higher than the current average concentration. However, in the scenario of 50% reduction of air pollution, 66% of the future predictions of precipitation contamination will be lower than the baseline. Therefore, it is quite obvious that without controlling the air pollutants, the atmospheric deposition may experience higher pollution in future winters.



a)

b)

c)

Fig 26. The concentration of Nitrate-N + Ammonium-N (mg/L) in atmospheric deposition near Toronto region in winter for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

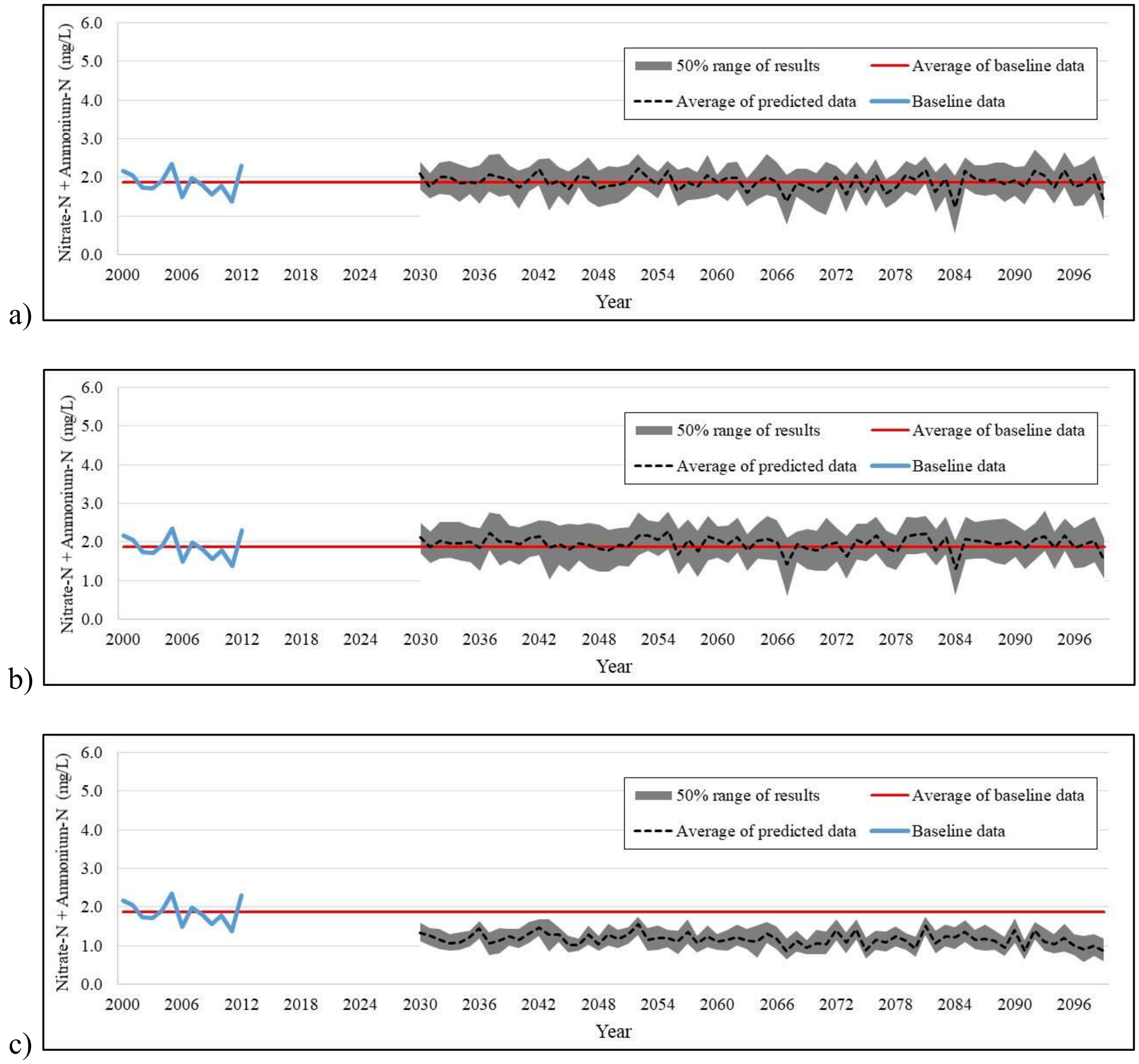
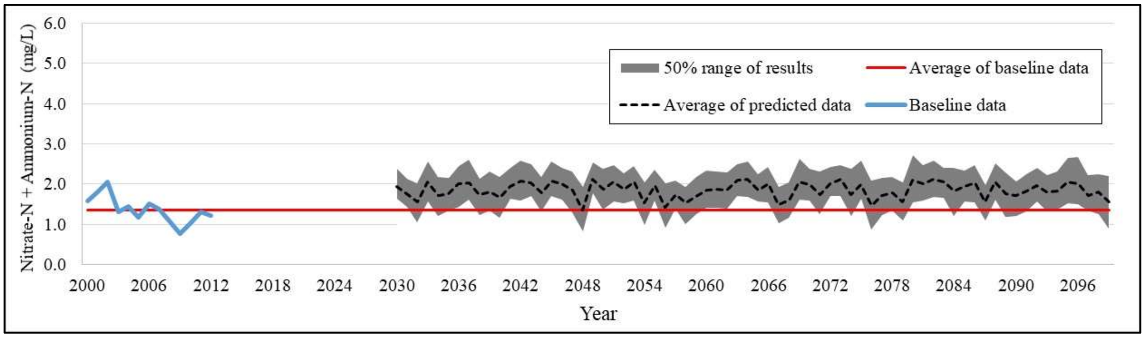
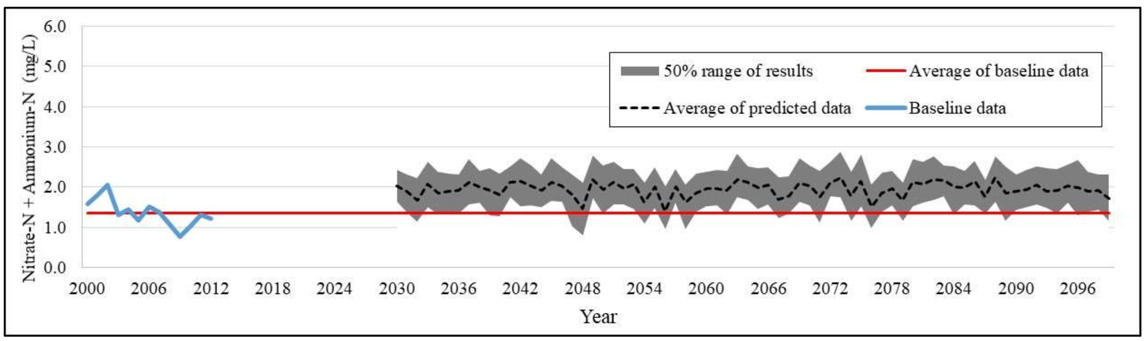


Fig 27. The concentration of Nitrate-N + Ammonium-N (mg/L) in atmospheric deposition near Toronto region in spring for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

Fig 27 shows that by increasing the air pollution by 50% in spring, in 56% of the cases in spring, the concentration of Nitrate-N + Ammonium-N would be higher than the current average concentration. Also, after a 100% increase in air contamination, the concentration will be higher and in 71% of the cases in spring, the contamination of precipitation will be greater than the current average concentration. It should be mentioned that in the scenario of 50% reduction of air pollution, all of the future predictions of precipitation contamination in spring will be lower than the baseline average.



a)



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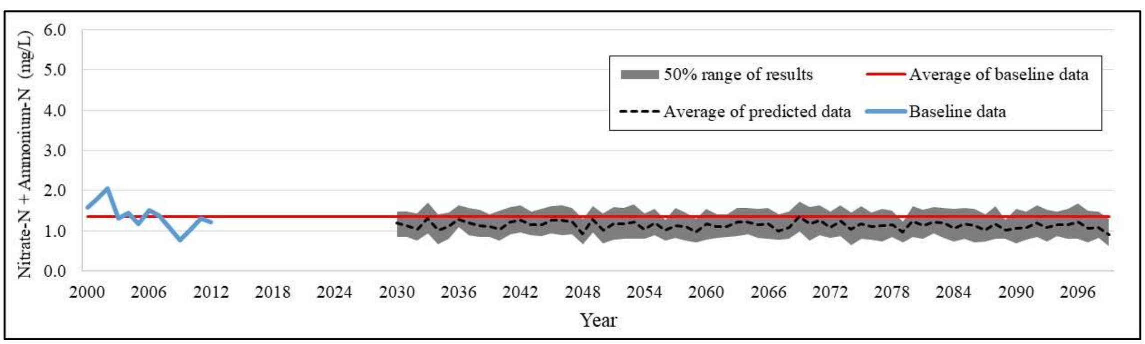


c)

Fig 28. The concentration of Nitrate-N + Ammonium-N (mg/L) in atmospheric deposition near Toronto region in summer for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

Focusing on the results of sensitivity analysis in summer (Fig 28) reveals that in the scenarios of increasing the air contamination, all of the cases in the future will experience a higher level of pollution in precipitation. However, an important finding is the result of a 50% decrease in air pollution which shows that in this situation 100% of the future predictions in summer will be lower than the current average concentration.

The results of atmospheric deposition in fall (Fig 29) show that increasing air contamination has a direct impact on precipitation chemistry. By increasing the concentration of the pollutants in the air by 50% and 100%, the atmospheric deposition in 93% and 99% of the cases will be higher than the current average concentration. Also, even by decreasing the air contamination by 50%, in 73% of the cases, the atmospheric deposition contamination in the fall will be higher than the current concentration. It is mostly because of the remained impacts of the summer that continues to fall.

Error! Reference source not found. shows a summary of the sensitivity analysis of air pollution impacts in different seasons. As it can be seen in this table, by increasing the air contamination, in all cases the pollution of atmospheric deposition will be higher than the current situation. While, by controlling the concentration of pollutants in air or reduction of them, the precipitation contamination in most cases would be lower than the baseline average concentration.

5.1.1. Water quality modeling in Lake Ontario in Toronto region

In this modeling phenomena, in order to extract 100 high performance models, 47704 trials were executed. Fig 30 and Fig 31 show the performances of the 100 models in terms of R-value and RMSE.

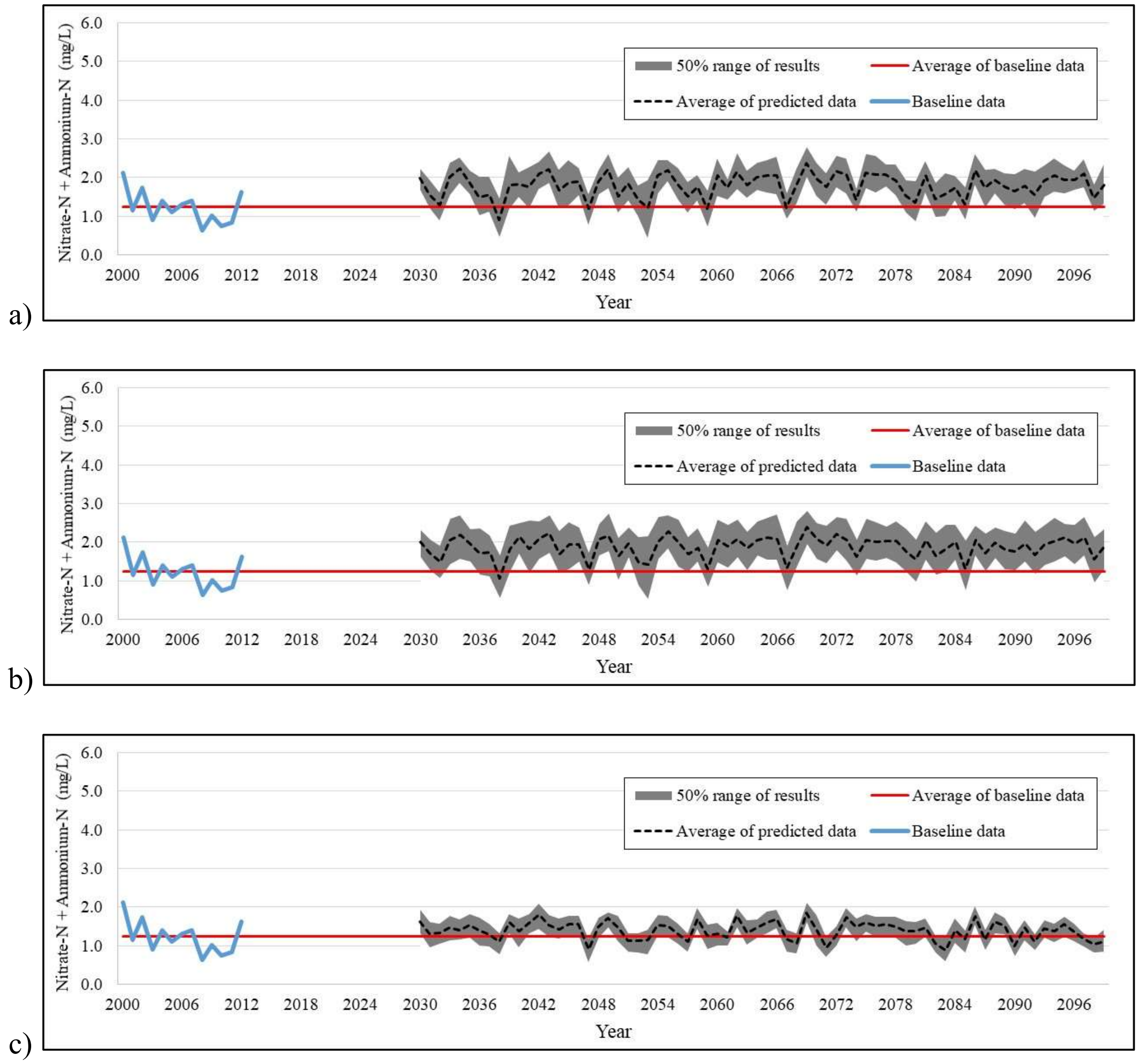


Fig 29. The concentration of Nitrate-N + Ammonium-N (mg/L) in atmospheric deposition near Toronto region in fall for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

5.1.1.1. Climate change impacts on water quality of Lake Ontario in Toronto region

Fig 32 shows the future predictions of Nitrate-N + Ammonium-N in Lake Ontario in Toronto region considering the 50% range of the predicted data and average of them. In addition, this figure also has the current average concentration of Nitrate-N + Ammonium-N for the period of 2000 to 2012 (the baseline).

Table 7. Changes in the concentration of Nitrate-N + Ammonium-N (mg/L) in atmospheric deposition in Toronto region under different air pollution scenarios in the future

	Changes in air pollution		
	50% increase	100% increase	50% decrease
Winter	Higher in 77% of the cases	Higher in 93% of the cases	Lower in 66% of the cases
Spring	Higher in 56% of the cases	Higher in 71% of the cases	Lower in 100% of the cases
Summer	Higher in 100% of the cases	Higher in 100% of the cases	Lower in 100% of the cases
Fall	Higher in 93% of the cases	Higher in 99% of the cases	Higher in 73% of the cases

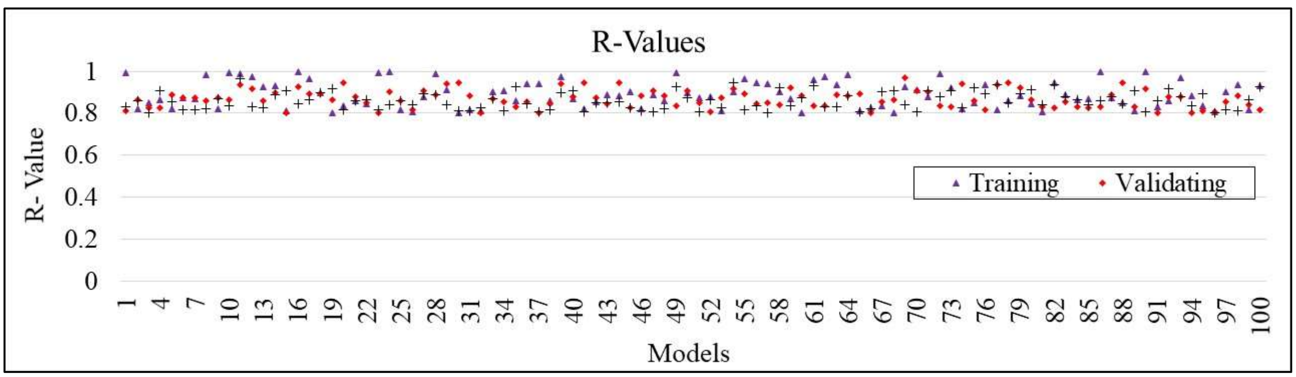


Fig 30. R-value of 100 water quality models of Lake Ontario in Toronto region

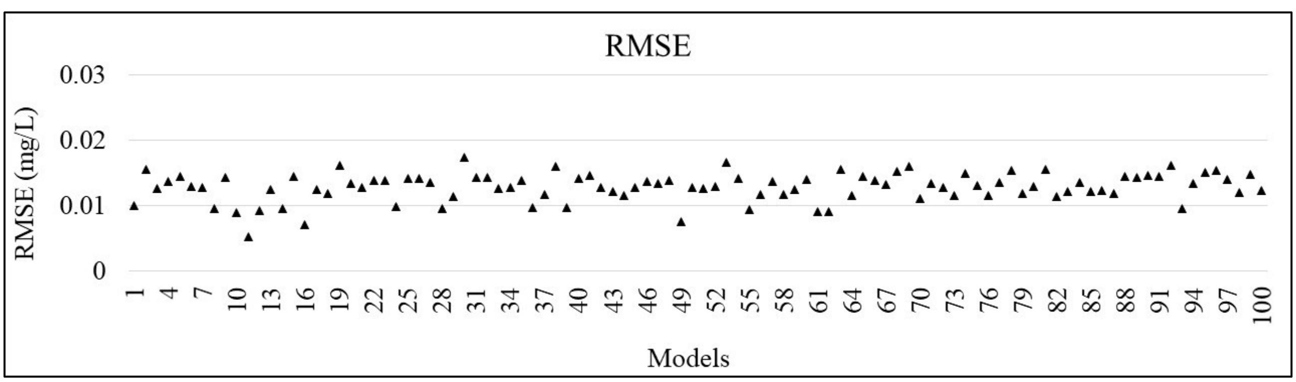


Fig 31. RMSE of 100 water quality models of Lake Ontario in Toronto region

Based on the predictions for the future situation, in 70% of the cases, the concentration will be lower than the baseline average concentration (the average concentration would be 15% lower). In addition, the average of Nitrate-N + Ammonium-N concentration in Lake Ontario in different time periods has been shown inTable 8. It shows that in all the time periods the concentration would be lower than the baseline. The reason is the air contamination does not have the strength to influence the water quality of Lake Ontario.

Table 8. The average of Nitrate-N + Ammonium-N (mg/L) concentration in Lake Ontario in Toronto region in different time periods

	Time period	Average of Nitrate-N + Ammonium-N (mg/L)
Baseline	2000-2012	0.137
	2030-2039	0.121
	2040-2049	0.118
	2050-2059	0.114
Future scenario	2060-2069	0.118
	2070-2079	0.117
	2080-2089	0.114
	2090-2099	0.113

In terms of seasonal analysis (Fig 33), the modeling results showed that in spring and summer, the future concentration of Nitrate-N + Ammonium-N will be lower than the baseline average concentration although in fall and winter the situation has the possibility to become undesirable. Based on the predictions, in winter and fall, in 50% of the cases, the concentration of Nitrate-N + Ammonium-N will be lower than the baseline average.

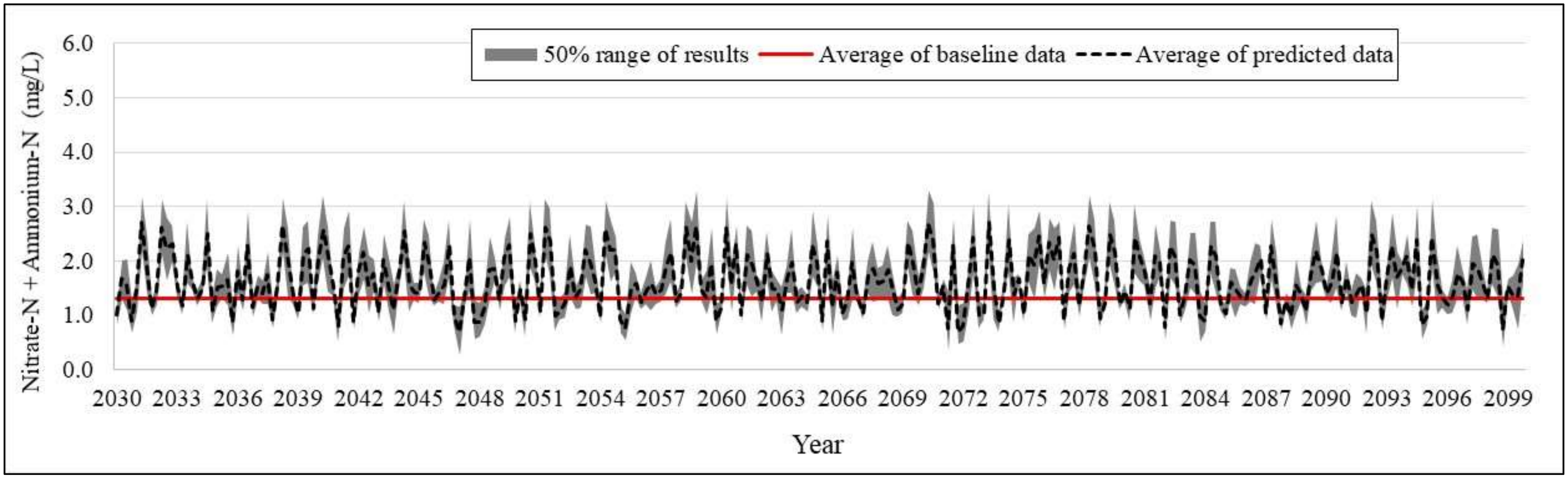


Fig 32. The concentration of Nitrate-N + Ammonium-N (mg/L) in Lake Ontario in Toronto region under the future scenario of climate change

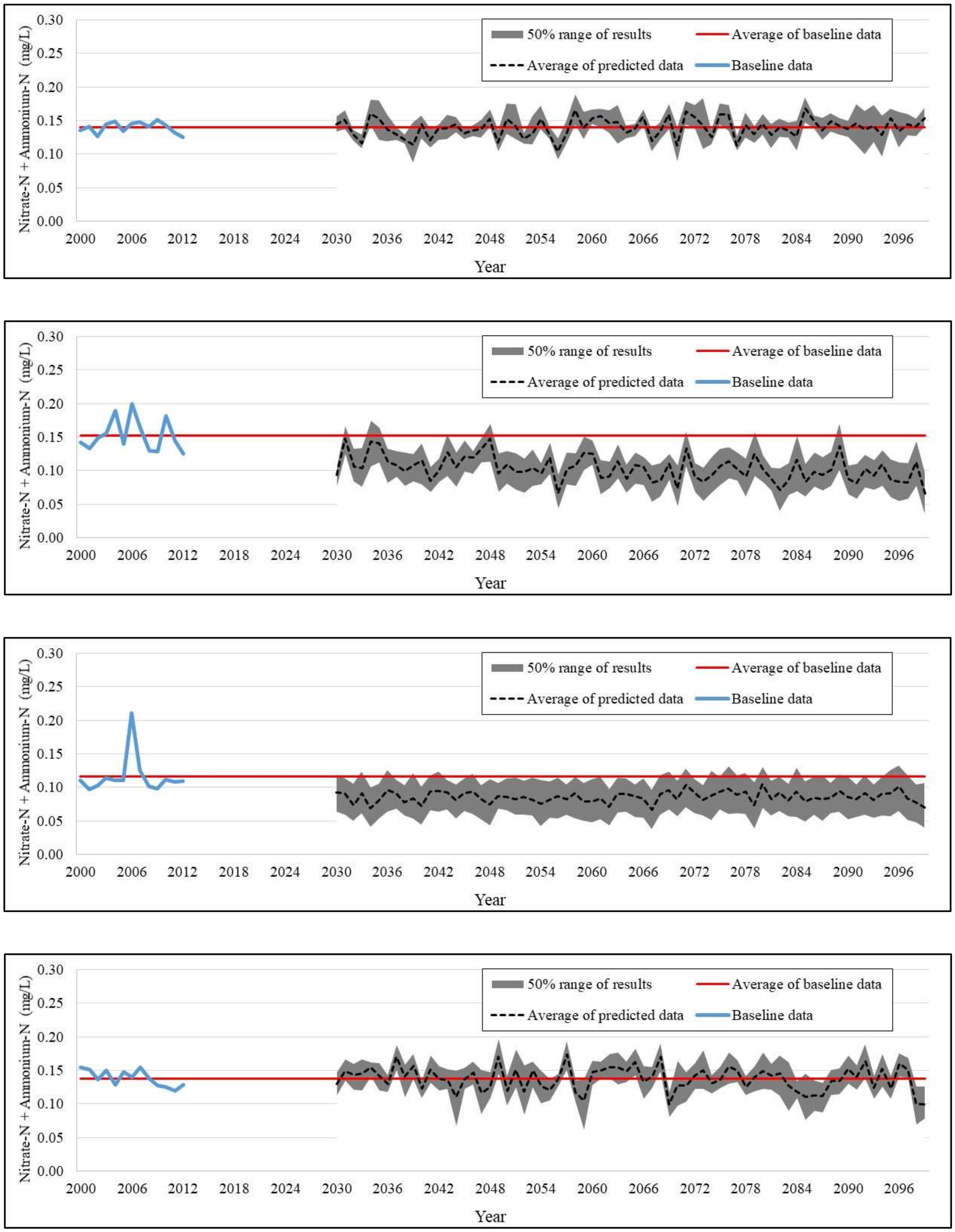
5.1.1.2. Sensitivity analysis of air pollution under climate change situation on water quality of Lake Ontario in Toronto region

The sensitivity analysis follows the same procedure to the previous section (related to atmospheric deposition). Fig 34 to Fig 37 are showing the results of sensitivity analysis for winter, spring, summer, and fall respectively.

Also, Table 9 shows a summary of the sensitivity analysis of air pollution impacts. As it can be seen in this table, by increasing the air contamination, there is a possibility to decline the water quality of Lake Ontario specially in winter and fall (because of more rainfall) while by controlling the concentration of pollutants in air or reduction of them, the water contamination of Lake Ontario definitely will be lower than the baseline average concentration.

Table 9. Changes in the concentration of Nitrate-N + Ammonium-N (mg/L) in Lake Ontario in Toronto region under different air pollution scenarios in the future

	Changes in air pollution		
	50% increase	100% increase	50% decrease
Winter	Higher in 72% of the cases	Higher in 76% of the cases	Lower in 100% of the cases
Spring	Lower in 100% of the cases	Lower in 100% of the cases	Lower in 100% of the cases
Summer	Lower in 93% of the cases	Lower in 53% of the cases	Lower in 100% of the cases
Fall	Higher in 53% of the cases	Higher in 56% of the cases	Lower in 100% of the cases



a) b) c) d)

Fig 33. The concentration of Nitrate-N + Ammonium-N (mg/L) in Lake Ontario in Toronto region under a future scenario of climate change for different seasons a) Winter b) Spring c) Summer d) Fall

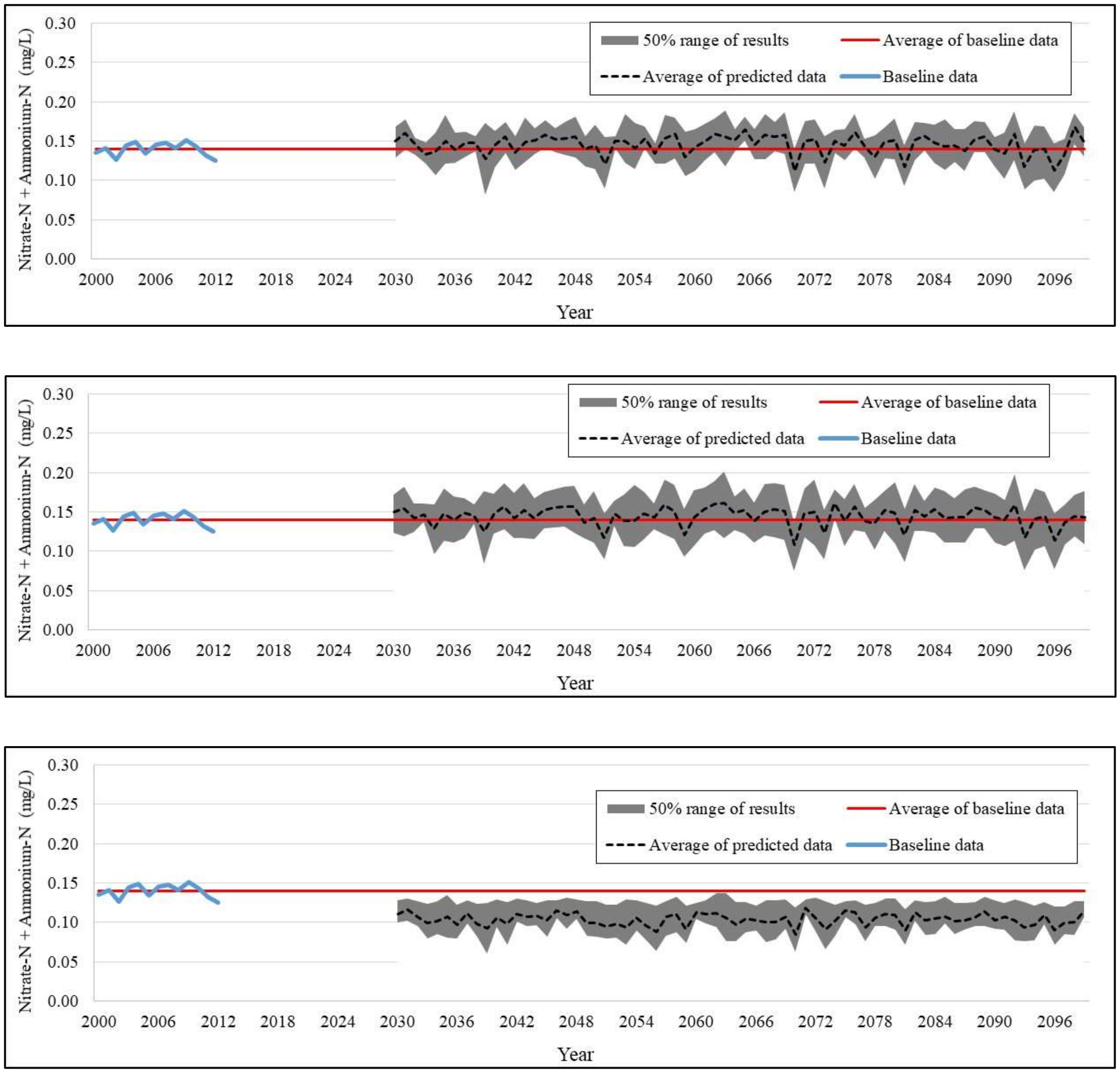


Fig 34. The concentration of Nitrate-N + Ammonium-N (mg/L) in Lake Ontario in Toronto region in winter for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

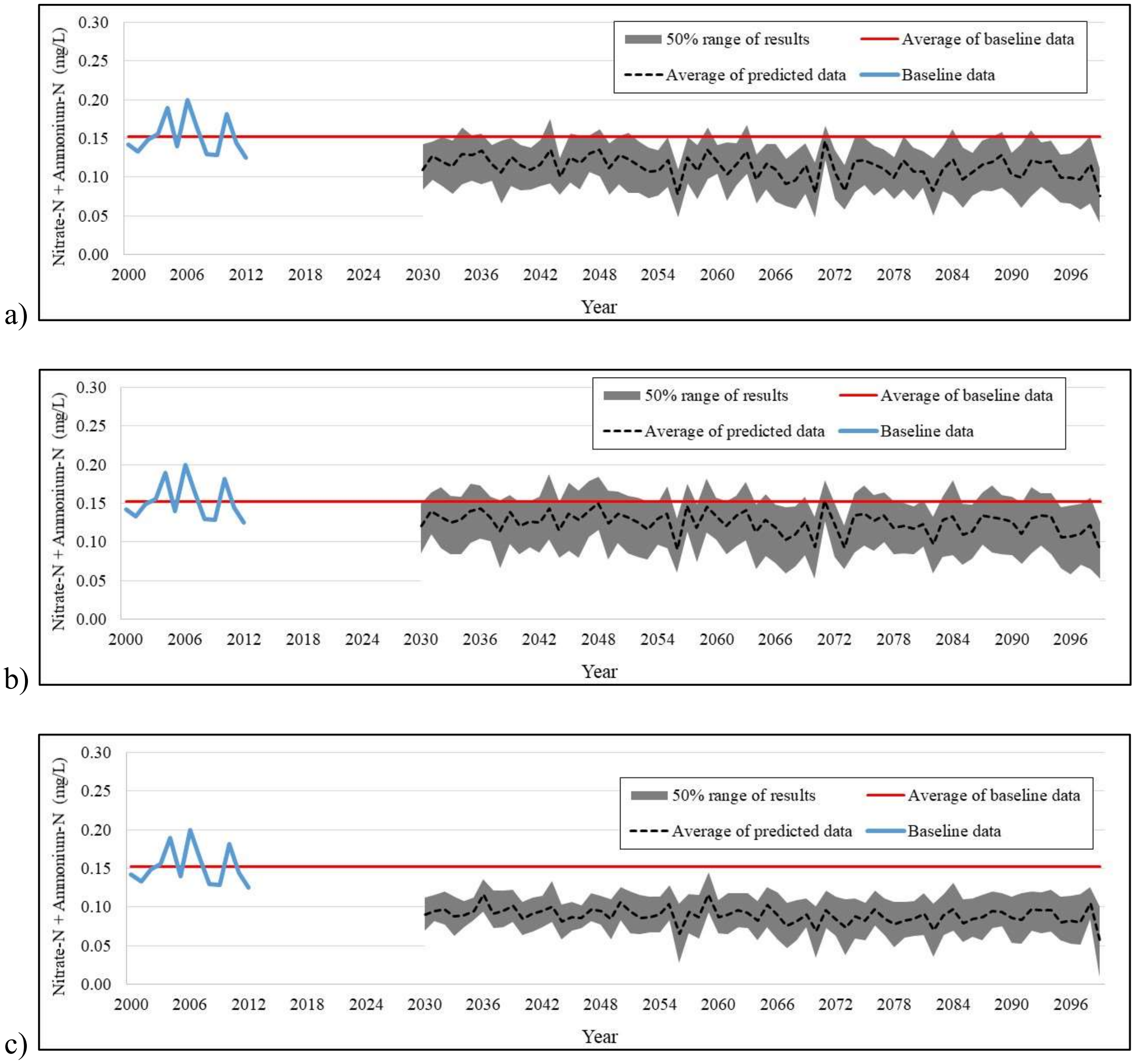


Fig 35. The concentration of Nitrate-N + Ammonium-N (mg/L) in Lake Ontario in Toronto region in spring for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

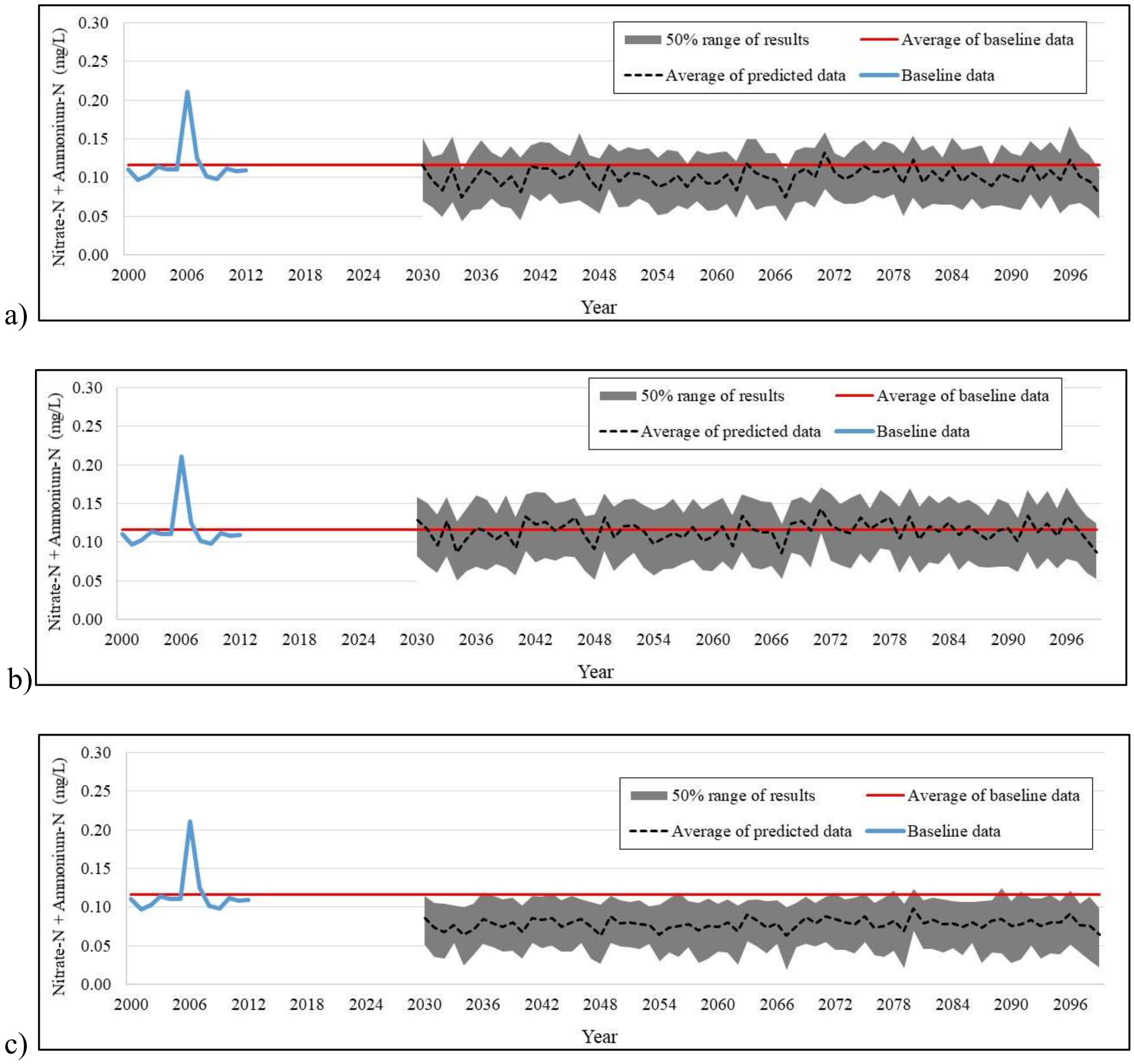


Fig 36. The concentration of Nitrate-N + Ammonium-N (mg/L) in Lake Ontario in Toronto region in summer for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

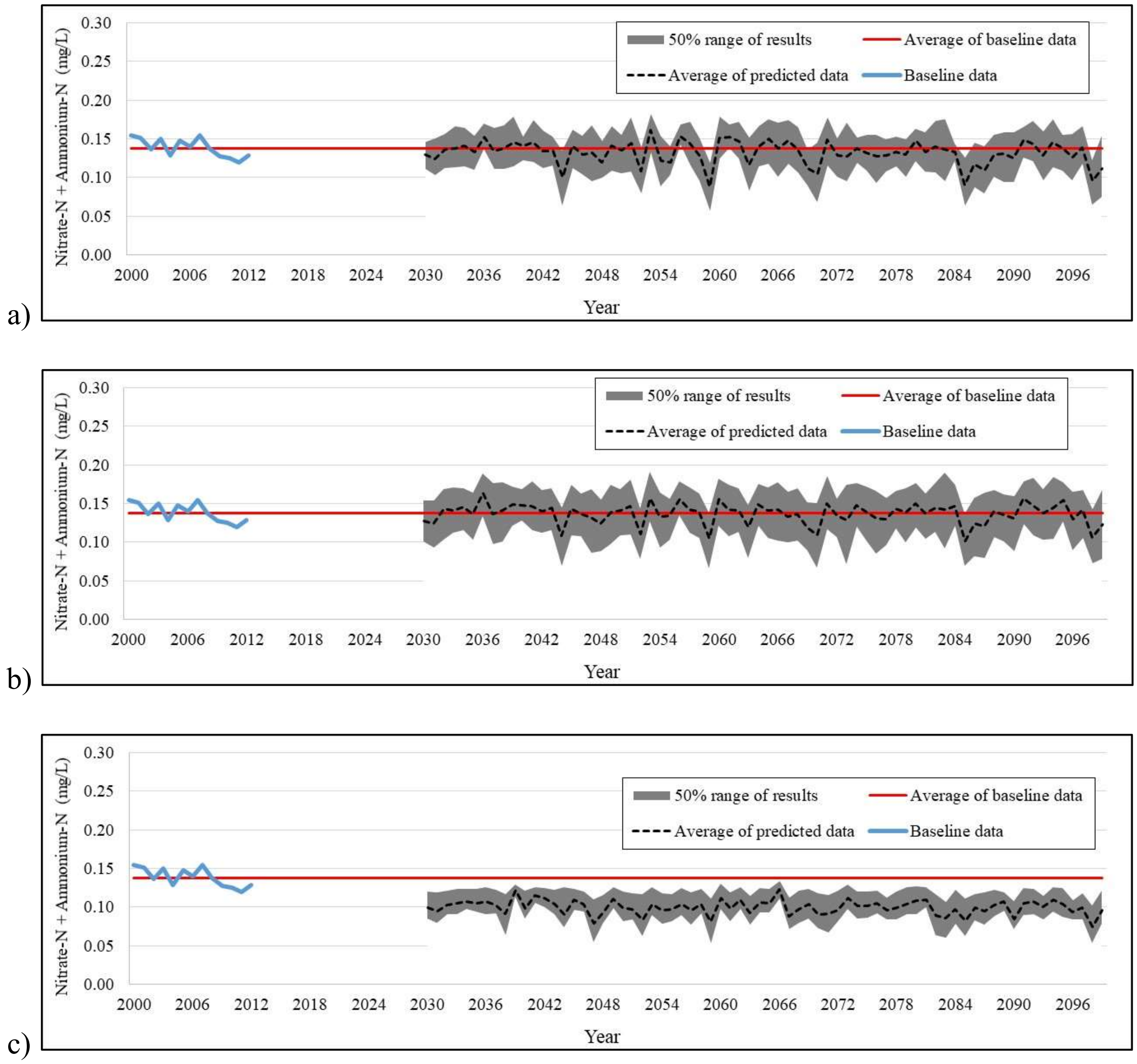


Fig 37. The concentration of Nitrate-N + Ammonium-N (mg/L) in Lake Ontario in Toronto region in fall for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

5.1.2. Summary of the modeling results in the Toronto region

Looking at the impacts of climate change on the mean annual temperature in Toronto region reveals that it will increase from 10 °C in 2012 to almost 25 °C in 2099. In addition to the temperature variation, the amount of precipitation in some seasons will be quite lower than the current amount. Undoubtedly, these changes in meteorological characteristics of the study area can cause some environmental changes. The results of modeling of the atmospheric deposition in Toronto region under climate change scenarios showed that in most cases (64%), the atmospheric deposition have lower quality (in terms of Nitrate-N + Ammonium-N). It can be because of the less amount of precipitation which can lead to lower dilution of contaminants in the air. This phenomenon will happen mostly during the summer and fall. As mentioned, this is mostly because of the lower amounts of precipitation in summer. The results of the sensitivity analysis of air pollution demonstrated that by increasing air pollution, the atmospheric deposition contamination will be higher in all seasons. However, by controlling the air quality and decreasing air contamination, precipitation contamination may become lower. But the important question is what are the consequences of climate change and atmospheric deposition on water quality of Lake Ontario in Toronto region? The water quality predictions showed that in most cases (70%), the concentration of Nitrate-N + Ammonium-N in Lake Ontario will be lower than the current average amount. It means that the atmospheric deposition can not impact the water quality of Lake Ontario considerably. However, regarding the different seasons, the situation in fall and winter showed a marginal quality. Focusing on the air pollution sensitivity analysis illustrated that increasing the contaminants in the air can cause water quality decline in fall and winter which can be expected from the predictions of atmospheric deposition. Technically, in fall and winter, the amount of precipitation is high enough to influence the water quality. In conclusion, it can be said that the water quality of Lake Ontario did not show a direct relationship with the atmospheric deposition. However, the changes in air contamination can cause some significant impacts on lake water quality.

5.2.Modeling results in Cobourg region

Fig 38 and Fig 39 show the variation of annual mean temperature and total precipitation between 2000 to 2012 (baseline period) and future period (2030 to 2099) in the Cobourg region. In addition to annual variations, the seasonal amounts of total precipitation have been shown in Fig 40. The temperature shows a clear increasing trend due to climate change while the amount of precipitation is generally the same as the baseline. But, focusing on seasonal variation, there is more wet winter and more dry summer and spring.

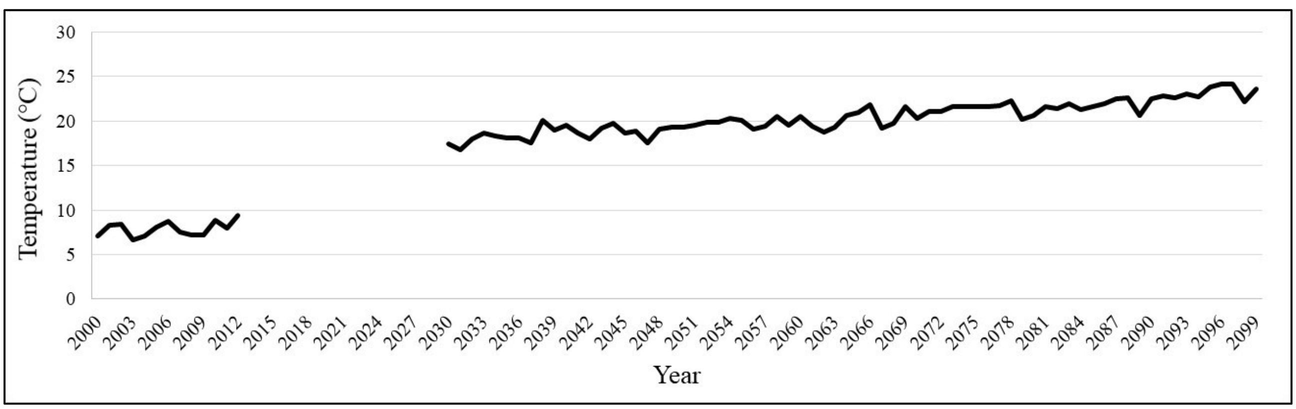


Fig 38. Annual mean temperature during the baseline (2000-2012) and future time period (2030-2099) in Cobourg region

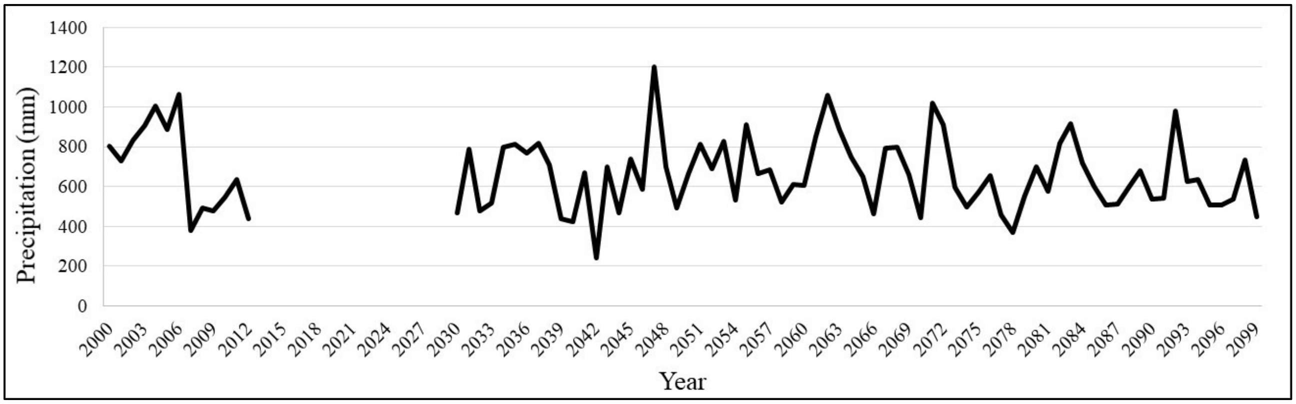


Fig 39. Annual total precipitation during the baseline (2000-2012) and future time period (2030-2099) in Cobourg region

5.2.1. Atmospheric deposition modeling in Cobourg region

In order to extract 100 high performance model of atmospheric deposition in the Cobourg region, 8358 trials were executed. Fig 41 and Fig 42 show the performances of the 100 models in terms of R-value and RMSE. As it can be seen in these figures, the R-value is always greater than 0.8 for training, validating and testing datasets. Also, the values of RMSE are usually less than 0.25 mg/L.

5.2.1.1.Climate change impacts on atmospheric deposition in Cobourg region

Fig 43 represents the future predictions of the atmospheric deposition of Nitrate-N + Ammonium-N in the Cobourg region considering the 50% range of the predicted data and average of data as well as the current average concentration of the mentioned variable for the period of 2000 to 2012 (the baseline).

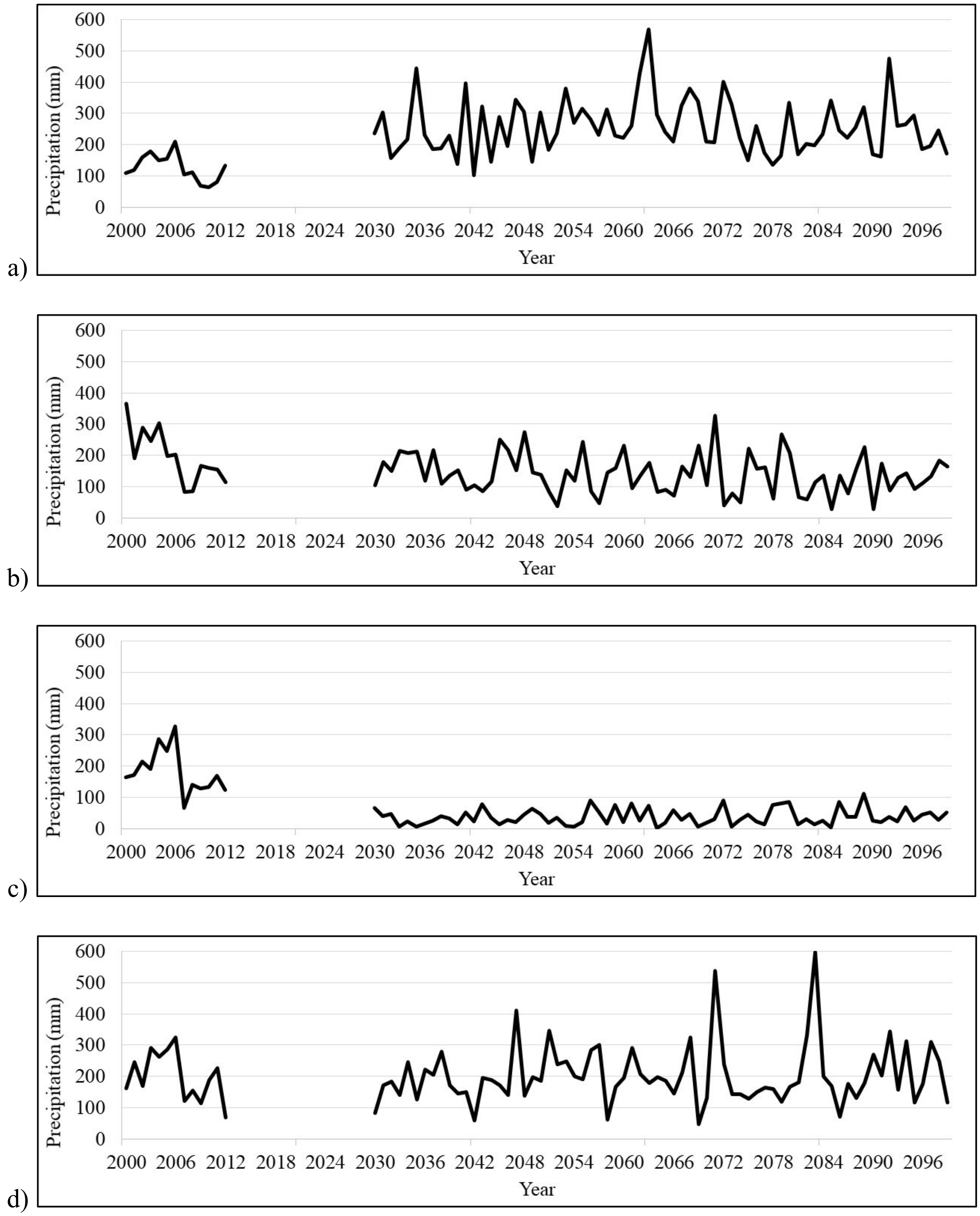


Fig 40. Seasonal total precipitation during the baseline and future time period in Cobourg region a) Winter b) Spring c) Summer d) Fall

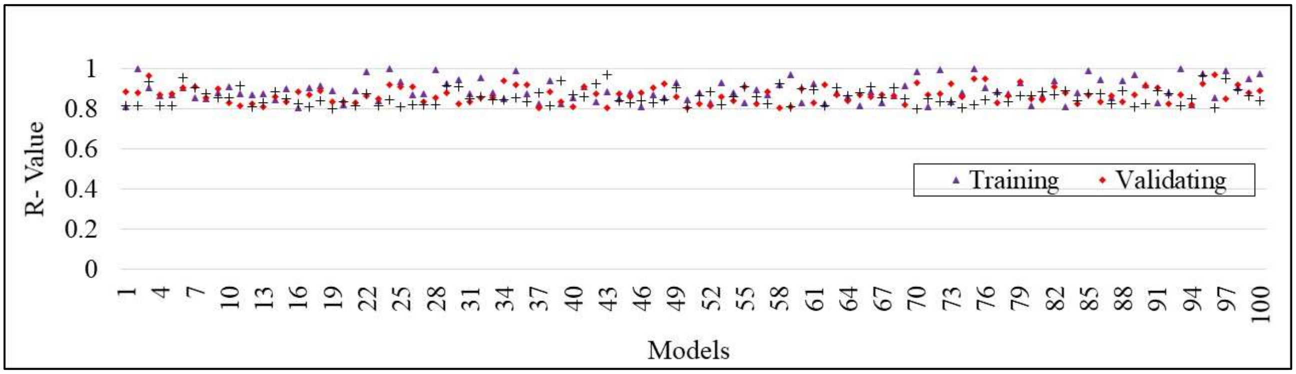


Fig 41. R-value of 100 water quality models of atmospheric deposition in Cobourg region

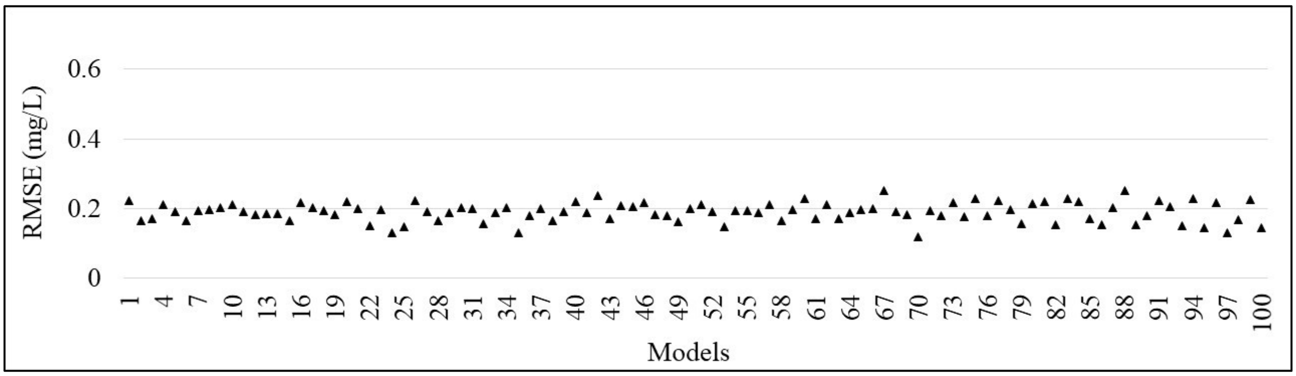


Fig 42. RMSE of 100 water quality models of atmospheric deposition in Cobourg region

Based on the predictions for the future situation, in 70% of the cases, the concentration of the contaminant would be higher than the baseline average concentration (the average concentration would be 25% higher). In addition, the average of Nitrate-N + Ammonium-N concentration in atmospheric deposition in different time periods has been shown in **Error! Reference source not found.**Table 10. It shows that in all of the time periods, the concentration is higher than the baseline.

Table 10. The average of Nitrate-N + Ammonium-N concentration in atmospheric deposition in Cobourg region in different time periods

	Time period	Average of Nitrate-N + Ammonium-N (mg/L)
Baseline	2000-2012	1.305
	2030-2039	1.633
	2040-2049	1.622
	2050-2059	1.653
Future scenario	2060-2069	1.605
	2070-2079	1.716
	2080-2089	1.575
	2090-2099	1.604

In terms of the seasonal variations, the predictions are available in Fig 44. The results show that except to winter, which the pollution of the precipitation is lower than the baseline (in 63% of the cases), the other seasons are experiencing higher contamination of precipitation (66%, 99% and 77% of the cases for spring, summer and fall respectively).

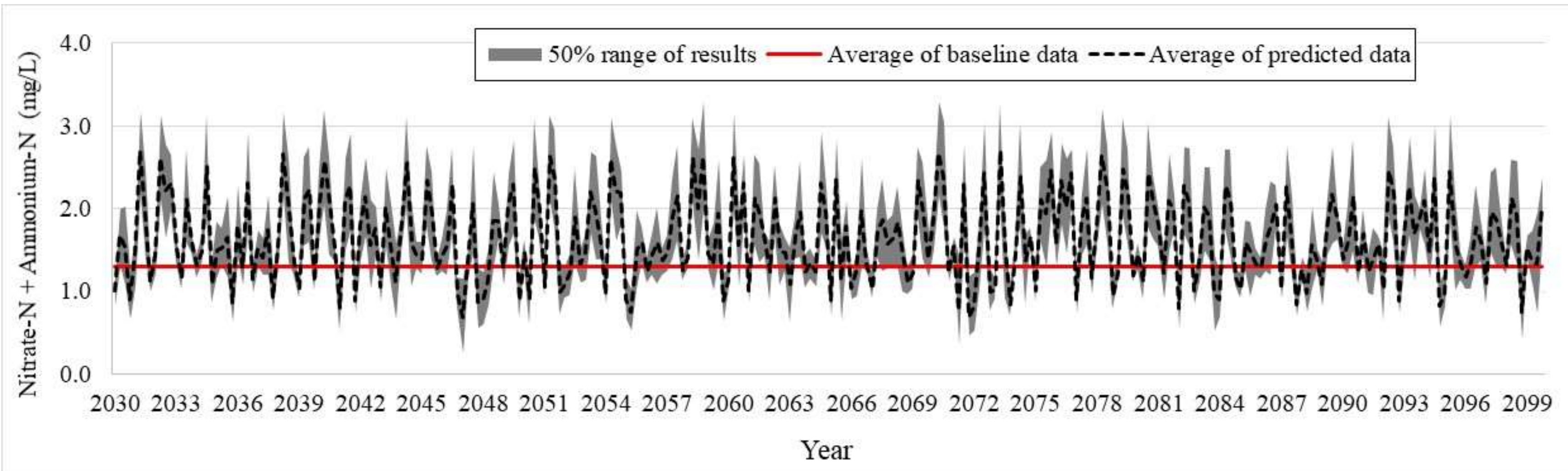


Fig 43. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Cobourg region under the future scenario of climate change

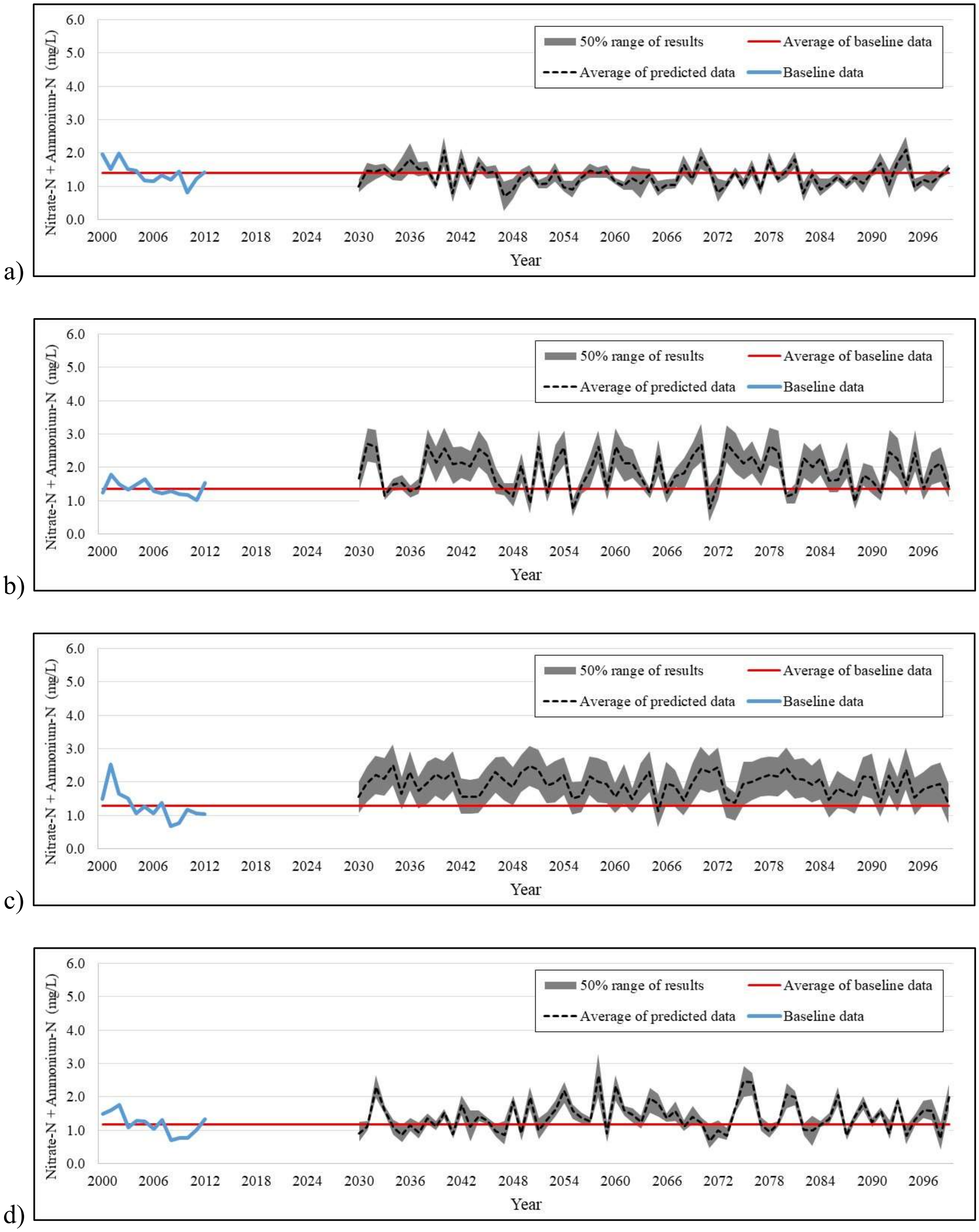


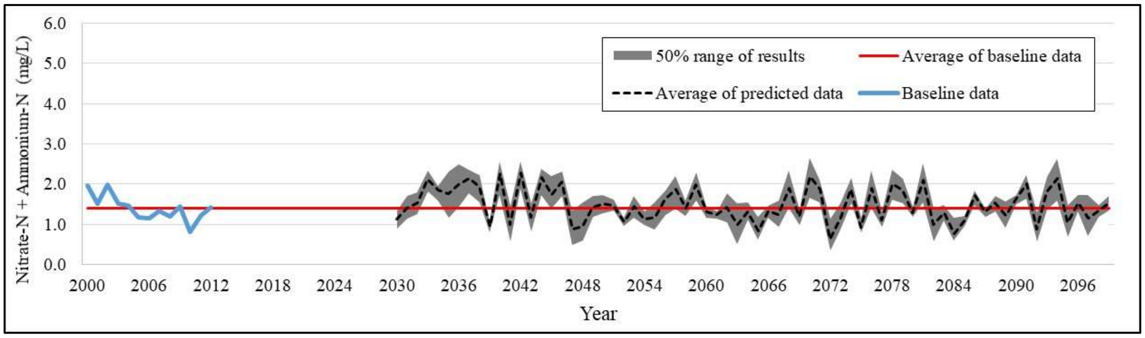
Fig 44. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Cobourg region under future scenario of climate change for different seasons a) Winter b) Spring c) Summer d) Fall

5.2.1.2. Sensitivity analysis of air pollution under climate change situation on atmospheric deposition in Cobourg region

Fig 45 to Fig 48 show the concentration of Nitrate-N + Ammonium-N in the precipitation in winter, spring, summer, and fall under different scenarios of air pollution in the Cobourg region.

The amounts of predictions in winter showed that in both cases of increasing the air pollution concentration, the precipitation contamination will be higher than baseline average concentration (51% and 62% of the cases for scenarios of increasing the air pollution). However, in the scenario of 50% reduction of air pollution, 73% of the future predictions will have a lower concentration of contamination comparing to the current situation.

In terms of the variation of precipitation pollution in spring, Fig 46 shows that by increasing the air pollution by 50% and 100%, in 83% and 87% of the cases the contamination will be higher than the current average concentration. Also, by decreasing the air pollution by 50%, still in 50% of the future predictions, the contamination of the atmospheric deposition will be higher than the current concentration.



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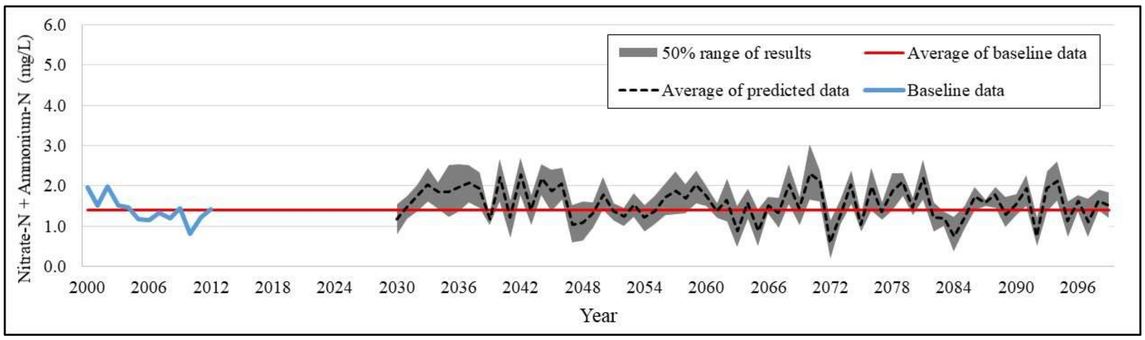

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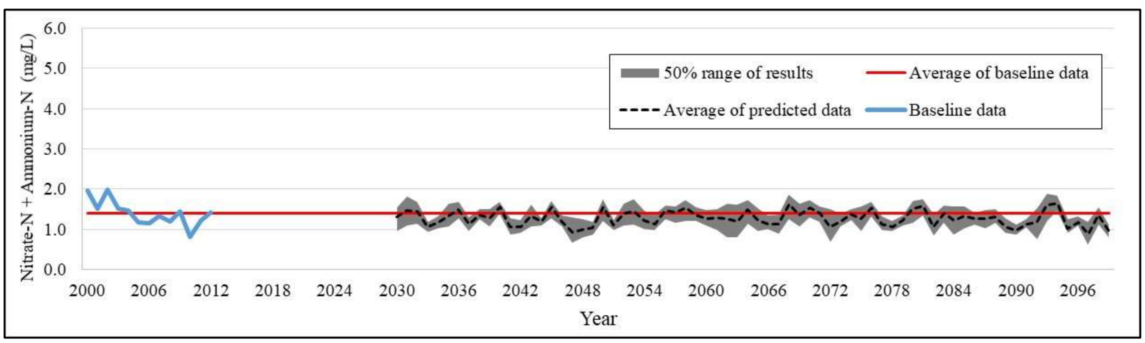


c)

Fig 45. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Cobourg region in winter for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

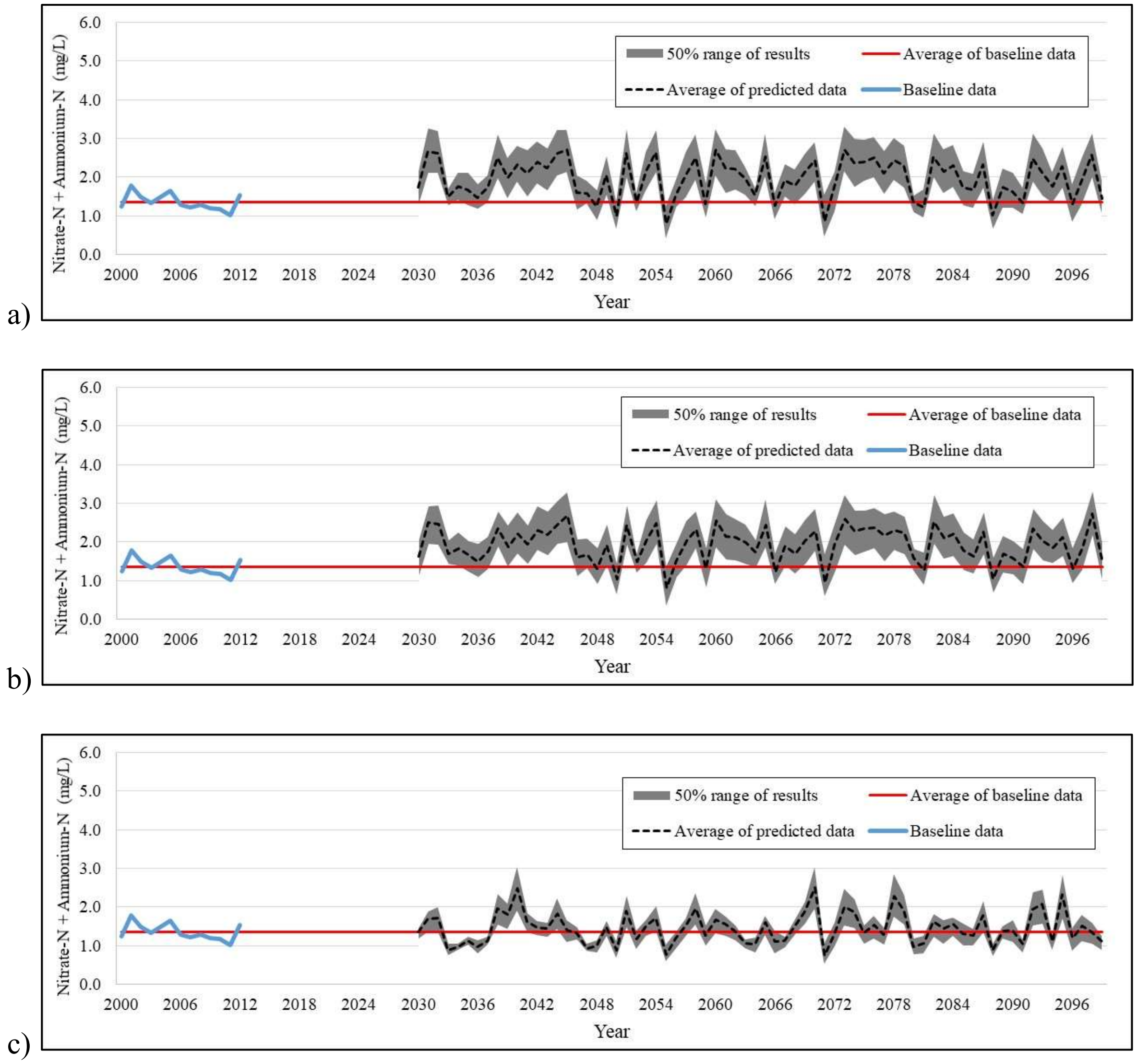
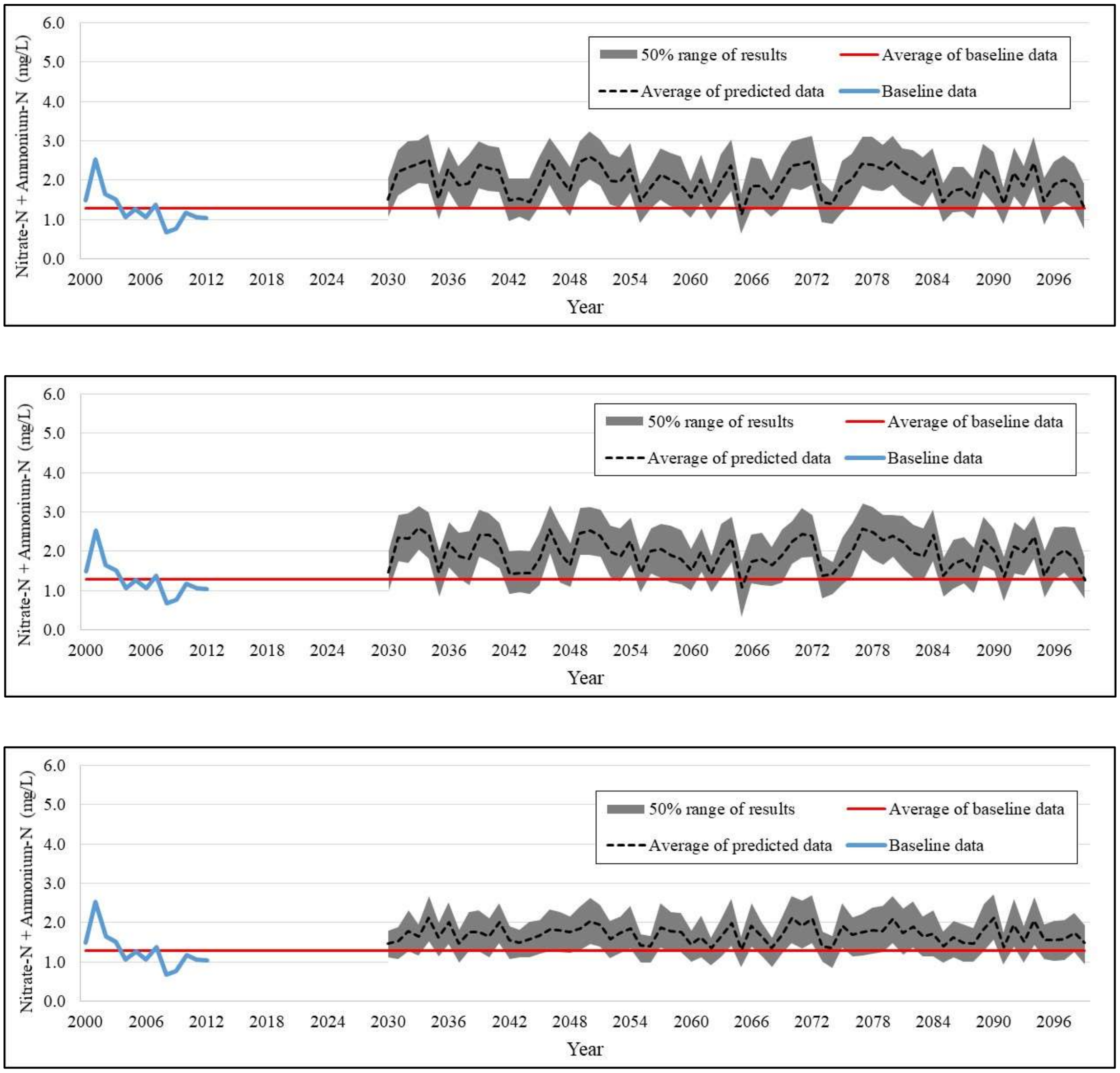


Fig 46. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Cobourg region in spring for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

Focusing on the results of sensitivity analysis in summer shows that in all scenarios of air pollution, the precipitation contamination will be higher than the current average concentration.



a)

b)

c)

Fig 47. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Cobourg region in summer for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

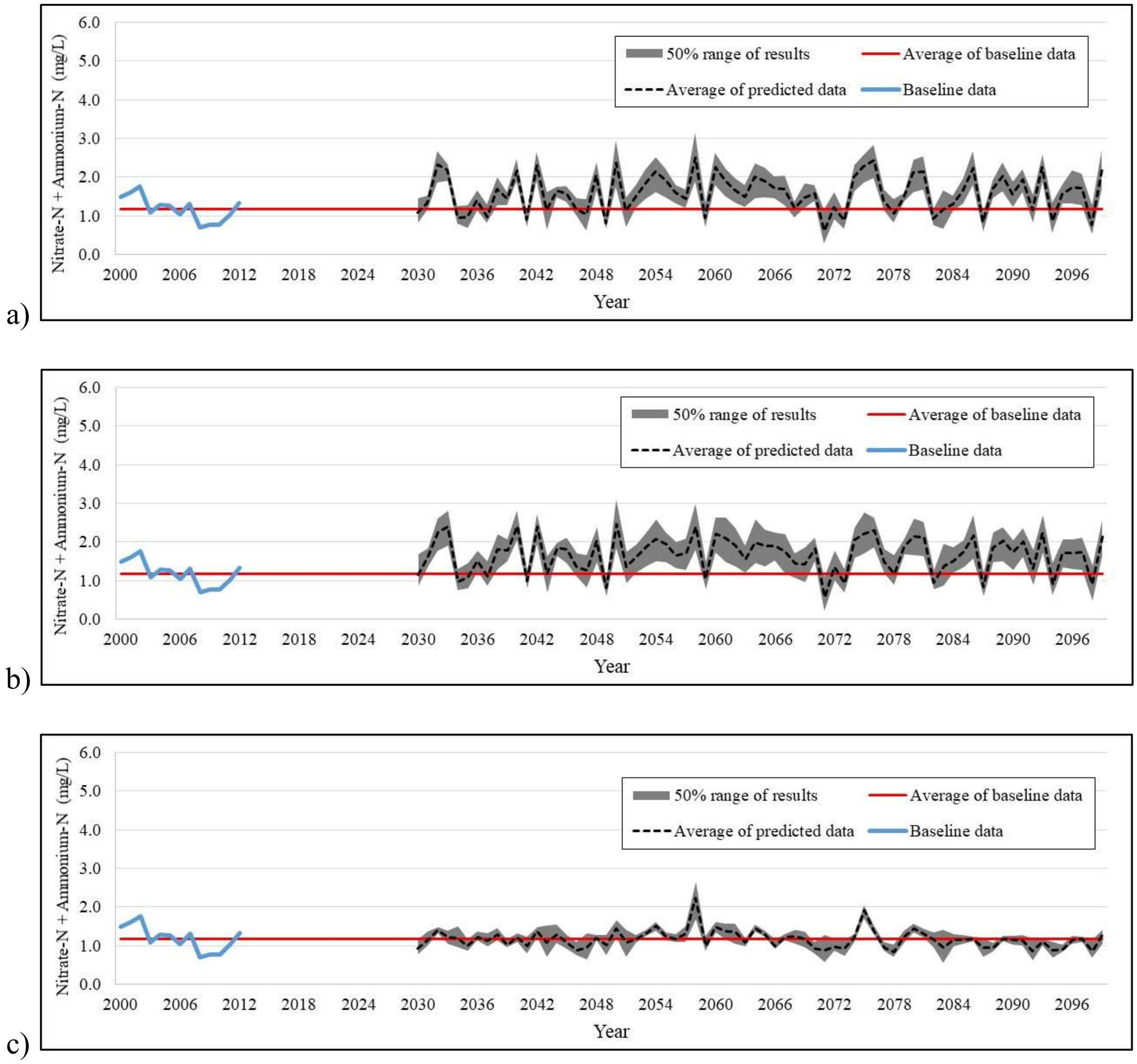


Fig 48. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Cobourg region in fall for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

The results of atmospheric deposition in fall are similar to winter results. It shows that increasing air contamination has a direct impact on precipitation chemistry. By increasing the concentration of the pollutants in the air by 50% and 100%, the atmospheric deposition in 72% and 79% of the cases will be higher than the current average concentration. By contrast, in the decreasing air contamination scenario, in 58% of the cases, the atmospheric deposition contamination will be lower than the current concentration.

Table 11 shows a summary of all sensitivity analysis of air pollution impacts in different seasons. Based on these results, in all scenarios of air pollution, the contamination of the atmospheric deposition will be higher than the current average concentration except for winter and fall. In these two seasons, by decreasing the air contamination, the concentration of Nitrate-N + Ammonium-N in precipitation will be lower than the current average concentration (in 73% and 58% of the cases in winter and fall respectively).

Table 11. Changes in the concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Cobourg region under different air pollution scenarios in the future

	Changes in air pollution		
	50% increase	100% increase	50% decrease
Winter	Higher in 51% of the cases	Higher in 62% of the cases	Lower in 73% of the cases
Spring	Higher in 83% of the cases	Higher in 87% of the cases	Lower in 50% of the cases
Summer	Higher in 100% of the cases	Higher in 100% of the cases	Higher in 99% of the cases
Fall	Higher in 72% of the cases	Higher in 79% of the cases	Lower in 58% of the cases

5.2.2. Water quality modeling in Lake Ontario in Cobourg region

In the modeling of water quality in Lake Ontario in the Cobourg region, in order to extract 100 high performance model, 500 trials were executed. Fig 49 and Fig 50 show the performances of the 100 models in terms of R-value and RMSE.

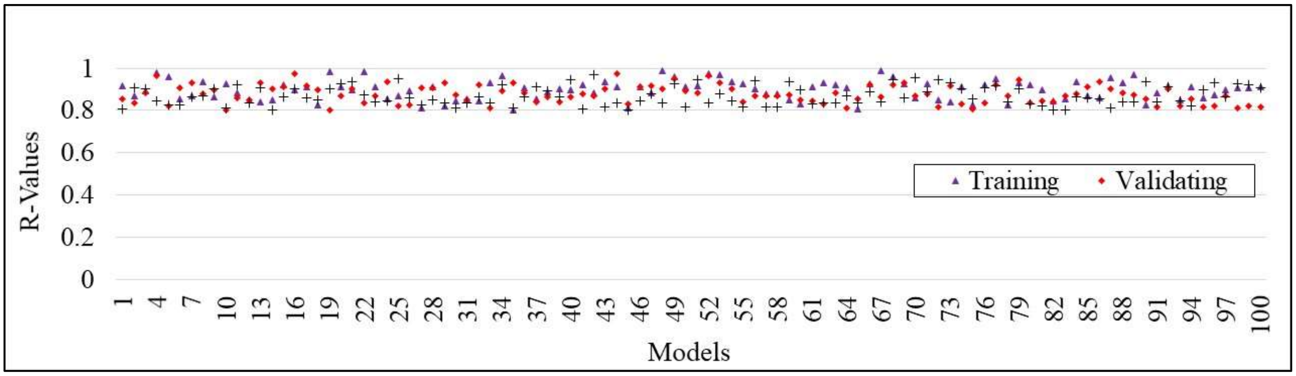


Fig 49. R-value of 100 water quality models of Lake Ontario in Cobourg region

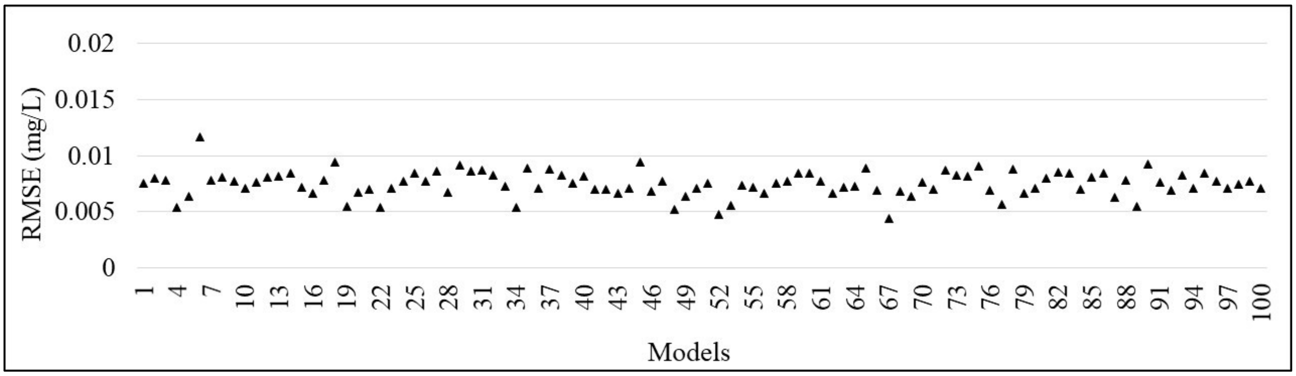


Fig 50. RMSE of 100 water quality models of Lake Ontario in Cobourg region

5.2.2.1.Climate change impacts on water quality of Lake Ontario in Cobourg region

In Fig 51, the predictions of Nitrate-N + Ammonium-N in Lake Ontario in the Cobourg region are presented. These results have been shown by two different amounts: 50% range of the predicted data and average of data. Based on the predictions for the future situation, in 83% of the cases, the concentration of the contaminant in water would be lower than the baseline average concentration (the average concentration would be 11.7% lower). In addition, the average of Nitrate-N + Ammonium-N concentration in Lake Ontario in different time periods has been shown in Table 12. It shows that in all of the time periods, the concentration would be lower than the baseline average.

Table 12. The average of Nitrate-N + Ammonium-N concentration in Lake Ontario in Cobourg region in different time periods

	Time period	Average of Nitrate-N + Ammonium-N (mg/L)
Baseline	2000-2012	0.097
Future scenario	2030-2039	0.088
	2040-2049	0.088
	2050-2059	0.087
	2060-2069	0.085
	2070-2079	0.085
	2080-2089	0.084
	2090-2099	0.084

Regarding the seasonal analysis (Fig 52), most of the future concentration of Nitrate-N + Ammonium-N would be lower than the baseline average concentration. In winter, spring, summer, and fall in 93%, 99%, 74% and 100% of the cases the water pollution will be lower than the baseline.

5.2.2.1. Sensitivity analysis of air pollution under climate change situation on water quality of Lake Ontario in Cobourg region

In terms of sensitivity analysis of the models with respect to air quality, Fig 53 to Fig 56 show the results of sensitivity analysis for winter, spring, summer, and fall respectively.

In addition to the figures, Table 13 shows a summary of the sensitivity analysis of air pollution impacts in the Cobourg region. As it can be seen in this table, by increasing the air contamination, there is a possibility to decline the water quality of Lake Ontario, especially in summer.

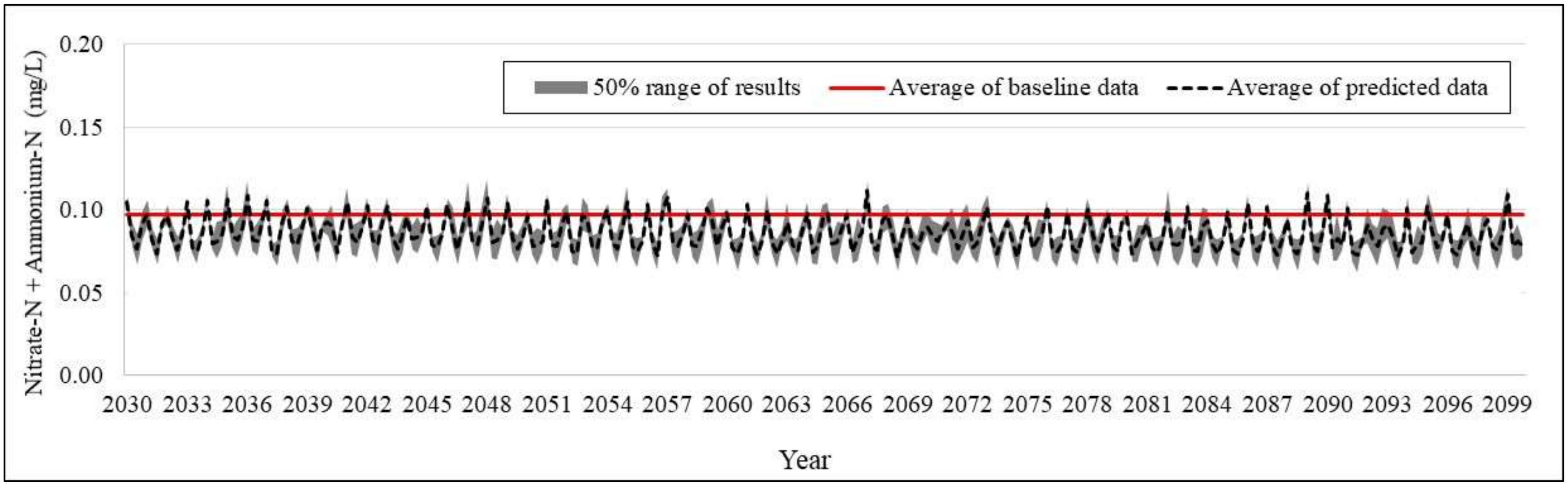
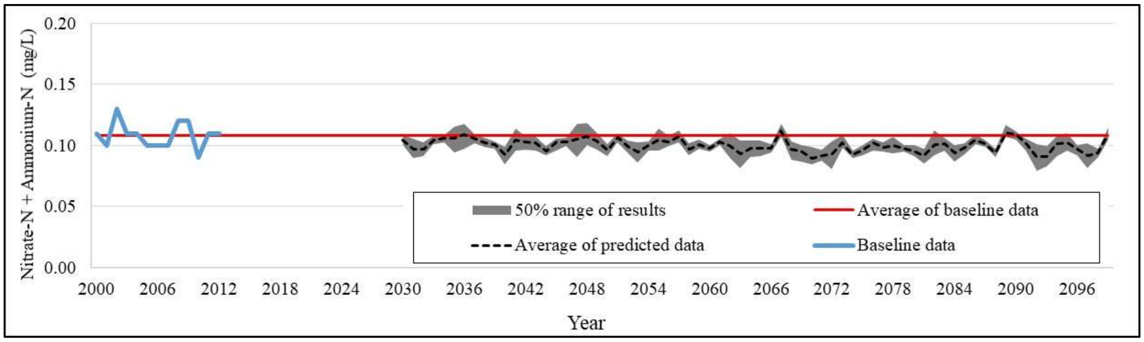
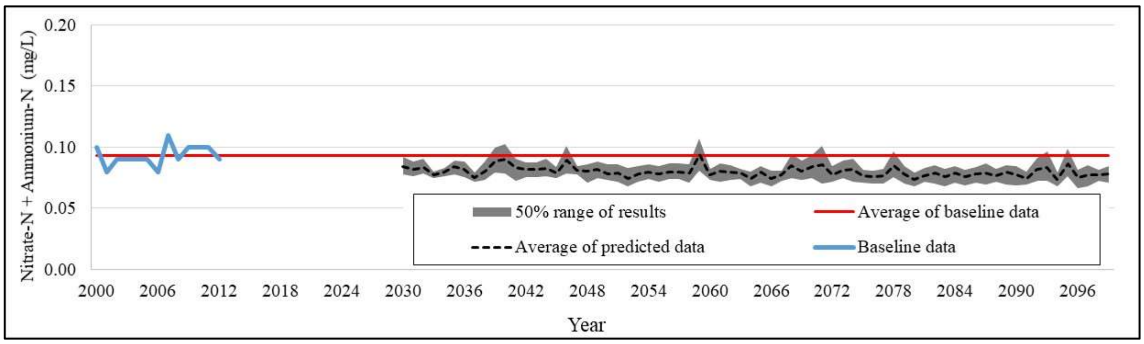


Fig 51. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Cobourg region under future scenario of climate change



a)



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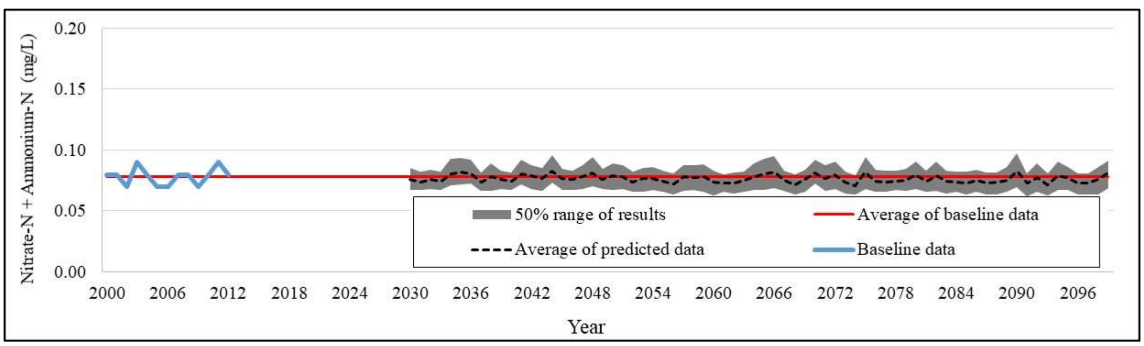

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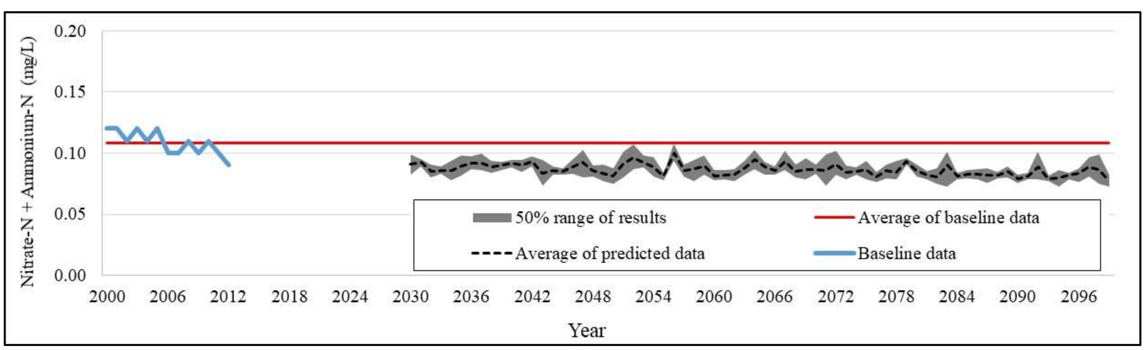


d)

Fig 52. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Cobourg region under a future scenario of climate change for different seasons a) Winter b) Spring c) Summer d) Fall

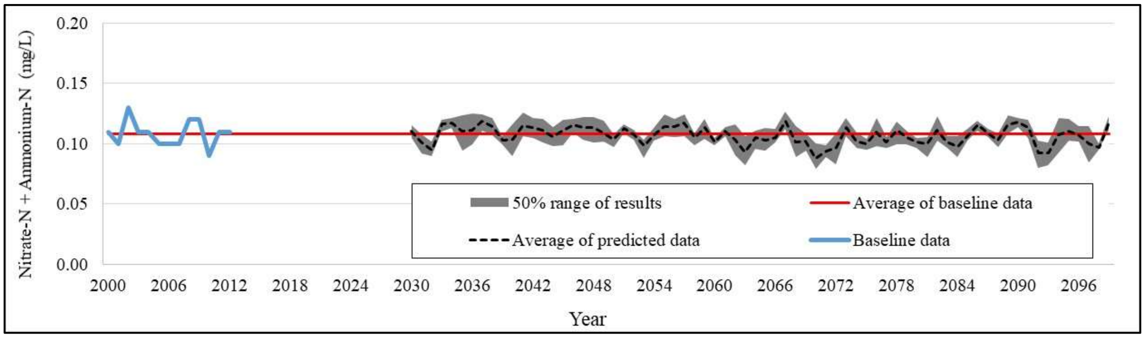
In the scenario of 100% increase in air pollution, the water pollution in winter, spring, and summer will experience higher values than the current average concentration. However, by controlling and reducing the concentration of pollutants in the air, the Lake Ontario contamination in Cobourg region in all cases would be lower than the baseline average concentration.

Table 13. Changes in the concentration of Nitrate-N + Ammonium-N in Lake Ontario in Cobourg region under different air pollution scenarios in the future

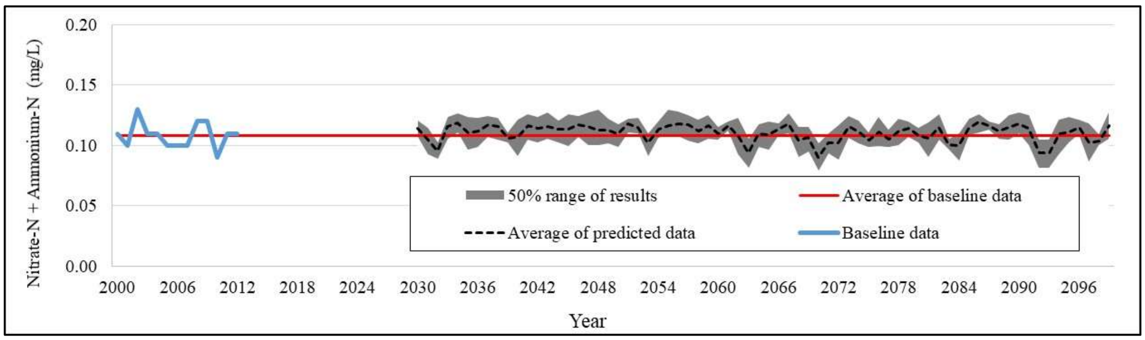
	Changes in air pollution		
	50% increase	100% increase	50% decrease
Winter	Lower in 53% of the cases	Higher in 69% of the cases	Lower in 100% of the cases
Spring	Lower in 83% of the cases	Higher in 54% of the cases	Lower in 100% of the cases
Summer	Higher in 67% of the cases	Higher in 89% of the cases	Lower in 100% of the cases
Fall	Lower in 98% of the cases	Lower in 89% of the cases	Lower in 100% of the cases

5.2.1. Summary of the modeling results in Cobourg region

The variation of precipitation shows that the amount of rainfall in spring and summer will be lower than the baseline. However, in the winter, the precipitation will be more while in fall, the precipitation will not change considerably. In addition to the changes in the precipitation, the air temperature will increase from an average of 10 °C in 2012 to 25 °C in 2099. These transitions in temperature and precipitation have a direct impact on atmospheric deposition.



a)



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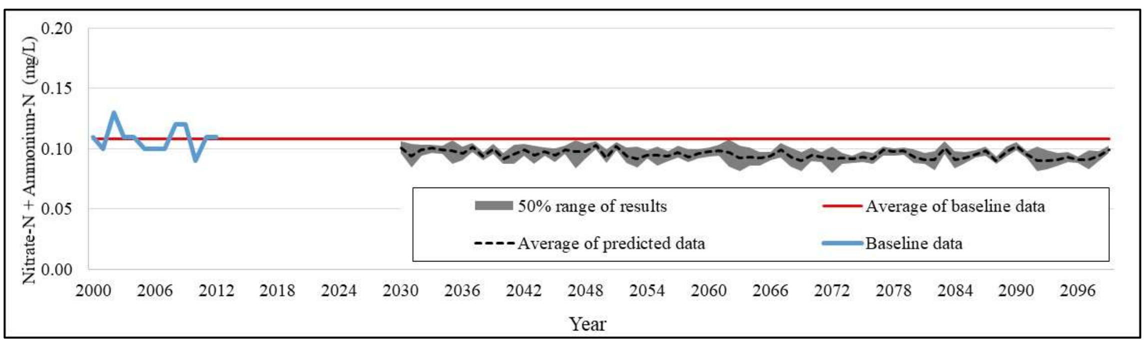


c)

Fig 53. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Cobourg region in winter for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

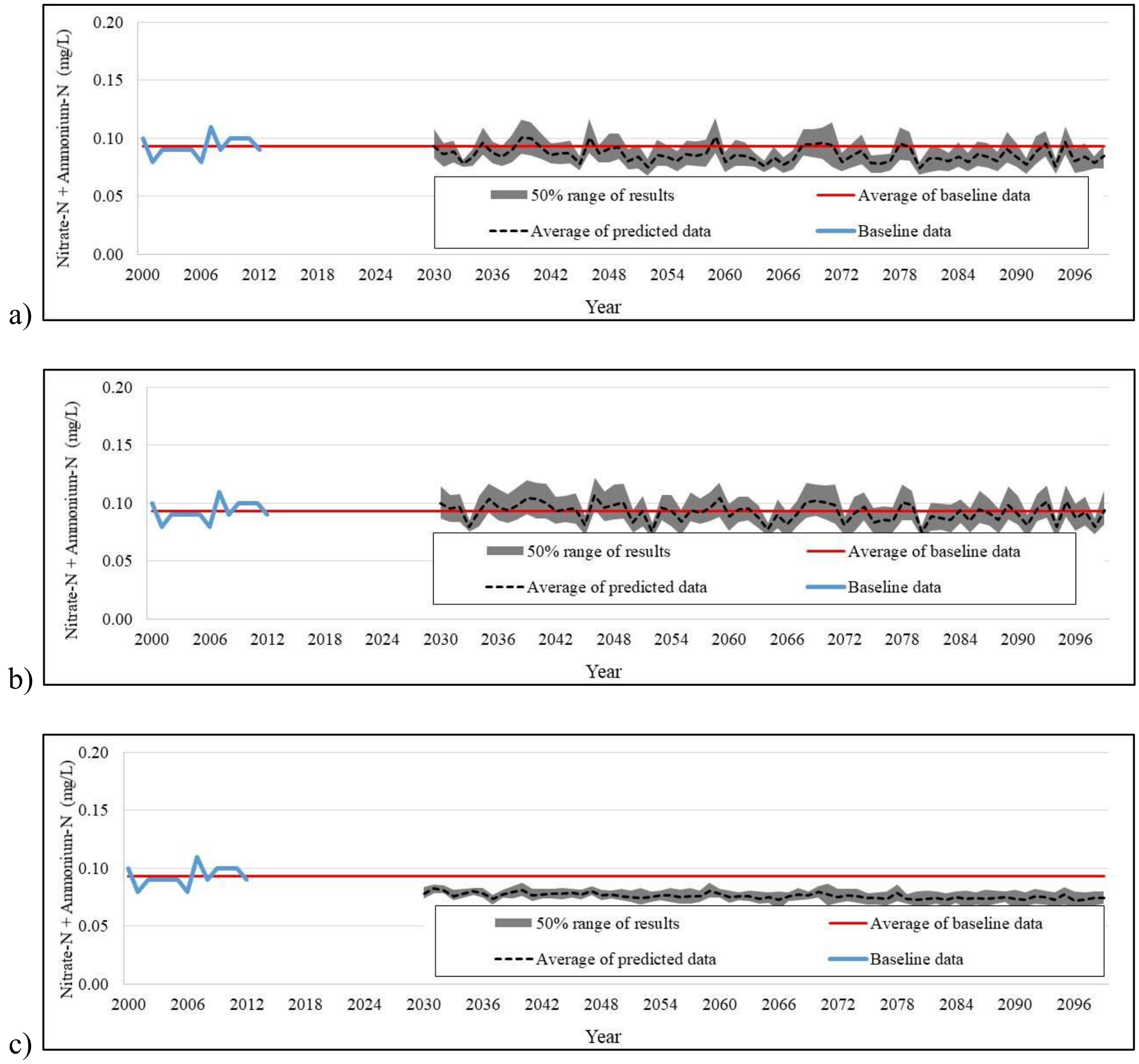
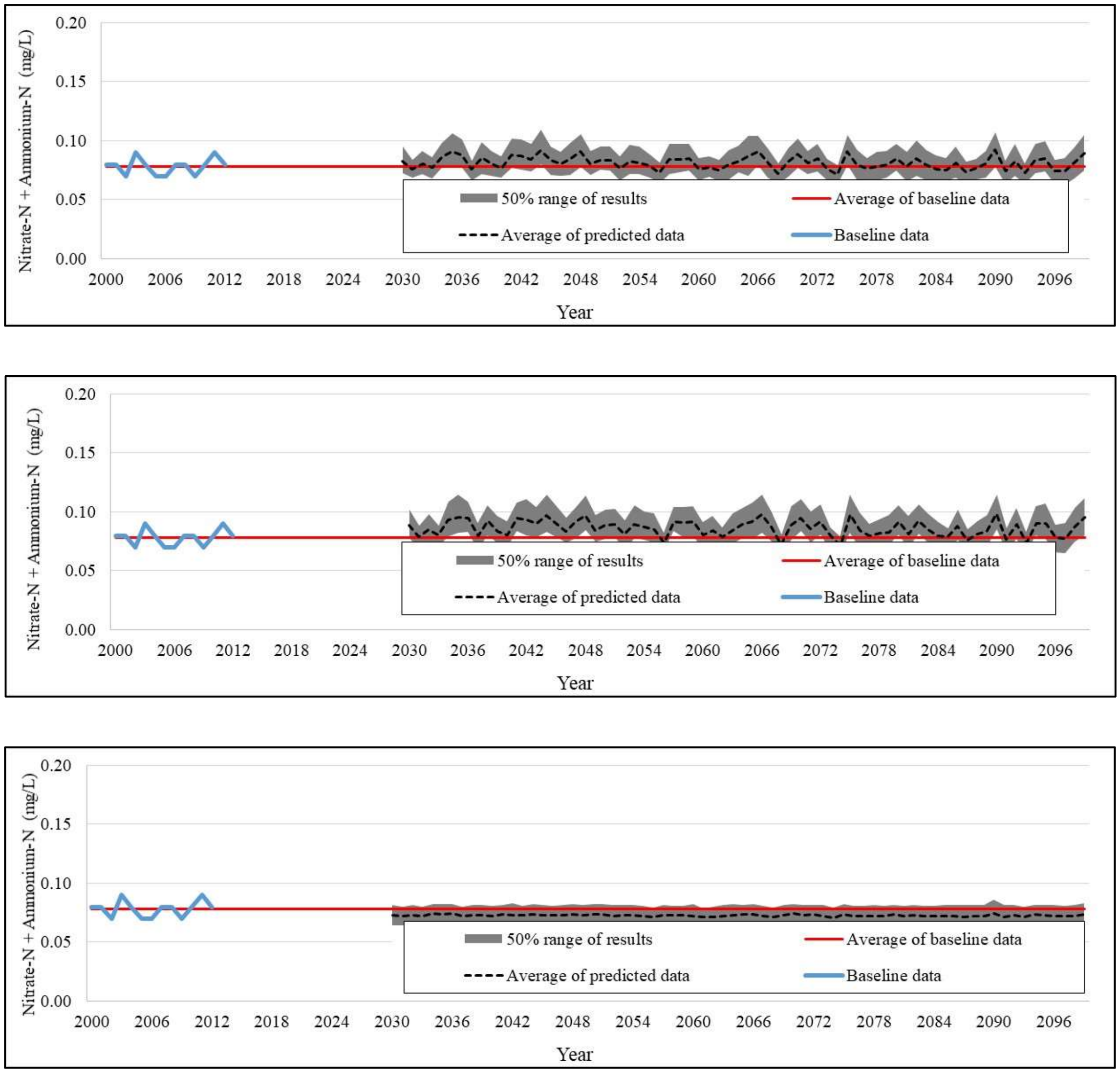


Fig 54. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Cobourg region in spring for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

a)


b)

c)

Fig 55. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Cobourg region in summer for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

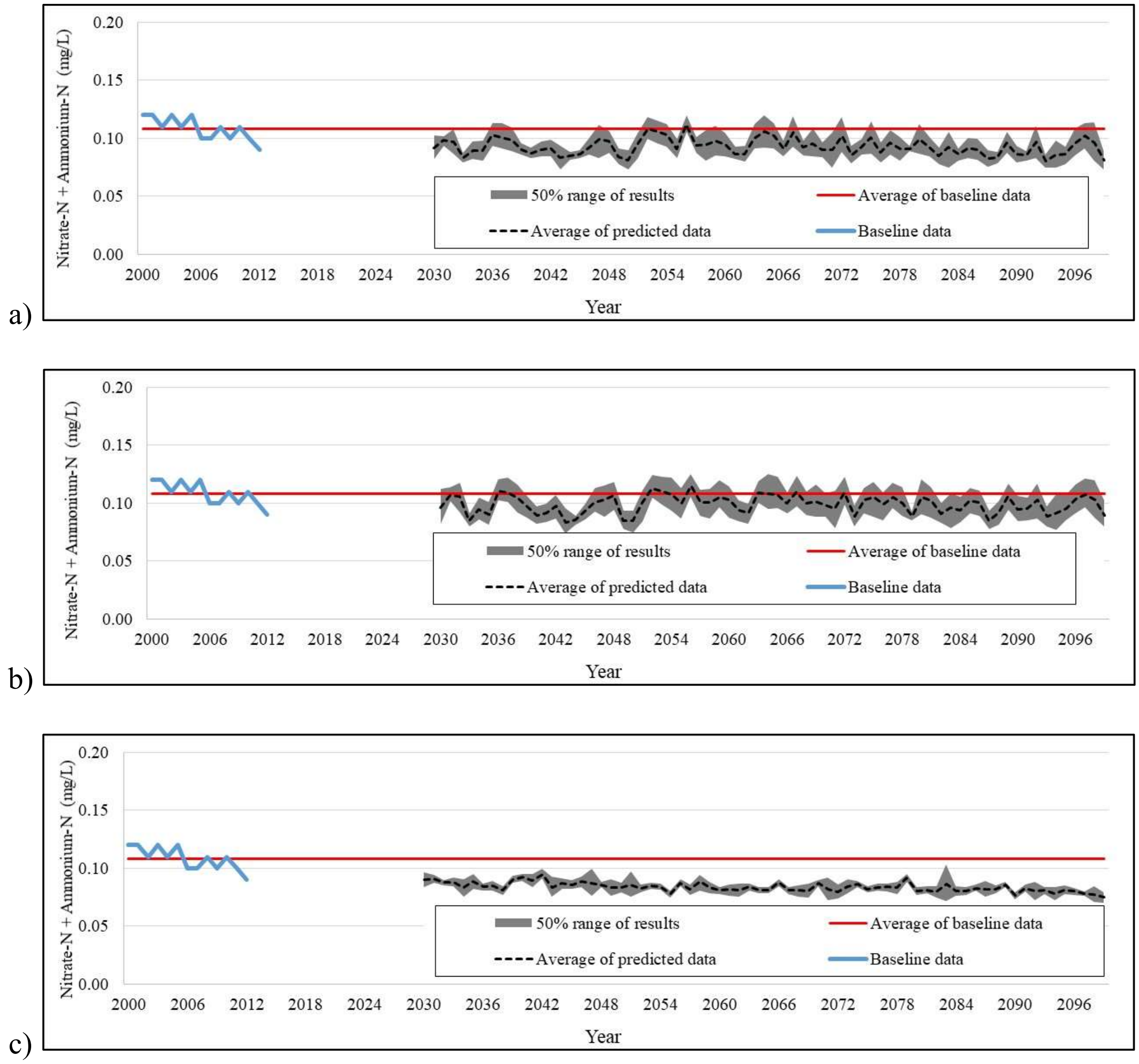


Fig 56. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Cobourg region in fall for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

Due to fewer amounts of rainfall in summer and spring to dilute the air contaminants, the concentration of contaminants in these seasons will be higher than the baseline. While in winter, because of the more dilution process, the pollution of precipitation is lower than the baseline average. However, during the fall, the amount of precipitation is not changed considerably while the atmospheric contamination shows a higher concentration. It seems that in this season, the increasing of contamination is mainly because of the changes in air temperature and continuing the impacts of remained polluted air after a dry summer. The results of sensitivity analysis demonstrated that the concentration of the pollutants in precipitation in Cobourg region is completely correlated with air pollution and increasing the concentration of NO and NO_2 in the air can decline the precipitation quality. Also, these results showed that even by decreasing the air pollutants by 50%, still, the situation in summer is critical. Another important fact about the sensitivity analysis is that by having the current concentration of pollutants in air, the atmospheric deposition pollution in spring and fall will be higher than the current average amount, However, by decreasing the air pollution (by 50%), the contamination in the spring and fall will become much lower and in most of the cases the atmospheric deposition pollution will be lower than the baseline average.

While in most of the cases the atmospheric deposition quality will decline in the future, it is important to evaluate its impact on water quality of Lake Ontario near the Cobourg region. The results of the water quality predictions showed that the water quality of Lake Ontario in the Cobourg region has a low correlation with atmospheric deposition. In fact, having more pollution in precipitation can not change the water quality of Lake Ontario considerably. However, by increasing the air pollutants, the strength of atmospheric deposition will be high enough to decline the water quality of Lake Ontario in Cobourg region.

5.3.Modeling results in the Grimsby region

Fig 57 and Fig 58 show the variation of annual mean temperature and total precipitation between 2000 to 2012 (baseline period) and future period (2030 to 2099) in the Grimsby region. In addition to annual variations, the seasonal amounts of total precipitation have been shown in Fig 59. The temperature has a clear increasing trend due to climate change while the amount of precipitation is generally lower than the baseline. But, focusing on seasonal variation, the presence of more wet winter and more dry summer and spring is obvious.

5.3.1. Atmospheric deposition modeling in the Grimsby region

Regarding the modeling of atmospheric deposition in the Grimsby region, 3666 trials were executed. Fig 60 and Fig 61 show the performances of the 100 models in terms of R-value and RMSE. As it can be seen in these figures, the R-value is always greater than 0.8 for training, validating and testing datasets. Also, the values of RMSE are usually less than 0.4 mg/L.

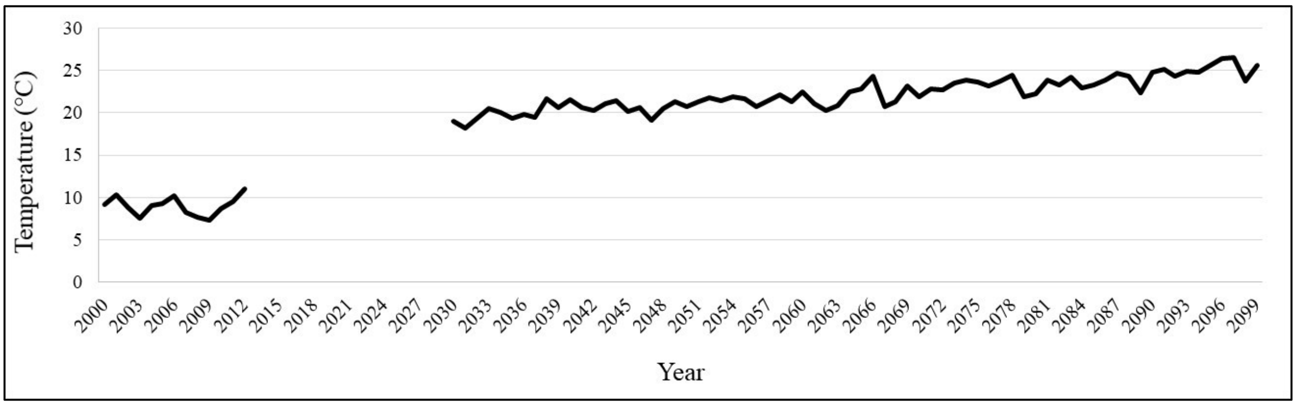


Fig 57. Annual mean temperature during the baseline (2000-2012) and future time period (2030-2099) in Grimsby region

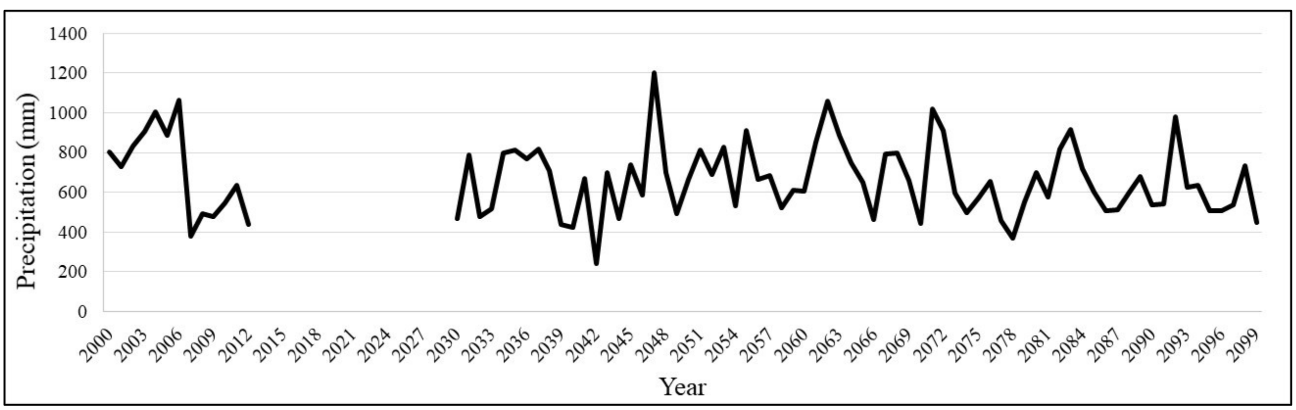


Fig 58. Annual total precipitation during the baseline (2000-2012) and future time period (2030-2099) in the Grimsby region

5.3.1.1. Climate change impacts on atmospheric deposition in Grimsby region

Fig 62 shows the modeling results of the atmospheric deposition of Nitrate-N + Ammonium-N in Grimsby region in the future. Based on the predictions of the model, in 75% of the cases, the concentration of the contaminant would be lower than the baseline average concentration (the average concentration would be 15.4% lower). In addition, the average of Nitrate-N + Ammonium-N concentration in atmospheric deposition in different time periods has been shown in Table 14. It shows that in all the time periods the concentration is lower than the baseline.

Focusing on seasonal pollution situation, the predictions (Fig 63), in winter, spring and fall the concentration of the contaminant will be lower than the baseline (96%, 98% and 66% of the cases in winter, spring and fall respectively). However, in summer the situation is different and in 79% of the cases, the precipitation contamination will be higher than the current average concentration.

Table 14. The average of Nitrate-N + Ammonium-N concentration in atmospheric deposition in Grimsby region in different time periods

	Time period	Average of Nitrate-N + Ammonium-N (mg/L)
Baseline	2000-2012	1.694
Future scenario	2030-2039	1.420
	2040-2049	1.472
	2050-2059	1.457
	2060-2069	1.335
	2070-2079	1.492
	2080-2089	1.432
	2090-2099	1.428

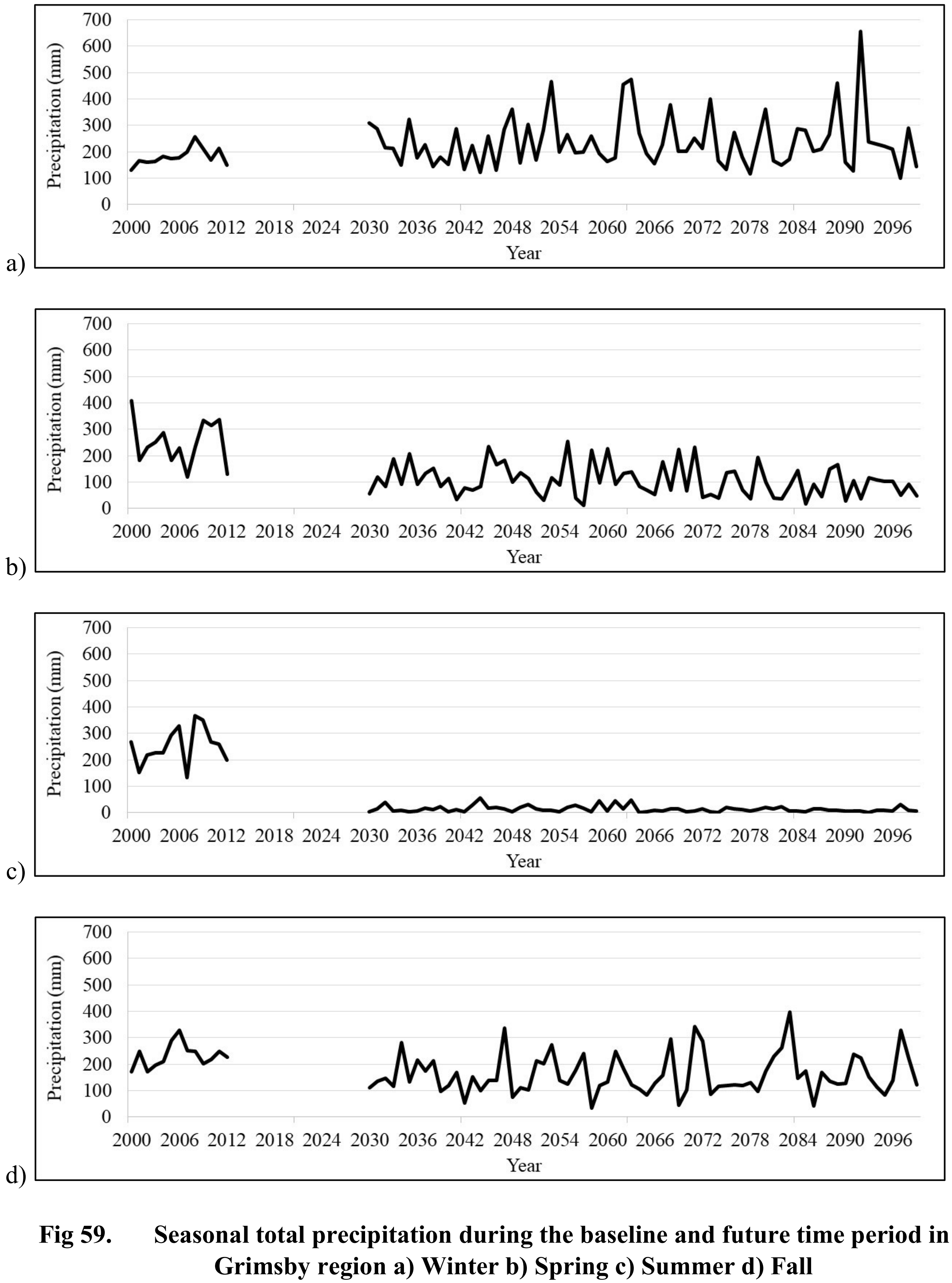


Fig 59. Seasonal total precipitation during the baseline and future time period in Grimsby region a) Winter b) Spring c) Summer d) Fall

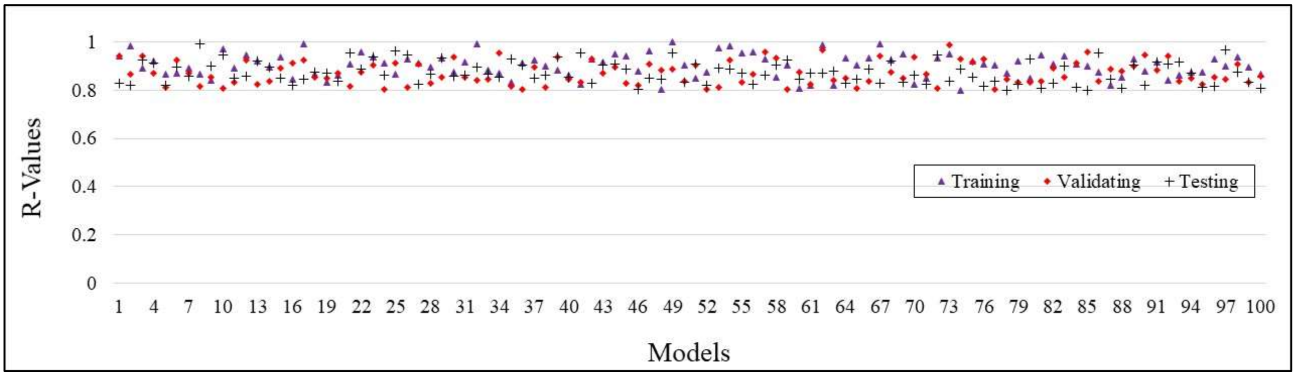


Fig 60. R-value of 100 water quality models of atmospheric deposition in Grimsby region

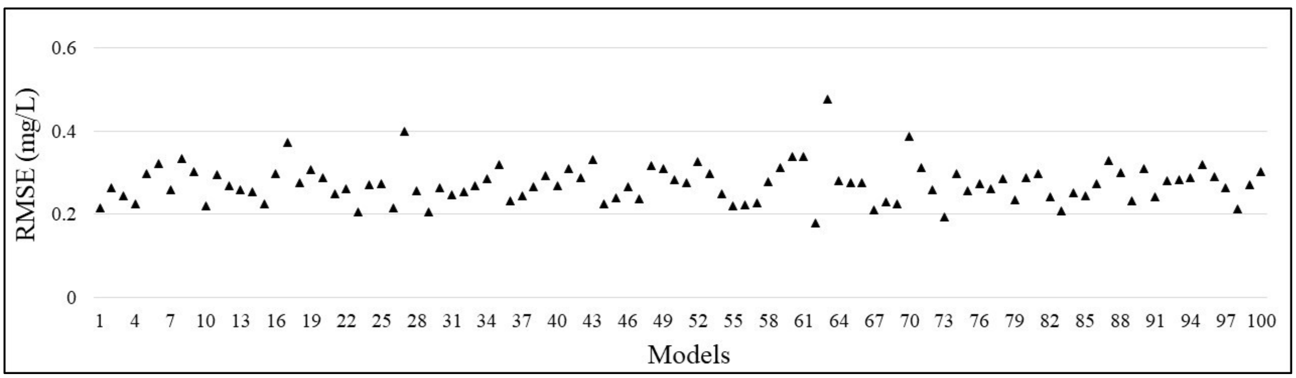


Fig 61. RMSE of 100 water quality models of atmospheric deposition in Grimsby region

5.3.1.2.Sensitivity analysis of air pollution under climate change situation on atmospheric deposition in Grimsby region

Fig 64 to Fig 67 show the concentration of Nitrate-N + Ammonium-N in the precipitation in winter, spring, summer, and fall under different scenarios of air pollution in the Grimsby region.

The predictions in winter showed that in the first scenario of air pollution increases (50% increase), in 61% of the cases the precipitation pollution will be lower while on the other scenario (100%

increase of air pollution), in 70% of the cases the precipitation pollution will be higher. Also, by enhancing the air quality (decreasing the air pollution concentration by 50%) all of the future predictions will be lower than the current average concentration.

Fig 65 shows the model predictions in spring which illustrates a similar trend to winter. In spring, 86%, 69% and 100% of the cases will experience a lower concentration of pollution for scenarios of 50% and 100% increase and 50% decrease in air pollution.

The situation in summers will be completely different than winter and spring. By increasing air pollution, the concentration of the pollutant will raise. In the scenarios of 50% and 100% increase of the air contamination, in 96% and 100% of the cases, the average of atmospheric deposition predictions will be higher than the baseline concentration. However, by improving the air quality by 50%, in 59% of the cases, the precipitation pollution will be lower than the current situation.

The results of atmospheric deposition in fall are similar to summer. It shows that increasing air contamination has a direct impact on precipitation chemistry. By increasing the concentration of the pollutants in the air by 50% and 100%, the atmospheric deposition in 64% and 93% of the cases would be higher than the current average concentration. On the other hand, in the decreasing air contamination scenario, in 96% of the cases, the atmospheric deposition contamination will be lower than the current concentration.

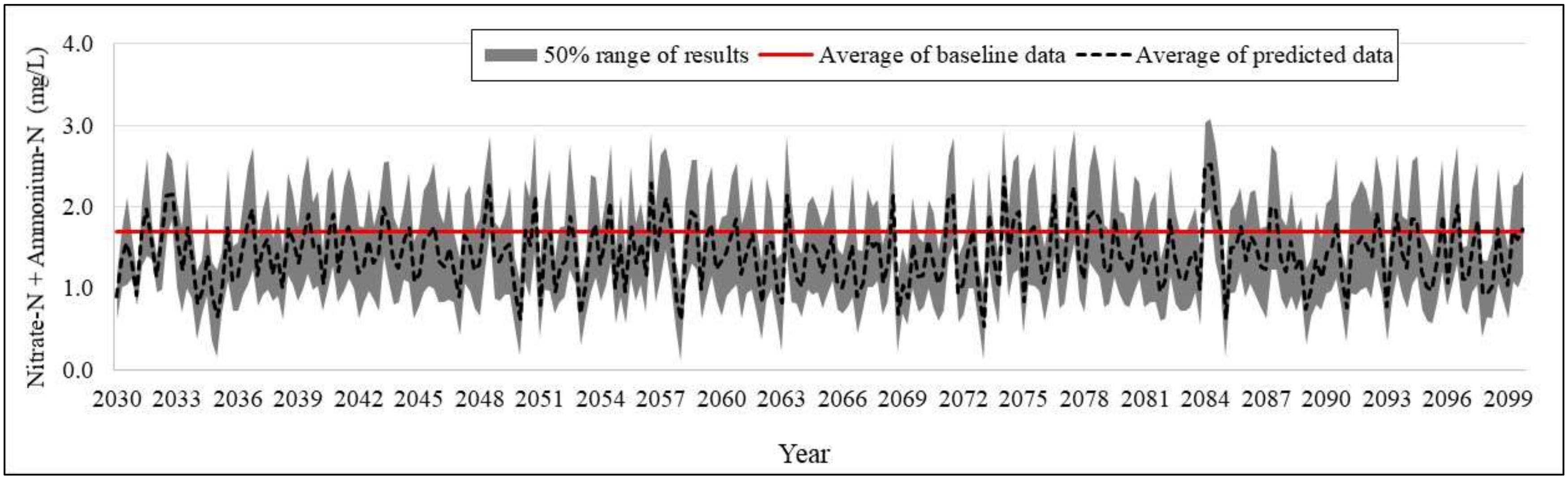
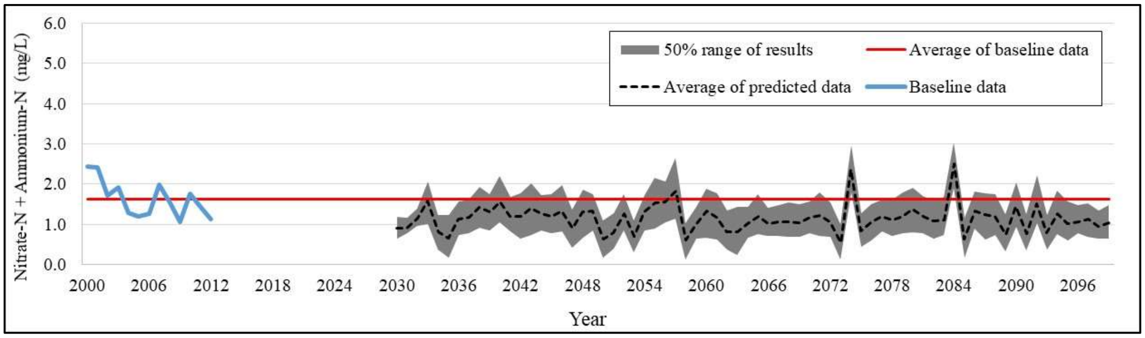


Fig 62. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Grimsby region under the future scenario of climate change



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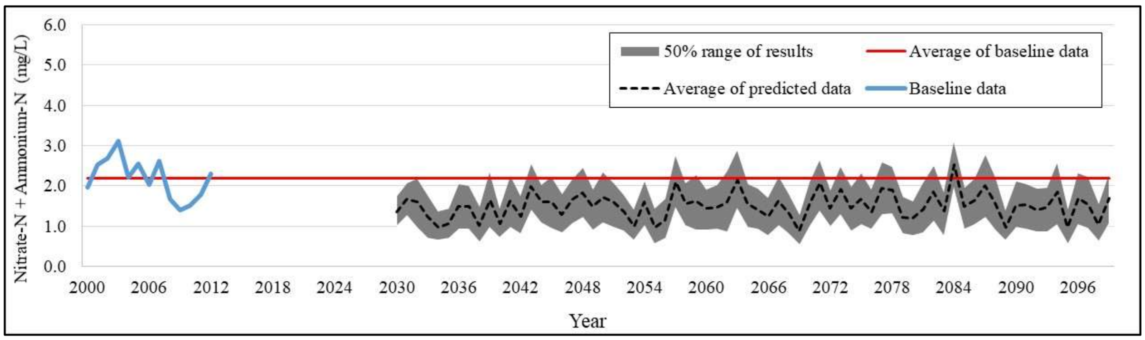

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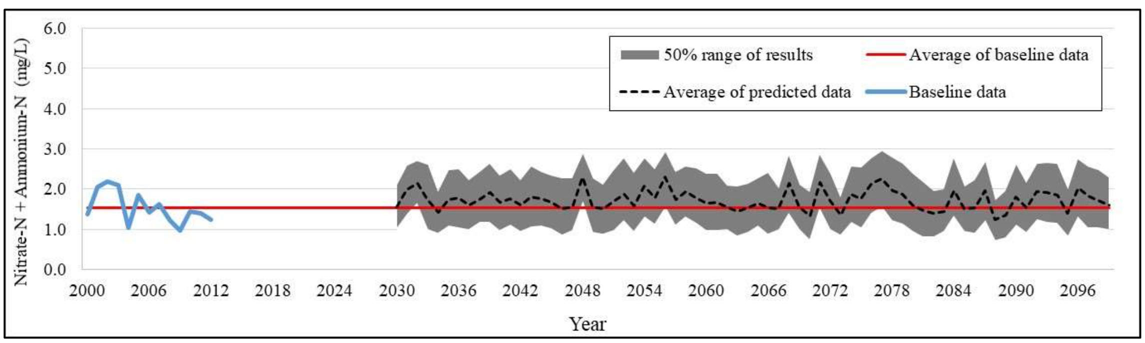

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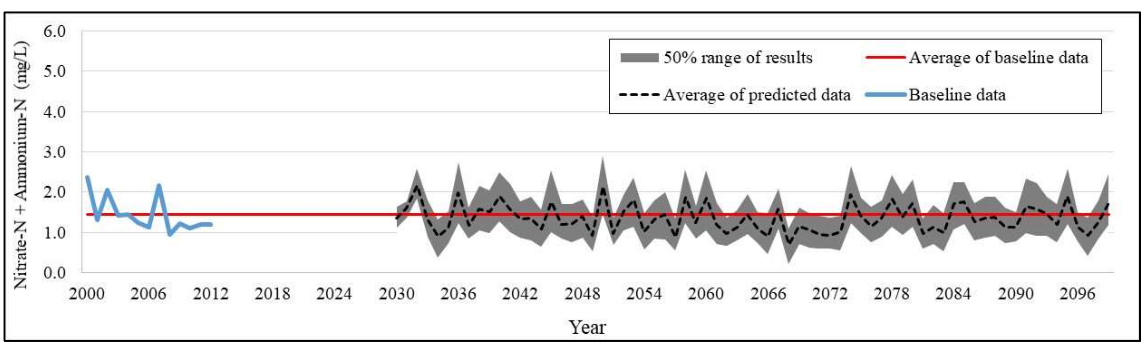
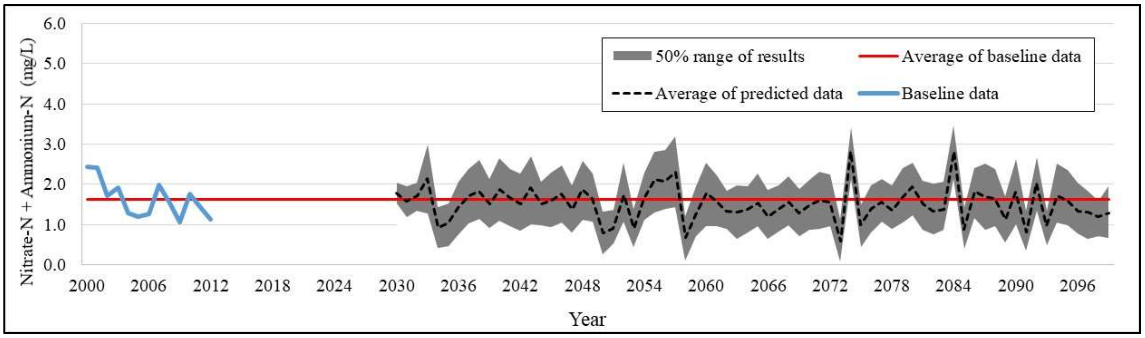
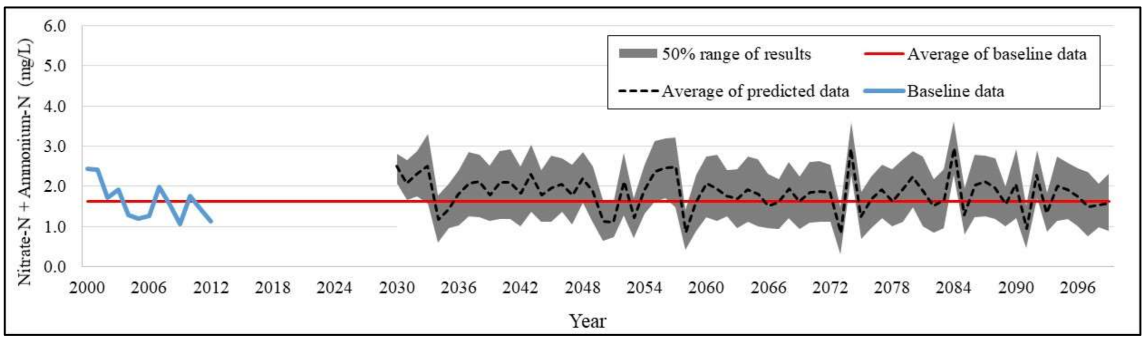


d)

Fig 63. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Grimsby region under a future scenario of climate change for different seasons a) Winter b) Spring c) Summer d) Fall



a)



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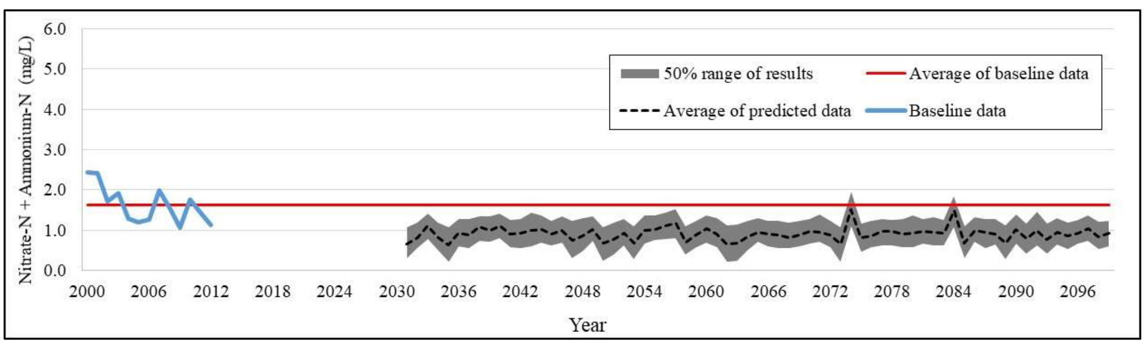
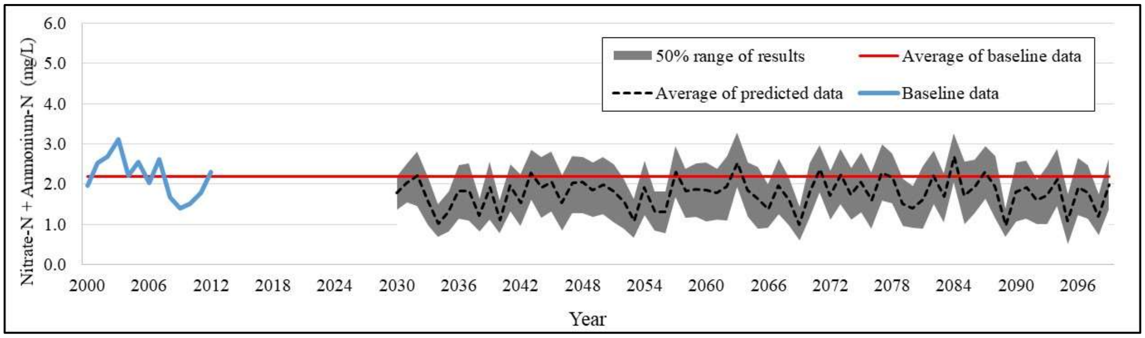
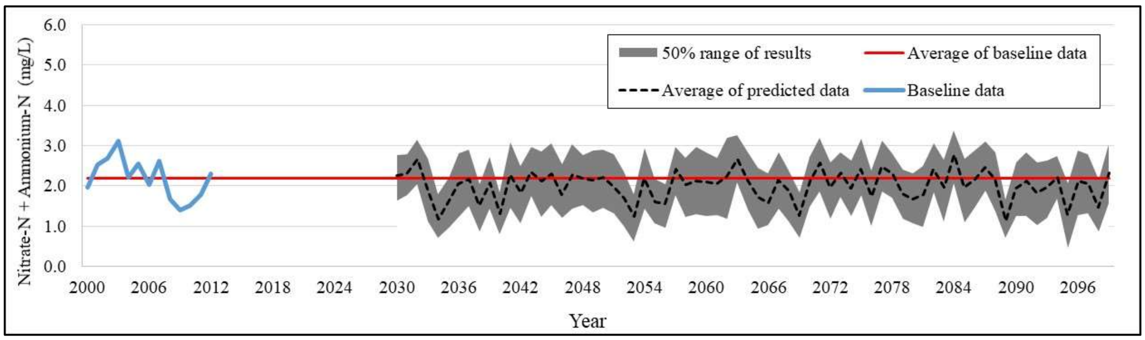


c)

Fig 64. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Grimsby region in winter for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease



a)



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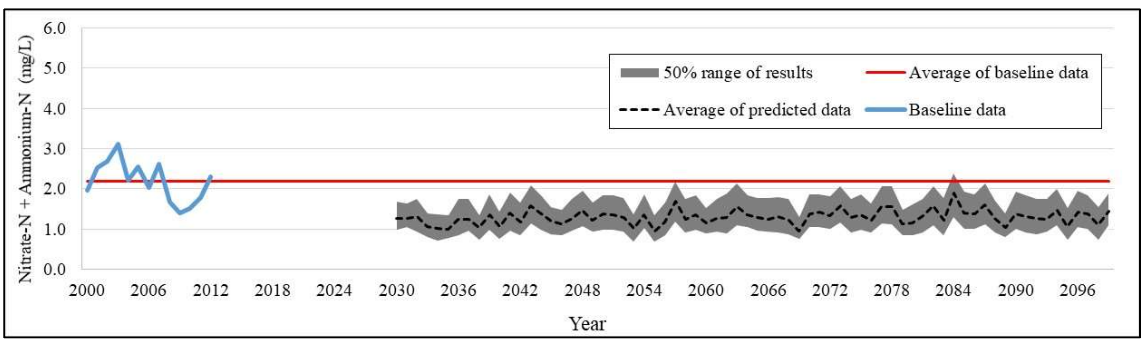
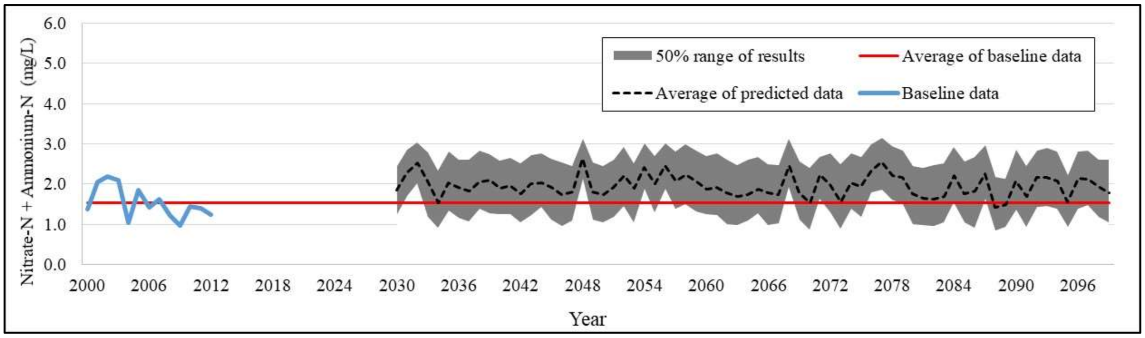
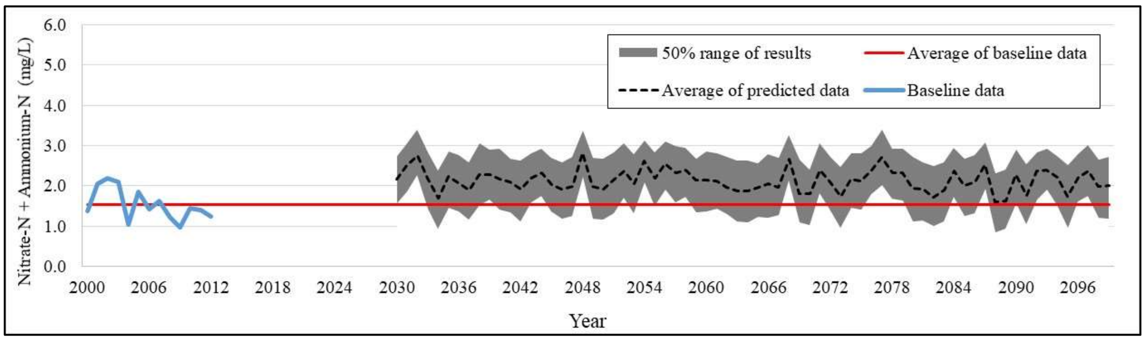


c)

Fig 65. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Grimsby region in spring for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease



a)



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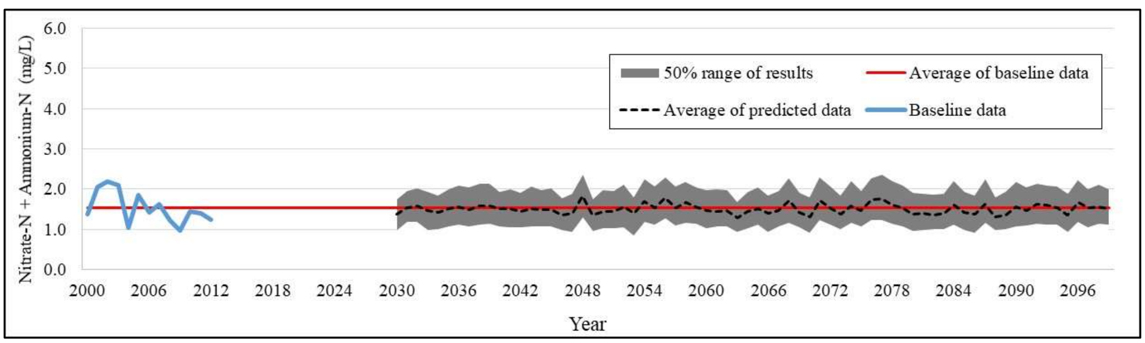


c)

Fig 66. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Grimsby region in summer for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

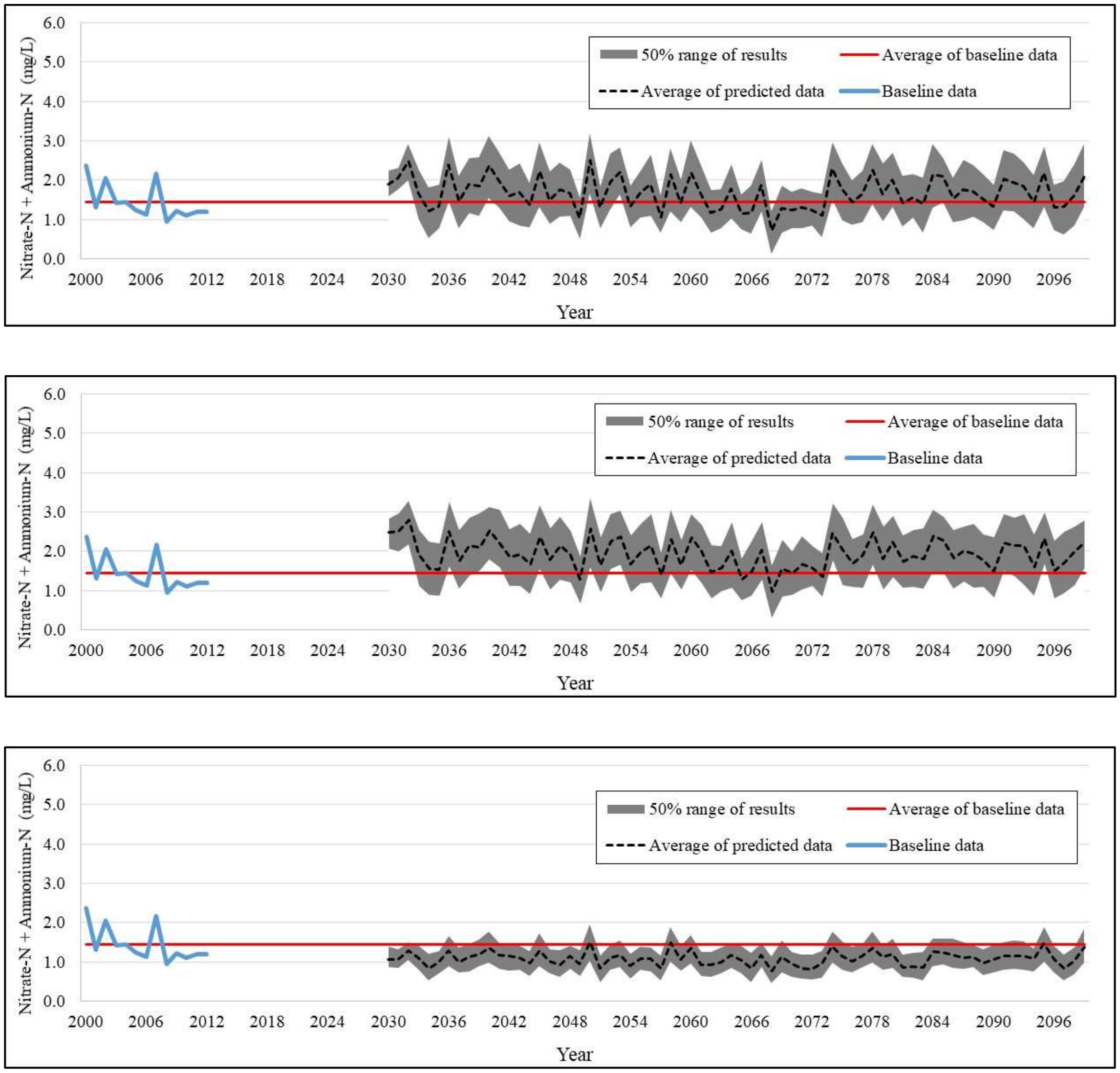


Fig 67. The concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Grimsby region in fall for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

Table 15 shows the summary of all sensitivity analysis of air pollution impacts in different seasons in the Grimsby region. Based on these results, by increasing the air contamination, the likelihood of decreasing the precipitation quality will raise especially in summer and fall. However, by decreasing the air contamination, the concentration of Nitrate-N + Ammonium-N in precipitation will be lower than the current average concentration.

Table 15. Changes in the concentration of Nitrate-N + Ammonium-N in atmospheric deposition in Grimsby region under different air pollution scenarios in the future

	Changes in air pollution		
	50% increase	100% increase	50% decrease
Winter	Lower in 61% of the cases	Higher in 70% of the cases	Lower in 100% of the cases
Spring	Lower in 86% of the cases	Lower in 69% of the cases	Lower in 100% of the cases
Summer	Higher in 96% of the cases	Higher in 100% of the cases	Lower in 59% of the cases
Fall	Higher in 64% of the cases	Higher in 93% of the cases	Lower in 96% of the cases

5.3.2. Water quality modeling in Lake Ontario in Grimsby region

In the modeling of water quality in Lake Ontario in Grimsby region, in order to extract 100 high performance model, 176336 trials were executed. Fig 68 and Fig 69 show the performances of the 100 models in terms of R-value and RMSE.

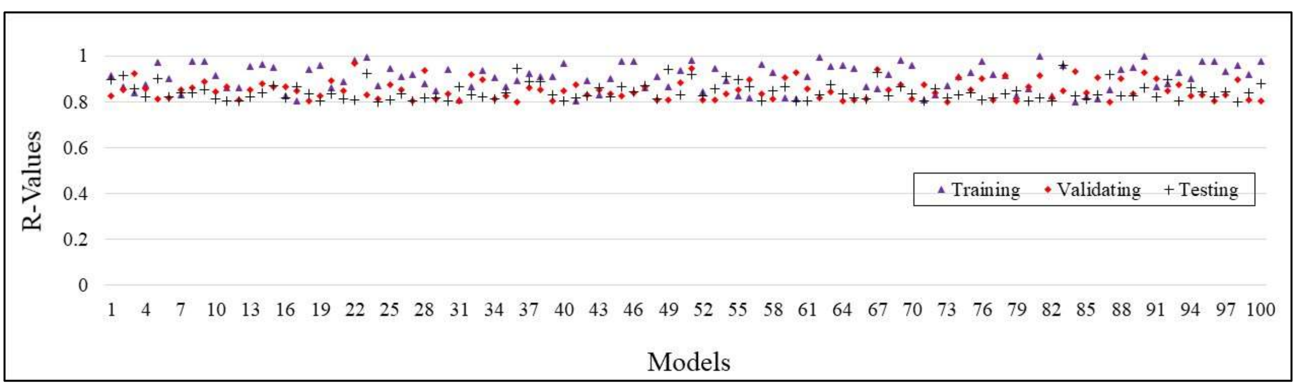


Fig 68. R-value of 100 water quality models of Lake Ontario in Grimsby region

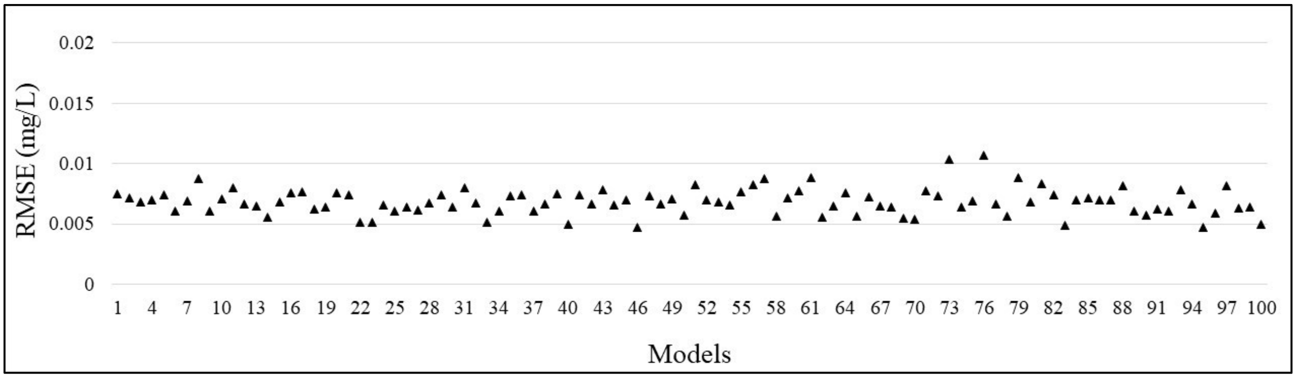


Fig 69. RMSE of 100 water quality models of Lake Ontario in Grimsby region

5.3.2.1. Climate change impacts on water quality of Lake Ontario in Grimsby region

In Fig 70, the predictions of Nitrate-N + Ammonium-N in Lake Ontario in the Grimsby region are presented. Based on the predictions for the future situation, in 82% of the cases, the concentration of the contaminant in water would be higher than the baseline average concentration (the average concentration would be 8% higher). In addition, the average of Nitrate-N + Ammonium-N concentration in Lake Ontario in different time periods has been shown in Table 16. It shows that in all the time periods the concentration is higher than the baseline average.

Regarding the seasonal analysis (Fig 71), most of the future concentration of Nitrate-N + Ammonium-N will be higher than the baseline average concentration (All seasons except spring). In winter, summer and fall in 84%, 77% and 100% of the cases the water pollution will be higher than the baseline. However, in the spring, in 56% of the cases, the contamination of the precipitation will be lower than the baseline average.

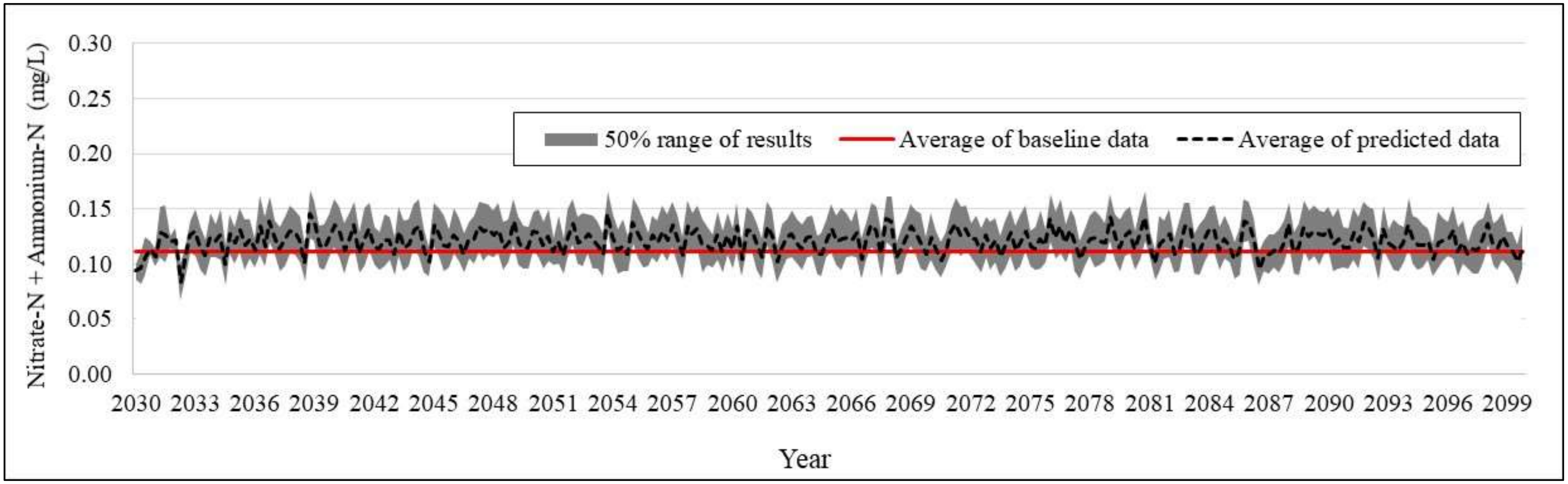


Fig 70. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Grimsby region under the future scenario of climate change

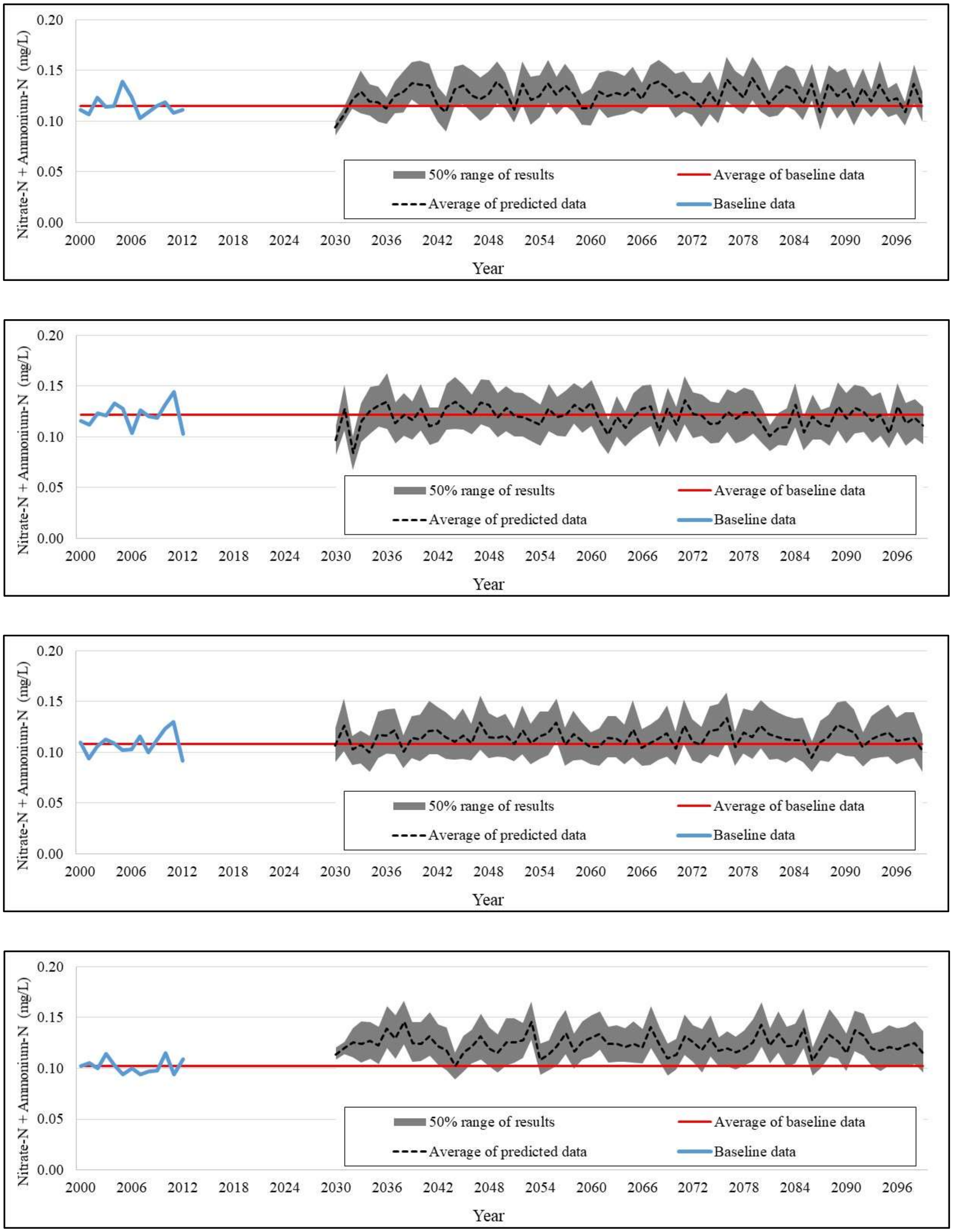
Table 16. The average of Nitrate-N + Ammonium-N concentration in Lake Ontario in Grimsby region in different time periods

	Time period	Average of Nitrate-N + Ammonium-N (mg/L)
Baseline	2000-2012	0.112
	2030-2039	0.119
	2040-2049	0.122
	2050-2059	0.122
Future scenario	2060-2069	0.121
	2070-2079	0.122
	2080-2089	0.120
	2090-2099	0.120

5.3.2.2. Sensitivity analysis of air pollution under climate change situation on water quality of Lake Ontario in Grimsby region

In terms of sensitivity analysis of the models with respect to air quality, Fig 72 to Fig 75 are showing the results of sensitivity analysis for winter, spring, summer, and fall respectively.

In addition to the figures, Table 17 shows a summary of the sensitivity analysis of air pollution impacts. As can be seen in this table, by increasing the air contamination, in all seasons and most of the cases, the water contamination will be higher than the current situation. Even, by decreasing the air pollutants, still in winter and fall no improvement happens. However, this scenario shows that by improving the air quality, the precipitation contamination will be lower than the baseline average concentration.



a) b) c) d)

Fig 71. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Grimsby region under a future scenario of climate change for different seasons a) Winter b) Spring c) Summer d) Fall

Table 17. Changes in the concentration of Nitrate-N + Ammonium-N in Lake Ontario in Grimsby region under different air pollution scenarios in the future

	Changes in air pollution		
	50% increase	100% increase	50% decrease
Winter	Higher in 89% of the cases	Higher in 89% of the cases	Higher in 73% of the cases
Spring	Higher in 60% of the cases	Higher in 66% of the cases	Lower in 84% of the cases
Summer	Higher in 90% of the cases	Higher in 97% of the cases	Lower in 84% of the cases
Fall	Higher in 100% of the cases	Higher in 100% of the cases	Higher in 94% of the cases

5.3.3. Summary of the modeling results in the Grimsby region

In the Grimsby region, the precipitation generally will be lower than the current concentration. This phenomenon will happen in spring, summer, while in winter, the precipitation will be slightly higher than the baseline. The amount of precipitation in fall is unchanged. The temperature trend will be completely the same as Toronto and Cobourg regions and will increase from the average of 12 °C in 2012 to 25 °C in 2099.

Although the amount of precipitation in spring is lower than the baseline (Fig 58), the atmospheric deposition pollution is lower than the baseline which is not reasonable. However, in summer, this value is higher than the baseline average. In winter and fall, precipitation contamination is much lower than the current concentration. Technically, it seems that the modeling of atmospheric deposition in this area is not showing some reasonable results. The possible reason might be because of the long distance between the atmospheric deposition station (Longwoods) and the Grimsby region which is almost 200 km. In addition, the Longwoods station is near the cities of

Windsor and Detroit which are industrial cities and as a result, the data of atmospheric deposition in this station could not reflect the situation of atmospheric deposition in the Grimsby region.

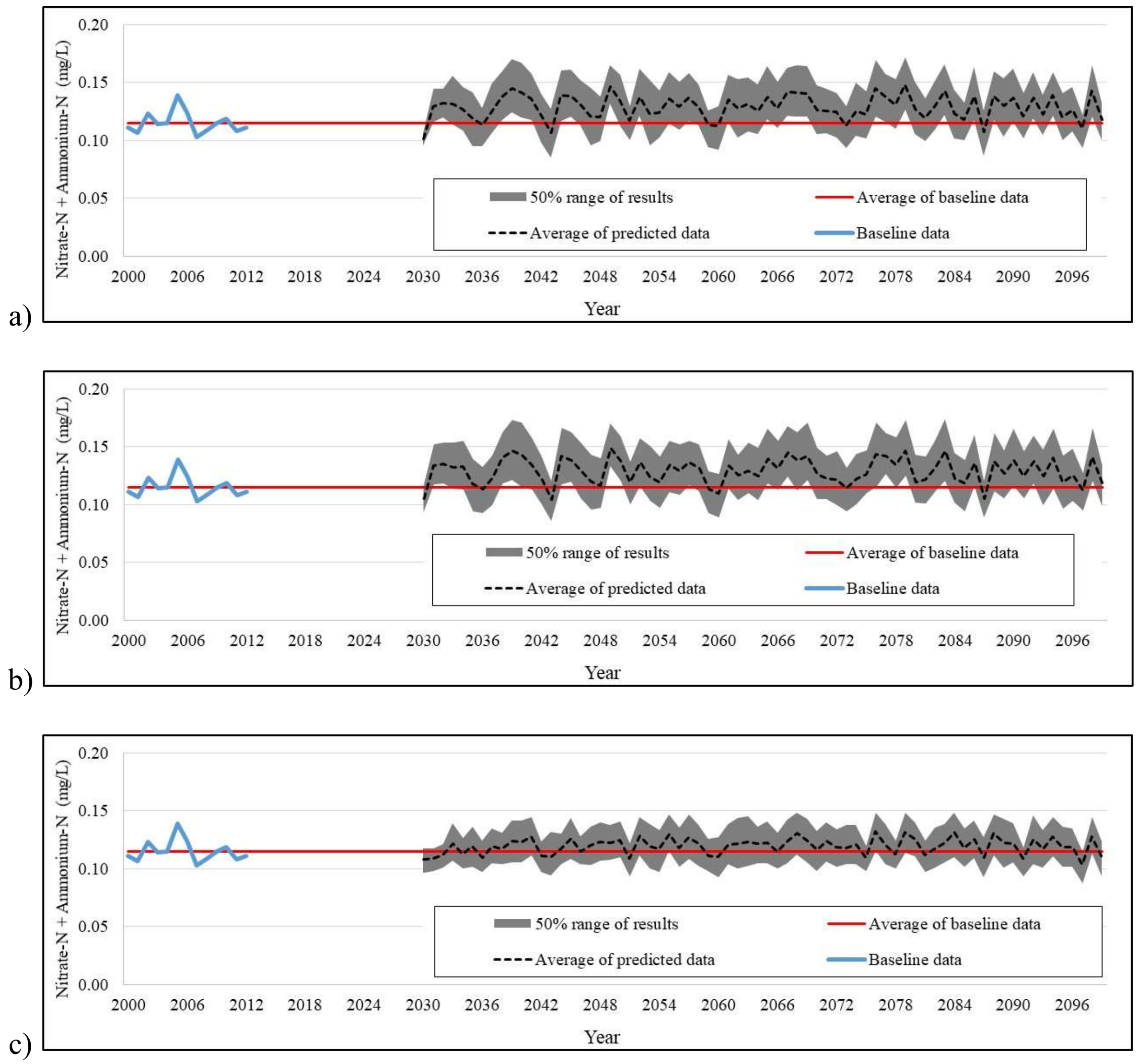
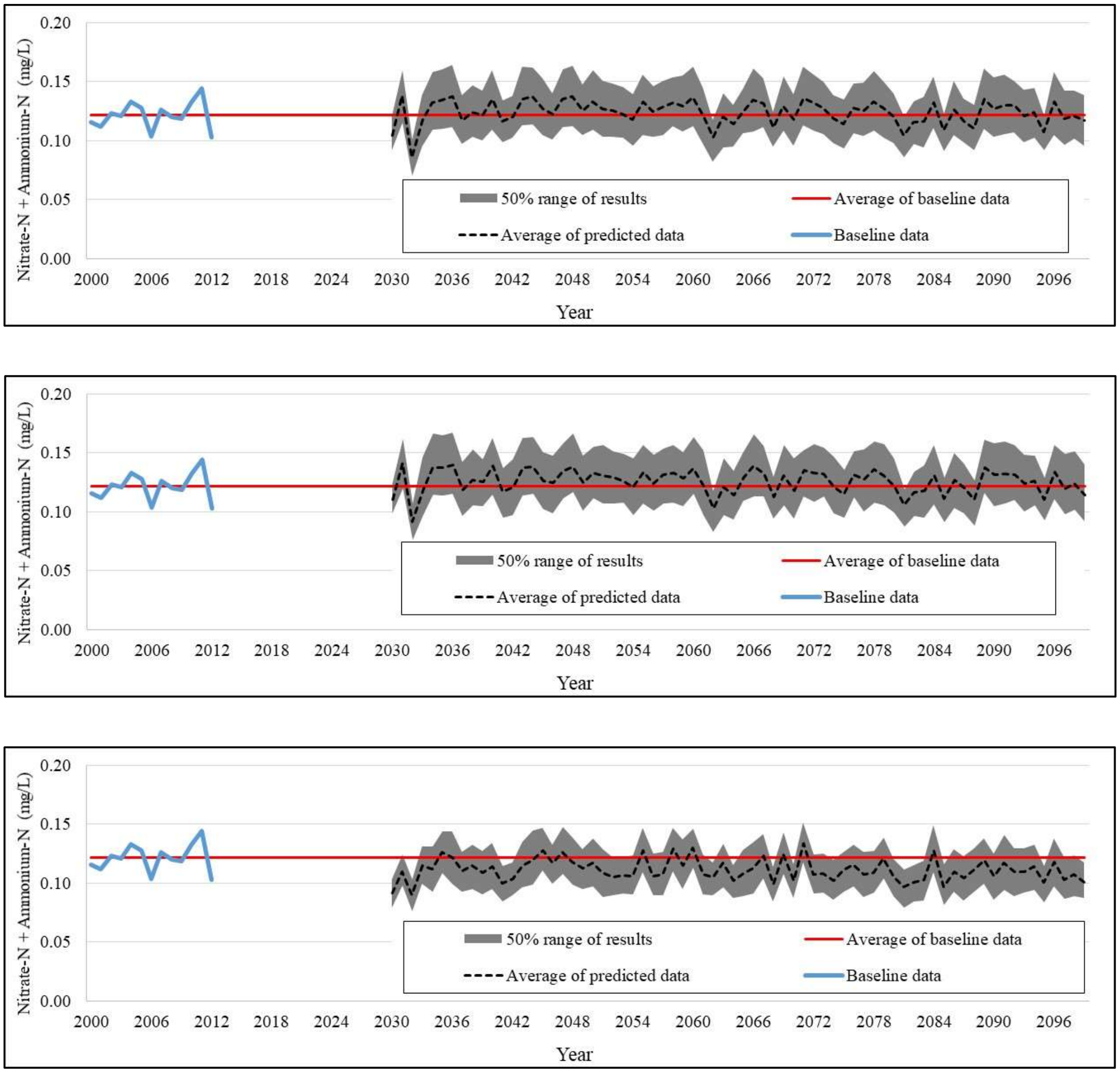
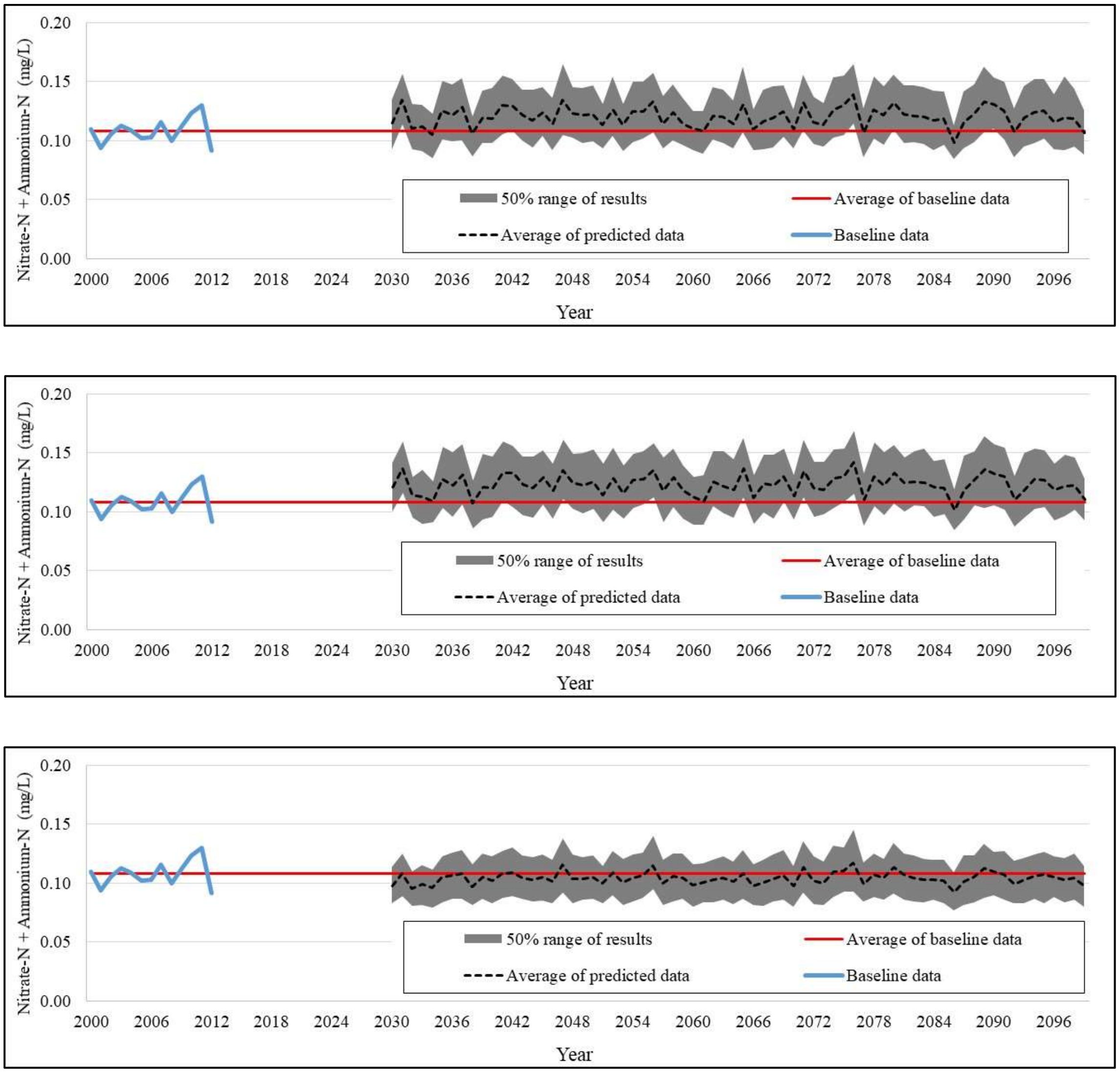


Fig 72. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Grimsby region in winter for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease



a)
b)
c)

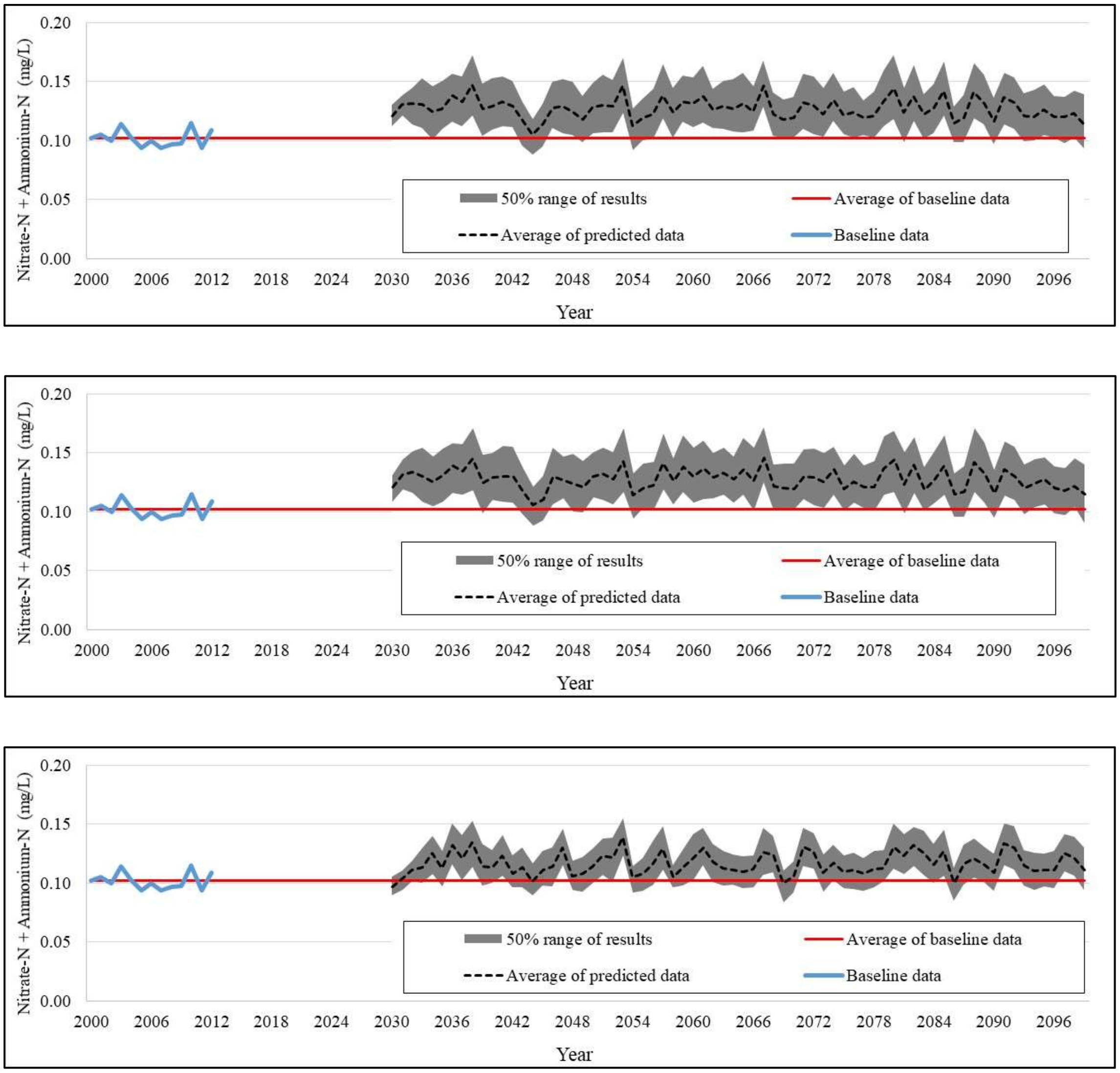
Fig 73. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Grimsby region in spring for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease



a) b) c)

Fig 74. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Grimsby region in summer for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

On the other hand, the results of water quality modeling are quite reasonable. With respect to a considerable decline in precipitation throughout the year, the pollution of Lake Ontario near the Grimsby region will be higher than the current situation. In addition, by increasing the air pollutants, the situation will be more critical. However, declining the air pollutants in spring and summer can improve the situation while in fall and winter this action can not cover the lack of precipitation and the water contamination still is higher than the current average concentration.



a) b) c)

Fig 75. The concentration of Nitrate-N + Ammonium-N in Lake Ontario in Grimsby region in fall for different air pollution scenarios a) 50% increase b) 100% increase c) 50% decrease

5.4. Discussion

The proposed method has been applied in three different regions near Lake Ontario: Toronto, Cobourg, and Grimsby. These regions have different characteristics in terms of population and air contamination. The Toronto region has more residential areas and as a result, it has more air pollution (Fig 6 and Fig 7). Grimsby area has less population comparing to Toronto region, but it is close to some other cities such as Hamilton and Niagara. On the other hand, the Cobourg area is more natural and has the lowest population and most of the lands in this area are forest and agriculture. These differences between the three regions were the main reason for selecting them to apply the proposed method of this study. In this way, it was possible to evaluate the impacts of climate change and air contamination on atmospheric deposition and water quality in different situations.

The results of atmospheric deposition in three regions show that in total, by applying the climate change data in the future, regarding the lower precipitation (except in winters), the contamination of the atmospheric deposition will be higher than the current average concentration. The results of atmospheric deposition modeling in Grimsby region was not reasonable but comparing the results of Toronto and Cobourg regions shows that considering the baseline atmospheric deposition concentrations in these regions (1.3 mg/L in Cobourg region and 1.45 mg/L in Toronto region), the climate change has more impacts on the Cobourg region rather than the Toronto region. Focusing on the current air contamination in theses regions shows that the concentration of air contamination in Cobourg region is quite lower than the Toronto region (Fig 6 and Fig 7). Therefore, in Cobourg region, the concentration of the pollutants in precipitation is more correlated to the meteorological specification rather than the air contamination while the situation in Toronto region is vice versa. Regarding this fact, the precipitation contamination in Cobourg region in future will be (average of 1.63 mg/L) higher than the Toronto station (average of 1.51 mg/L) because of the changes in the meteorological characteristics and assuming that the air contamination will be the same as baseline. As mentioned, in a different way, the precipitation quality in the Toronto region is more related to air quality. The results of sensitivity analysis of air contamination show that Toronto region is more sensitive to air contamination rather than the Cobourg region. In fact, by decreasing the air contamination, the precipitation contamination will decline considerably in Toronto region comparing to Cobourg region. In Cobourg region, still the impacts of climate change are high and reducing the air contamination can not improve the precipitation quality considerably.

In total, comparing the results of the atmospheric deposition modeling to the previous studies shows that the findings of this research are reasonable. Simpson et al. (2014) showed that impact of emission changes is much greater than the impact of climate change in Europe which is quite similar to the results of this study in Toronto region. Also, St-Laurent et al. (2017) showed that precipitation contamination in summer will be higher than the current concentration which will lead to increasing the NO_3^- concentrations in surface water. Also in all of the previous studies it has been proved that in the areas with more precipitation, the precipitation contamination will be lower than the current concentration which is the same as the results of this study in winters.

In terms of water quality modeling, the results of modeling are more reasonable rather than the atmospheric deposition models. It is mostly because of the distance between atmospheric deposition monitoring stations to the air quality monitoring stations. However, generally, the air quality monitoring stations are closer to the water quality monitoring stations and as a result, the modeling process shows more reasonable results.

The results of water quality modeling in Toronto and Cobourg regions are quite the same. Generally, air contamination can not impact the water quality of Lake Ontario in these regions. However, by increasing the air contamination, in seasons with more precipitation, it is possible to influence the water quality of Lake Ontario. On the other hand, in Grimsby region, considering the less precipitation throughout the year, the water contamination in Lake Ontario will be higher than the current average concentration which is because of less dilution process.

None of the previous studies focused on the impacts of atmospheric deposition and climate change on water quality at the same time. Kothawala et al. (2011) demonstrated a direct relationship between in stream NO_3^- to atmospheric deposition in south-central Ontario, Canada. However, in most climate change research studies, the impacts of atmospheric deposition considered negligible. Nevertheless, by applying the ANN and implementing the climate change impacts on the atmospheric deposition and the water quality and also implementing the air contamination sensitivity analysis the novelties of this research would be:

- The application of ANN showed a good efficiency to quantify the impacts of climate change and atmospheric deposition on water quality
- The climate change will reduce the precipitation in summer and as a result in most cases, the contamination of precipitation in summer and the following autumn can be quite undesirable due to less dilution of pollution
- Increasing the air contamination especially in a residential area can lead to decline the water quality and as a result, the atmospheric deposition should not be omitted from the water quality simulation process
- The proposed method can be applied in other places

6. Chapter 6: Conclusion

6.1. Conclusion

Climate change can cause various impacts on our environment due to increasing air temperature and precipitation severity. Based on the results of climate change models, it is expected to have about 15 °C by the end of the 21st century. In addition to temperature increases, the trend of precipitation will change considerably. The amount of precipitation in summer will be dramatically lower than the current amount and in winter, the precipitation will increase. Therefore, it is important to evaluate the impacts of these changes on precipitation chemistry as well as water resource quality. Most of the previous studies just focused on the impacts of climate change on water quality. A few of them tried to address the impacts of climate change on the atmospheric deposition and none of them concentrated on both atmospheric deposition and climate change impacts on water quality. Most of the previous studies in terms of Lake Ontario's water quality were focusing on the local statistical trends. In most cases, a physically based model has been developed for Lake Ontario without considering the impacts of atmospheric deposition.

In this research, the developed models tried to quantify the impacts of climate change on both atmospheric deposition and water quality of Lake Ontario in three different regions: Toronto, Cobourg, and Grimsby. The modeling parameter was Nitrate-N + Ammonium-N.

To develop the models, a data driven modeling approach (ANNs) has been selected for water and precipitation quality. In this method, by using the historical data in monitoring stations, a relationship between inputs (air quality and meteorological characteristics) and outputs (precipitation and water quality) was developed.

The results of water quality and atmospheric deposition simulations illustrated that climate change has more impacts on atmospheric deposition rather than the water quality of Lake Ontario. In most cases, the situation in summer and the following fall can be quite undesirable due to less precipitation. In these two seasons, the contamination of precipitation became higher comparing to the baseline average concentration. However, these changes usually did not affect the water quality of Lake Ontario although it has some minor impacts in the places with more contaminated air (City of Toronto) or fewer precipitation events in the future (Town of Grimsby).

In addition to the evaluation of climate change impacts on precipitation and water quality, a sensitivity analysis of air pollution has been conducted. In this section three scenarios of air contamination levels have been applied to the models (2 scenarios of increasing and 1 scenario of decreasing the air contamination). This process showed that air pollution has a direct impact on atmospheric deposition. Even in more wet seasons which have more rainfall, by increasing the air contamination, there is a possibility to decline the precipitation quality comparing to the current situation. In addition to atmospheric deposition, the declining of the air quality can lead to some unsatisfactory impacts on the water quality of Lake Ontario especially in fall and winter near big cities like Toronto. However, the results of the scenario of declining the air contamination demonstrated that by controlling the air pollution, in almost all of the cases, the atmospheric deposition and water contamination will be lower than the current levels.

With respect to the findings of this research, it should be mentioned that by controlling the air quality at the current situation or decreasing the contamination concentration in the air, the atmospheric deposition can not impact the water quality of Lake Ontario. However, the scenarios of air pollution increasing showed that air contamination can alter the water quality of Lake Ontario in some cases and as a result, it should be mentioned that omitting the atmospheric deposition impacts from the water quality modeling processes, can lead to an underestimation of the future contamination level.

Ultimately, by applying the methodology of this research, the impacts of climate change, atmospheric deposition and different levels of air contamination on water quality have been quantified appropriately. In Canada, with respect to the current situation of air quality and precipitation, the modeling results showed that atmospheric deposition will not be a major concern in the future. However, in other places with less precipitation and higher air contamination, the atmospheric deposition could be a threat that needs to be investigated more accurately.

6.2.Recommendations for future work

To reduce the uncertainty of the results some extra investigations can be applied in the future including:

- Focusing on the contamination load in water and precipitation instead of its concentration.

In this study, the modeling process focused on the prediction of the contamination concentrations. However, the contamination load is another important factor that can have its own impacts on water quality and should be evaluated separately.

- Applying the downscaled results of other climate change models.

As mentioned in section 4.6, in terms of the climate change predictions, only one of the emission scenarios (RCP8.5) has been selected. Nevertheless, by applying the meteorological predictions of other emission scenarios, a better understanding of all the possible impacts of climate change will be provided.

- Comparing the results of this research with a similar physically based model.

As mentioned in Chapter 2, there are a lot of physically based models that can be applied in the same research approach. Therefore, by having the results of similar research which uses a physically based model, there would be the possibility to compare the results of two modeling approach (data driven and physically based models).

- Applying other methods of data driven modeling and comparing the efficiencies.

Similar to what has been explained in the previous section, by having the results of other modeling techniques, it is possible to compare the results and evaluate the performance of different modeling approaches for various applications.

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Appendixes

Appendix A: The raw data series of inputs and outputs of models

Table 18. The seasonal average concentration of Nitrate-N + Ammonium-N (mg/L) in atmospheric deposition monitoring stations

Year	Season	Egbert	Longwoods	Warsaw
2000	Winter	1.484	2.042	1.649
	Spring	2.107	2.237	1.539
	Summer	1.578	1.473	1.396
	Fall	2.354	2.358	1.586
2001	Winter	1.575	1.947	1.411
	Spring	2.300	2.361	1.838
	Summer	2.205	2.699	2.640
	Fall	1.107	1.277	1.533
2002	Winter	2.795	1.737	2.227
	Spring	1.225	2.675	1.346
	Summer	2.476	1.977	1.647
	Fall	1.574	2.246	1.672
2003	Winter	0.894	1.420	1.318
	Spring	1.912	2.908	1.548
	Summer	1.686	2.782	1.551
	Fall	0.882	1.428	1.019
2004	Winter	1.108	1.182	1.296
	Spring	1.878	1.847	1.524
	Summer	1.638	1.668	1.475
	Fall	1.237	1.280	1.000
2005	Winter	0.932	1.015	1.124
	Spring	2.431	2.450	1.734
	Summer	1.503	2.186	1.423
	Fall	1.073	1.179	1.079

Year	Season	Egbert	Longwoods	Warsaw
2006	Winter	1.083	1.219	1.322
	Spring	1.318	1.490	1.108
	Summer	1.558	1.893	1.183
	Fall	1.062	1.226	0.910
2007	Winter	1.091	1.804	1.064
	Spring	1.597	2.198	1.535
	Summer	1.959	2.028	1.301
	Fall	1.234	2.356	1.347
2008	Winter	0.929	1.247	0.998
	Spring	1.665	1.676	1.251
	Summer	1.266	1.583	0.926
	Fall	0.768	0.859	0.656
2009	Winter	1.002	1.166	1.061
	Spring	1.587	1.301	1.380
	Summer	1.179	1.140	0.980
	Fall	0.910	1.036	0.746
2010	Winter	0.800	1.411	0.912
	Spring	1.606	1.772	1.151
	Summer	1.195	1.652	1.138
	Fall	0.652	0.990	0.708
2011	Winter	0.983	1.287	1.220
	Spring	0.911	1.527	0.982
	Summer	1.419	1.759	1.082
	Fall	1.086	1.222	1.009
2012	Winter	1.108	1.185	1.173
	Spring	2.135	2.242	1.675
	Summer	1.535	1.368	1.187
	Fall	1.595	1.081	1.280

Table 19. The seasonal average concentration of Nitrate-N + Ammonium-N (mg/L) in water quality monitoring stations

Year	Season	Toronto	Cobourg	Grimsby
2000	Winter	0.173	0.115	0.111
	Spring	0.132	0.105	0.116
	Summer	0.128	0.083	0.110
	Fall	0.108	0.104	0.102
2001	Winter	0.145	0.123	0.107
	Spring	0.139	0.091	0.112
	Summer	0.106	0.077	0.094
	Fall	0.133	0.095	0.105
2002	Winter	0.136	0.131	0.123
	Spring	0.147	0.098	0.123
	Summer	0.112	0.073	0.106
	Fall	0.119	0.099	0.100
2003	Winter	0.140	0.118	0.114
	Spring	0.176	0.094	0.121
	Summer	0.115	0.084	0.113
	Fall	0.133	0.107	0.114
2004	Winter	0.135	0.116	0.115
	Spring	0.210	0.106	0.133
	Summer	0.116	0.071	0.109
	Fall	0.112	0.106	0.103
2005	Winter	0.113	0.110	0.139
	Spring	0.140	0.094	0.128
	Summer	0.114	0.066	0.102
	Fall	0.104	0.111	0.094

Year	Season	Toronto	Cobourg	Grimsby
2006	Winter	0.165	0.116	0.124
	Spring	0.127	0.000	0.104
	Summer	0.103	0.067	0.103
	Fall	0.120	0.088	0.100
2007	Winter	0.155	0.100	0.103
	Spring	0.170	0.111	0.126
	Summer	0.139	0.086	0.116
	Fall	0.127	0.093	0.094
2008	Winter	0.148	0.135	0.109
	Spring	0.141	0.099	0.120
	Summer	0.107	0.079	0.100
	Fall	0.114	0.088	0.097
2009	Winter	0.145	0.126	0.115
	Spring	0.141	0.108	0.119
	Summer	0.112	0.085	0.112
	Fall	0.113	0.076	0.098
2010	Winter	0.148	0.104	0.119
	Spring	0.183	0.097	0.132
	Summer	0.117	0.090	0.123
	Fall	0.114	0.094	0.115
2011	Winter	0.125	0.102	0.108
	Spring	0.152	0.106	0.144
	Summer	0.123	0.100	0.130
	Fall	0.104	0.089	0.094
2012	Winter	0.131	0.104	0.111
	Spring	0.131	0.096	0.103
	Summer	0.096	0.078	0.092
	Fall	0.128	0.093	0.109

Table 20. The seasonal average concentration of nitrogen oxide (μg/L) in air quality monitoring stations

Year	Season	Peterborough	Toronto Downtown	Toronto West	Burlington	Hamilton Downtown	Brampton	St. Catharines
2000	Winter	5.913	17.719	23.918	29.302	15.784	12.924	15.643
	Spring	2.385	10.270	11.039	17.825	9.512	7.713	8.689
	Summer	2.459	9.389	12.230	14.600	8.801	6.510	7.248
	Fall	7.632	19.297	29.929	27.269	24.792	21.697	17.474
2001	Winter	6.088	12.197	16.104	15.879	11.856	12.924	15.643
	Spring	1.575	7.077	10.676	12.614	9.408	7.713	8.689
	Summer	1.887	6.748	9.524	9.981	5.851	5.656	7.248
	Fall	6.560	14.199	22.299	17.899	19.153	20.180	17.474
2002	Winter	5.088	9.413	11.246	12.647	11.545	10.041	8.038
	Spring	1.547	5.739	9.620	10.341	8.961	6.932	2.540
	Summer	2.103	6.129	9.913	16.014	7.435	6.085	3.042
	Fall	5.904	11.534	16.455	14.144	14.340	13.532	2.004
2003	Winter	4.782	11.980	22.145	18.661	15.190	13.596	8.038
	Spring	1.772	6.395	24.423	8.357	8.651	5.952	2.540
	Summer	1.819	6.151	26.141	8.552	6.813	4.740	3.042
	Fall	5.203	10.320	37.344	18.229	16.375	17.391	2.004
2004	Winter	4.782	8.485	30.306	12.623	10.798	9.191	8.038
	Spring	1.772	4.990	19.310	8.365	7.258	5.968	2.540
	Summer	1.819	6.088	24.061	10.033	5.510	4.907	3.042
	Fall	5.203	11.002	32.937	13.226	14.423	14.596	2.004
2005	Winter	3.094	12.668	42.025	21.770	17.037	13.840	5.867
	Spring	1.081	4.518	20.160	9.218	7.346	5.546	5.128
	Summer	1.527	3.711	18.266	7.162	4.599	4.349	3.874
	Fall	5.047	8.442	24.567	12.062	10.459	12.318	7.562
2006	Winter	3.094	8.954	23.483	12.519	9.106	10.440	5.588
	Spring	1.081	5.014	16.629	7.841	6.411	4.881	4.498
	Summer	1.527	4.534	14.484	6.582	4.038	4.534	2.963
	Fall	5.047	9.355	25.733	12.569	12.427	14.851	8.816
2007	Winter	2.623	7.587	19.279	10.963	8.165	6.292	4.853
	Spring	1.409	3.945	13.262	6.252	5.839	3.626	3.819
	Summer	1.918	4.153	13.539	6.389	5.920	4.174	3.961
	Fall	3.149	7.967	24.348	11.561	10.915	9.551	5.741

Year	Season	Peterborough	Toronto Downtown	Toronto West	Burlington	Hamilton Downtown	Brampton	St. Catharines
2008	Winter	3.697	6.438	18.699	7.773	8.221	7.174	3.227
	Spring	3.597	3.660	10.123	3.724	4.317	3.655	2.499
	Summer	1.275	3.408	14.881	5.333	5.017	4.100	3.338
	Fall	3.082	6.623	21.196	9.056	8.426	8.168	5.348
2009	Winter	3.008	6.620	17.600	7.976	7.967	7.121	3.574
	Spring	0.915	3.494	7.694	3.007	3.219	3.018	2.152
	Summer	0.917	3.843	11.359	4.516	3.220	2.607	2.994
	Fall	2.680	6.431	17.141	8.126	8.976	13.550	6.112
2010	Winter	1.682	4.831	13.996	4.771	4.389	2.985	3.322
	Spring	0.920	3.423	10.069	3.381	4.969	2.240	1.960
	Summer	1.262	2.137	8.444	3.592	2.553	2.250	1.339
	Fall	3.136	6.279	21.326	8.226	8.300	7.526	4.362
2011	Winter	2.835	4.794	13.666	6.323	5.982	5.517	2.517
	Spring	1.139	2.133	7.327	2.885	4.241	2.807	1.433
	Summer	1.187	1.905	9.246	3.039	2.655	2.237	1.328
	Fall	3.674	4.932	19.105	6.335	6.819	8.029	3.828
2012	Winter	2.210	3.318	10.267	5.059	5.400	4.741	1.896
	Spring	0.947	1.949	8.473	2.395	3.080	1.945	1.385
	Summer	1.128	1.980	8.944	2.502	2.061	1.787	1.240
	Fall	2.731	3.940	17.485	7.919	7.904	9.430	5.340

Table 21. The seasonal average concentration of nitrogen dioxide (µg/L) in air quality monitoring stations

Year	Season	Peterborough	Toronto Downtown	Toronto West	Burlington	Hamilton Downtown	Brampton	St. Catharines
2000	Winter	13.772	30.142	27.315	20.601	21.702	21.964	18.354
	Spring	9.524	25.869	22.217	21.094	21.793	20.374	16.914
	Summer	7.111	20.941	18.738	16.776	18.309	18.416	14.295
	Fall	13.458	29.366	24.679	22.891	25.165	21.853	18.145
2001	Winter	13.790	30.602	24.348	20.602	25.130	21.964	18.354
	Spring	7.737	28.527	21.834	17.684	25.340	20.374	16.914
	Summer	7.460	22.879	17.851	14.868	18.380	14.690	14.295
	Fall	12.808	26.567	20.869	16.456	21.318	19.405	18.145
2002	Winter	13.467	25.404	21.930	18.127	22.437	17.954	19.104
	Spring	7.663	23.849	20.539	16.800	20.983	16.669	9.078
	Summer	6.401	20.780	18.298	20.216	18.731	13.716	6.909
	Fall	10.671	23.313	20.693	18.491	22.027	17.071	5.403
2003	Winter	9.766	27.997	30.024	20.247	25.259	20.720	19.104
	Spring	4.949	22.346	26.985	15.392	22.099	16.931	9.078
	Summer	5.113	19.748	22.260	13.940	17.133	13.805	6.909
	Fall	9.383	22.677	27.082	17.827	20.606	19.445	5.403
2004	Winter	9.766	24.673	30.351	17.600	15.080	19.399	19.104
	Spring	4.949	19.065	23.531	14.707	19.284	15.437	9.078
	Summer	5.113	17.448	21.290	14.133	14.985	12.717	6.909
	Fall	9.383	19.212	24.021	14.724	17.557	17.457	5.403
2005	Winter	8.925	26.086	33.428	22.214	23.835	21.677	19.877
	Spring	5.090	19.744	25.356	16.353	20.104	15.966	13.581
	Summer	4.348	16.041	22.475	14.831	14.108	12.305	10.044
	Fall	8.579	21.034	25.251	16.058	19.058	17.794	14.585
2006	Winter	8.925	22.792	26.607	18.008	18.515	17.200	13.820
	Spring	5.090	19.186	22.342	16.064	18.535	14.997	11.242
	Summer	4.348	14.923	18.269	13.463	13.240	10.253	8.784
	Fall	8.579	19.758	22.493	17.289	17.601	16.785	13.114
2007	Winter	8.294	22.880	26.290	19.582	19.975	15.861	13.797
	Spring	5.071	17.560	20.993	14.413	16.710	12.563	11.158
	Summer	4.565	13.940	17.311	13.831	13.643	11.067	10.432
	Fall	7.494	18.769	24.191	16.259	17.956	16.203	12.726

Year	Season	Peterborough	Toronto Downtown	Toronto West	Burlington	Hamilton Downtown	Brampton	St. Catharines
2008	Winter	9.418	20.929	26.427	16.254	18.385	16.121	12.303
	Spring	6.609	16.269	19.280	12.143	14.572	12.339	9.625
	Summer	3.463	12.928	16.383	11.758	11.390	10.188	8.208
	Fall	7.371	18.063	21.251	14.141	14.576	13.858	11.523
2009	Winter	8.905	21.611	24.760	16.341	18.047	16.422	12.453
	Spring	3.775	14.306	16.317	9.561	11.852	10.801	8.330
	Summer	2.963	12.347	14.830	10.712	9.651	8.810	7.683
	Fall	6.861	17.731	20.218	13.649	15.207	17.352	11.344
2010	Winter	5.924	19.970	22.948	13.699	15.471	11.360	11.980
	Spring	4.100	15.014	19.414	10.766	13.416	11.093	8.702
	Summer	3.732	12.085	16.567	10.616	8.609	8.189	6.552
	Fall	6.477	17.299	21.435	13.821	13.484	12.053	9.145
2011	Winter	8.610	19.449	24.352	15.579	16.600	14.751	10.999
	Spring	3.997	12.472	16.766	9.154	14.558	10.639	7.569
	Summer	3.362	11.875	15.269	9.854	10.293	8.044	6.378
	Fall	1.520	16.000	20.143	12.748	12.531	11.740	9.093
2012	Winter	1.417	14.830	18.349	11.059	13.191	12.158	9.113
	Spring	3.178	12.392	15.950	9.750	11.666	9.018	7.171
	Summer	3.691	11.983	14.001	10.392	8.549	7.492	6.389
	Fall	6.373	14.321	16.771	12.604	14.256	13.041	9.542

Table 22. The seasonal average temperature (°C) in different regions of Toronto, Cobourg and Grimsby

Year	Season	Toronto	Cobourg	Grimsby
2000	Winter	-1.5	-2.0	-0.1
	Spring	13.1	11.0	13.4
	Summer	18.9	17.2	19.4
	Fall	2.5	2.2	3.8
2001	Winter	-2.5	-2.7	-1.3
	Spring	14.3	12.3	14.4
	Summer	20.3	18.3	20.6
	Fall	6.5	5.5	7.7
2002	Winter	-0.5	-0.6	-0.8
	Spring	12.4	10.9	12.0
	Summer	22.3	19.9	20.9
	Fall	3.4	3.3	2.9
2003	Winter	-5.3	-5.8	-5.6
	Spring	12.1	10.3	11.2
	Summer	20.3	18.6	19.2
	Fall	4.6	3.3	5.5
2004	Winter	-3.6	-4.8	-2.2
	Spring	12.6	10.9	12.9
	Summer	19.5	18.2	19.8
	Fall	4.4	3.9	5.8
2005	Winter	-4.1	-4.1	-2.9
	Spring	14.1	12.3	13.3
	Summer	21.9	20.4	21.7
	Fall	4.2	3.8	4.8

Year	Season	Toronto	Cobourg	Grimsby
2006	Winter	-0.7	-1.5	0.4
	Spring	14.1	12.6	14.1
	Summer	20.1	18.8	20.3
	Fall	5.3	5.1	6.1
2007	Winter	-3.6	-4.7	-4.3
	Spring	13.7	12.0	13.2
	Summer	20.7	18.5	19.6
	Fall	4.8	4.6	4.3
2008	Winter	-3.0	-3.2	-3.3
	Spring	13.6	11.7	12.7
	Summer	19.4	18.0	18.6
	Fall	2.9	2.4	2.6
2009	Winter	-3.9	-4.0	-4.3
	Spring	12.8	11.3	12.0
	Summer	18.9	18.1	18.0
	Fall	4.1	3.5	3.6
2010	Winter	-1.4	-0.8	-2.1
	Spring	15.2	13.6	14.5
	Summer	20.7	19.6	19.4
	Fall	3.6	3.2	3.1
2011	Winter	-4.3	-5.1	-2.8
	Spring	13.4	12.1	12.7
	Summer	21.3	19.6	21.2
	Fall	6.0	5.4	7.0
2012	Winter	1.6	0.9	2.3
	Spring	14.8	12.9	14.7
	Summer	20.8	18.9	21.1
	Fall	4.8	5.1	5.9

Table 23. The seasonal total precipitation (mm) in different regions of Toronto, Cobourg and Grimsby

Year	Season	Toronto	Cobourg	Grimsby
2000	Winter	96.4	108.9	130.4
	Spring	372.9	364.8	408.0
	Summer	141.8	166.0	269.0
	Fall	144.6	162.9	172.0
2001	Winter	156.6	119.8	165.8
	Spring	190.4	192.1	181.8
	Summer	119.0	171.9	152.4
	Fall	224.4	245.4	248.4
2002	Winter	145.9	160.7	161.6
	Spring	243.5	290.1	232.9
	Summer	129.8	213.9	217.7
	Fall	142.7	169.1	170.8
2003	Winter	132.2	180.2	162.1
	Spring	277.4	245.0	252.1
	Summer	233.8	191.1	225.3
	Fall	252.2	291.0	196.7
2004	Winter	133.8	150.0	181.8
	Spring	225.8	304.4	287.0
	Summer	205.0	286.0	225.8
	Fall	190.4	264.0	209.9
2005	Winter	178.8	156.2	175.0
	Spring	143.8	198.5	183.6
	Summer	235.6	248.2	291.8
	Fall	208.5	285.7	290.3

Year	Season	Toronto	Cobourg	Grimsby
2006	Winter	198.2	210.1	176.7
	Spring	189.8	203.9	228.9
	Summer	223.0	327.9	328.6
	Fall	254.7	324.5	327.0
2007	Winter	96.6	105.8	199.0
	Spring	177.6	83.0	118.0
	Summer	96.8	66.4	132.8
	Fall	221.7	121.8	252.4
2008	Winter	227.4	112.0	257.4
	Spring	233.8	84.9	236.0
	Summer	369.2	139.8	366.1
	Fall	219.2	154.5	248.4
2009	Winter	186.8	68.6	211.4
	Spring	264.6	167.7	332.6
	Summer	269.0	127.8	350.2
	Fall	183.6	113.9	202.8
2010	Winter	111.8	65.2	170.0
	Spring	278.8	159.1	314.8
	Summer	236.4	134.2	269.0
	Fall	160.2	188.1	217.4
2011	Winter	180.4	80.5	212.6
	Spring	297.6	156.4	335.5
	Summer	189.6	170.0	258.2
	Fall	269.2	226.7	248.7
2012	Winter	98.8	132.6	150.6
	Spring	164.4	114.8	130.6
	Summer	273.4	123.2	199.0
	Fall	195.0	69.3	226.0

Table 24. The seasonal average temperature (°C) and total precipitation (mm) in the future in different regions

Year	Season	Temperature (°C)			Precipitation (mm)		
		Toronto	Cobourg	Grimsby	Toronto	Cobourg	Grimsby
2030	Winter	1.2	236.9	2.6	267.6	2.8	309.9
	Spring	24.5	105.5	21.5	41.4	25.3	56.5
	Summer	35.3	65.6	31.9	0.9	35.8	4.2
	Fall	10.8	82.8	13.5	158.7	12.2	110.5
2031	Winter	2.3	303.5	4.3	441.4	3.7	287.0
	Spring	21.2	179.7	19.3	108.6	22.1	119.9
	Summer	36.5	41.0	32.3	4.9	36.9	15.6
	Fall	9.0	171.0	11.2	233.1	10.2	136.4
2032	Winter	3.5	157.1	4.0	212.2	4.5	214.5
	Spring	22.3	151.0	20.4	65.0	23.3	84.2
	Summer	36.6	47.8	33.2	15.9	37.0	40.5
	Fall	11.2	183.5	14.3	183.3	12.7	145.9
2033	Winter	4.2	187.6	5.5	175.4	5.5	211.4
	Spring	24.7	214.7	22.1	138.0	25.5	186.9
	Summer	36.7	7.0	32.7	3.0	37.2	5.5
	Fall	12.0	141.8	14.1	197.9	13.6	116.0
2034	Winter	4.3	217.5	5.8	222.9	5.8	150.6
	Spring	23.1	209.0	20.8	141.1	24.4	92.8
	Summer	37.2	25.0	33.2	0.5	37.8	9.3
	Fall	11.0	247.2	13.5	430.9	12.2	280.9
2035	Winter	4.0	445.4	5.3	473.7	5.0	323.9
	Spring	21.3	213.0	19.5	191.2	22.5	206.0
	Summer	36.6	7.7	33.1	1.4	37.0	4.3
	Fall	11.6	125.6	14.5	144.0	13.1	134.2
2036	Winter	4.7	231.6	5.9	341.7	6.0	177.3
	Spring	23.9	120.6	20.9	107.9	24.7	91.7
	Summer	35.8	17.4	32.3	6.3	36.2	7.7
	Fall	10.5	221.5	13.2	311.3	12.1	215.7
2037	Winter	1.7	185.6	2.5	194.5	3.1	227.3
	Spring	24.4	216.3	22.1	281.4	26.1	131.9
	Summer	36.7	26.2	33.1	14.3	37.2	16.9
	Fall	10.2	205.5	12.6	327.4	11.4	174.2

Year	Season	Temperature (°C)			Precipitation (mm)		
		Toronto	Cobourg	Grimsby	Toronto	Cobourg	Grimsby
2038	Winter	6.8	189.8	7.8	253.9	7.9	142.9
	Spring	25.8	109.3	23.3	88.8	26.5	152.5
	Summer	38.0	40.2	34.2	7.7	38.8	11.5
	Fall	12.3	279.2	14.8	357.1	13.4	212.3
2039	Winter	4.6	229.3	6.3	210.1	6.1	178.8
	Spring	25.1	136.9	22.3	69.9	25.8	84.7
	Summer	36.7	33.7	33.1	9.7	37.5	23.2
	Fall	11.0	172.9	14.0	149.4	12.8	96.3
2040	Winter	7.1	138.1	8.3	223.8	8.3	152.7
	Spring	25.7	153.2	23.1	56.5	26.9	112.4
	Summer	37.5	13.4	33.7	1.8	38.8	3.5
	Fall	10.8	145.4	13.2	143.0	12.3	118.7
2041	Winter	3.8	397.3	4.9	406.0	5.7	286.0
	Spring	25.9	91.6	23.3	48.7	27.2	34.4
	Summer	36.5	53.2	32.5	10.4	36.8	11.2
	Fall	11.4	151.6	13.7	202.2	12.7	167.3
2042	Winter	1.6	101.8	2.7	112.5	3.4	133.2
	Spring	25.0	105.2	21.9	45.5	25.6	78.8
	Summer	38.7	24.8	34.7	1.7	40.1	3.7
	Fall	10.4	60.7	12.8	79.8	12.0	52.9
2043	Winter	4.6	321.9	5.6	406.2	6.1	224.5
	Spring	24.0	85.0	21.7	41.0	24.7	69.1
	Summer	36.3	78.3	32.7	16.1	37.5	28.5
	Fall	14.6	195.1	17.0	237.2	16.1	151.2
2044	Winter	7.9	144.7	9.3	163.1	9.3	121.5
	Spring	25.8	116.6	23.4	35.8	26.9	84.7
	Summer	37.1	36.7	33.7	18.8	38.5	54.9
	Fall	9.8	187.9	12.5	251.1	11.1	100.4
2045	Winter	3.4	288.5	5.3	346.3	5.0	258.7
	Spring	23.6	251.8	21.5	166.2	24.9	236.0
	Summer	36.2	13.4	32.7	11.1	36.8	17.9
	Fall	12.8	172.1	15.1	215.9	14.1	137.4
2046	Winter	3.6	196.7	5.3	207.9	5.3	130.3
	Spring	24.4	218.1	22.3	187.3	25.3	166.8
	Summer	36.9	28.0	33.5	11.1	37.9	20.9
	Fall	12.4	140.6	14.6	179.2	14.1	139.6
2047	Winter	1.4	344.8	3.2	499.7	2.9	285.0
	Spring	21.8	152.1	19.6	159.8	22.8	181.3
	Summer	36.5	20.3	33.0	4.5	37.0	14.9
	Fall	12.1	410.3	14.3	540.0	13.7	335.7

Year	Season	Temperature (°C)			Precipitation (mm)		
		Toronto	Cobourg	Grimsby	Toronto	Cobourg	Grimsby
2048	Winter	3.6	305.3	4.4	330.8	4.7	361.8
	Spring	25.2	275.6	23.6	170.2	26.5	100.1
	Summer	36.4	45.9	32.8	4.5	36.9	4.9
	Fall	12.7	137.4	15.3	195.3	14.0	74.6
2049	Winter	3.0	145.3	4.7	147.7	4.7	158.3
	Spring	25.3	144.5	22.5	90.3	26.3	136.6
	Summer	37.4	63.9	33.9	6.6	38.3	19.7
	Fall	14.3	197.6	16.5	245.5	15.9	110.5
2050	Winter	4.1	303.8	6.2	331.1	5.3	303.5
	Spring	25.4	138.0	22.2	97.6	25.8	112.7
	Summer	37.0	48.9	33.4	5.8	37.5	30.3
	Fall	12.9	187.4	15.5	230.6	14.5	103.0
2051	Winter	2.6	184.9	4.6	206.3	4.2	169.5
	Spring	29.9	84.7	25.9	86.5	29.9	61.0
	Summer	36.9	19.1	33.0	2.9	37.7	13.4
	Fall	11.8	345.5	14.4	514.9	13.4	211.3
2052	Winter	4.1	237.6	5.4	339.0	5.5	281.5
	Spring	27.9	38.6	24.6	19.5	28.6	31.4
	Summer	39.8	35.7	35.1	4.6	40.0	9.7
	Fall	11.8	239.8	14.4	324.4	13.2	200.4
2053	Winter	5.9	380.9	7.2	436.2	7.0	466.7
	Spring	26.7	152.5	24.3	117.1	27.4	116.7
	Summer	38.9	8.9	34.6	8.9	38.9	10.0
	Fall	10.6	248.0	13.3	265.5	12.3	273.5
2054	Winter	5.4	269.0	7.4	268.7	6.7	197.9
	Spring	26.8	119.7	23.6	82.6	27.0	87.7
	Summer	38.5	6.8	34.2	1.1	38.7	4.9
	Fall	13.5	199.5	16.1	180.5	15.2	139.1
2055	Winter	4.7	316.4	6.0	426.0	5.9	264.8
	Spring	26.6	243.8	23.5	188.0	27.1	252.6
	Summer	36.5	20.3	33.1	11.2	37.1	20.7
	Fall	15.0	191.6	17.5	284.8	16.3	124.9
2056	Winter	4.8	282.7	6.7	327.7	6.6	196.8
	Spring	25.7	85.5	23.6	57.4	27.1	39.7
	Summer	37.5	91.7	33.7	7.4	38.1	28.5
	Fall	9.5	285.2	12.4	273.6	11.2	176.4
2057	Winter	3.8	231.9	4.5	292.4	5.4	198.2
	Spring	28.5	46.8	24.8	8.9	29.0	12.5
	Summer	37.8	54.0	33.9	17.0	38.3	18.7
	Fall	11.6	301.9	14.4	367.7	13.1	240.7

Year	Season	Temperature (°C)			Precipitation (mm)		
		Toronto	Cobourg	Grimsby	Toronto	Cobourg	Grimsby
2058	Winter	4.3	313.1	5.7	330.0	5.5	260.2
	Spring	28.6	144.8	25.6	99.4	29.0	219.9
	Summer	38.3	15.6	34.5	1.1	38.7	4.5
	Fall	13.9	63.0	16.3	90.4	15.3	34.2
2059	Winter	5.1	230.3	6.2	249.2	6.6	194.1
	Spring	24.8	159.7	22.6	62.4	25.9	95.8
	Summer	39.0	77.5	35.0	7.7	39.4	43.9
	Fall	11.8	167.9	14.5	292.0	13.3	119.8
2060	Winter	6.2	221.8	7.4	217.1	7.7	162.7
	Spring	24.6	230.8	22.2	170.0	25.3	226.3
	Summer	39.7	20.9	35.5	0.5	40.2	7.1
	Fall	15.4	196.4	17.3	218.2	16.9	131.5
2061	Winter	3.2	260.5	5.0	256.9	4.7	176.7
	Spring	26.9	94.8	24.5	48.6	27.8	91.9
	Summer	37.4	80.5	33.9	237.4	38.5	46.2
	Fall	12.0	291.8	14.4	307.8	13.6	248.8
2062	Winter	2.7	428.2	4.5	580.8	4.0	454.5
	Spring	25.9	136.7	22.8	102.3	26.5	133.7
	Summer	36.2	25.4	32.6	5.8	36.4	13.5
	Fall	12.5	208.4	15.1	371.6	14.0	182.3
2063	Winter	3.6	569.8	5.2	527.9	4.7	473.6
	Spring	24.8	177.1	22.2	110.1	25.5	139.6
	Summer	38.7	73.9	34.6	3.3	38.7	48.4
	Fall	13.1	178.1	15.4	244.6	14.5	121.8
2064	Winter	4.5	295.7	6.0	402.1	5.6	269.7
	Spring	27.4	83.4	24.4	71.7	28.1	83.1
	Summer	41.4	1.2	36.4	0.0	41.1	1.9
	Fall	13.5	197.6	15.7	273.5	15.0	105.4
2065	Winter	5.7	240.4	7.1	331.8	6.9	193.4
	Spring	28.2	90.5	25.0	57.0	29.0	70.1
	Summer	39.3	19.3	35.5	2.2	40.5	2.5
	Fall	13.5	185.3	16.2	260.0	15.1	84.3
2066	Winter	8.0	209.1	9.3	236.6	9.7	154.5
	Spring	31.7	71.8	27.5	42.7	32.6	52.8
	Summer	39.7	60.8	35.5	1.2	40.6	9.3
	Fall	12.6	146.7	15.2	183.1	14.2	126.1
2067	Winter	1.0	324.5	2.9	340.6	2.4	226.4
	Spring	25.7	165.7	23.2	130.2	26.5	177.5
	Summer	38.9	27.6	35.0	1.1	39.4	6.0
	Fall	13.5	212.4	15.6	322.0	14.8	157.1

Year	Season	Temperature (°C)			Precipitation (mm)		
		Toronto	Cobourg	Grimsby	Toronto	Cobourg	Grimsby
2068	Winter	4.6	379.7	6.1	370.0	5.9	376.6
	Spring	25.7	131.5	23.2	43.2	26.6	69.2
	Summer	39.1	47.0	34.7	5.9	39.1	15.3
	Fall	12.0	326.1	14.8	378.1	13.7	294.4
2069	Winter	8.0	338.9	9.2	434.3	9.1	202.2
	Spring	24.8	231.4	23.2	171.3	25.9	222.7
	Summer	38.4	7.9	34.4	1.1	38.7	15.6
	Fall	17.6	47.5	19.8	55.0	19.2	44.0
2070	Winter	5.9	211.2	7.8	192.3	7.2	202.8
	Spring	25.9	105.1	23.5	99.5	26.9	67.4
	Summer	38.5	19.3	34.4	0.9	39.1	3.0
	Fall	13.2	130.8	15.6	148.7	14.5	102.3
2071	Winter	7.0	207.3	8.4	231.1	8.3	251.5
	Spring	25.4	327.1	23.4	281.5	26.4	233.2
	Summer	40.3	30.8	36.2	1.3	40.7	5.2
	Fall	14.2	537.8	16.5	504.8	15.7	342.8
2072	Winter	6.3	402.0	7.9	504.7	7.6	213.8
	Spring	26.6	41.4	24.3	36.4	27.3	41.5
	Summer	40.3	90.8	35.7	2.5	40.3	13.8
	Fall	14.1	239.4	16.6	368.3	15.4	288.3
2073	Winter	7.4	330.4	8.7	317.2	8.7	398.8
	Spring	28.6	77.9	25.5	55.0	29.4	52.7
	Summer	40.3	8.2	35.9	1.5	40.3	3.4
	Fall	14.1	143.8	16.6	223.3	15.6	85.8
2074	Winter	8.5	223.1	9.4	246.3	9.6	165.3
	Spring	29.4	51.2	26.1	35.3	30.2	40.6
	Summer	41.4	27.8	36.8	0.3	42.1	1.3
	Fall	12.2	142.3	14.3	215.1	13.7	115.6
2075	Winter	6.3	150.3	8.0	268.9	7.6	132.6
	Spring	27.7	221.4	25.0	109.6	28.8	134.6
	Summer	40.8	46.2	36.2	7.0	41.2	19.7
	Fall	15.4	130.1	17.3	185.4	16.8	119.1
2076	Winter	6.5	259.9	8.0	329.6	7.6	273.2
	Spring	29.8	158.0	26.2	128.9	30.0	140.5
	Summer	39.4	24.1	35.1	11.4	39.5	14.1
	Fall	14.1	150.9	17.1	186.2	15.7	121.0
2077	Winter	7.0	173.8	8.6	186.1	8.2	179.7
	Spring	27.9	163.0	25.0	56.8	29.0	68.9
	Summer	40.5	14.2	36.3	4.0	41.3	10.8
	Fall	14.9	165.5	16.9	212.3	16.2	120.0

Year	Season	Temperature (°C)			Precipitation (mm)		
		Toronto	Cobourg	Grimsby	Toronto	Cobourg	Grimsby
2078	Winter	8.6	135.0	9.9	121.1	9.9	116.2
	Spring	29.1	61.4	25.7	35.7	29.9	36.0
	Summer	40.6	75.6	36.2	6.4	41.1	7.5
	Fall	15.7	159.3	17.5	205.2	17.0	129.2
2079	Winter	5.9	164.2	7.6	187.7	7.2	233.1
	Spring	26.3	267.7	23.9	229.5	27.2	194.8
	Summer	39.5	80.7	35.7	8.2	40.1	11.8
	Fall	11.3	119.2	13.5	127.4	12.8	98.3
2080	Winter	4.4	335.6	5.9	325.6	5.5	362.1
	Spring	28.3	207.3	25.4	99.0	29.6	100.4
	Summer	40.0	86.1	35.6	5.3	39.9	20.4
	Fall	12.9	167.4	15.7	270.5	14.2	174.0
2081	Winter	6.9	169.4	8.0	266.1	8.2	165.2
	Spring	28.1	68.0	25.2	69.9	29.1	39.7
	Summer	41.9	14.6	37.0	2.0	42.2	14.6
	Fall	14.7	180.9	16.4	236.7	16.2	229.8
2082	Winter	8.4	203.8	9.2	401.5	9.5	150.0
	Spring	29.5	59.3	25.9	28.4	29.9	37.1
	Summer	39.1	31.7	34.9	9.0	39.3	23.9
	Fall	13.2	331.7	15.6	378.6	14.2	262.3
2083	Winter	5.7	199.3	6.3	160.3	7.1	171.4
	Spring	31.0	113.9	27.6	72.9	31.6	86.2
	Summer	40.4	15.0	36.1	4.3	40.8	6.4
	Fall	15.8	596.9	18.1	679.1	17.1	396.9
2084	Winter	5.8	234.0	7.4	342.8	6.9	286.4
	Spring	27.5	135.2	24.8	92.8	28.3	145.2
	Summer	41.1	26.6	36.8	0.6	41.2	7.6
	Fall	13.9	201.7	16.2	281.7	15.2	146.6
2085	Winter	5.9	341.1	7.3	311.3	7.1	282.4
	Spring	29.3	29.8	26.1	18.9	29.8	16.4
	Summer	40.6	3.7	36.4	0.7	40.7	3.4
	Fall	14.4	168.5	16.5	270.9	15.8	175.1
2086	Winter	6.1	245.9	7.5	261.1	7.4	201.6
	Spring	28.4	135.4	25.7	111.2	29.3	90.4
	Summer	41.3	85.4	36.7	11.4	41.2	14.1
	Fall	15.9	72.8	18.1	125.4	17.5	42.9
2087	Winter	4.6	221.7	6.1	241.0	6.1	210.2
	Spring	32.4	78.9	29.0	25.1	33.0	45.8
	Summer	41.8	39.3	37.4	3.6	42.5	14.7
	Fall	15.8	176.4	17.7	244.4	17.1	168.6

Year	Season	Temperature (°C)			Precipitation (mm)		
		Toronto	Cobourg	Grimsby	Toronto	Cobourg	Grimsby
2088	Winter	8.2	254.8	9.9	263.7	9.3	263.7
	Spring	27.5	158.1	24.7	153.6	28.3	149.0
	Summer	42.4	37.5	37.4	5.4	42.3	8.9
	Fall	16.2	132.5	18.4	176.3	17.6	135.5
2089	Winter	4.7	320.7	6.4	309.0	6.1	461.4
	Spring	27.4	226.9	24.5	170.5	28.2	166.3
	Summer	40.6	113.0	36.1	4.9	40.6	10.4
	Fall	13.4	180.1	15.7	193.5	14.8	124.9
2090	Winter	3.6	170.4	5.3	192.5	4.9	160.9
	Spring	31.6	28.3	27.6	16.9	32.2	27.1
	Summer	44.4	25.1	39.0	6.1	44.4	6.1
	Fall	16.4	269.6	18.2	321.3	17.7	128.0
2091	Winter	8.9	161.8	9.7	192.3	10.0	126.6
	Spring	30.6	173.7	27.1	125.6	31.3	104.8
	Summer	42.8	21.9	38.0	1.4	43.5	6.9
	Fall	14.3	204.0	16.7	221.3	15.6	237.8
2092	Winter	6.5	476.5	8.2	489.3	7.6	656.9
	Spring	30.5	89.1	27.0	27.9	30.9	36.5
	Summer	41.3	38.8	36.8	2.7	41.2	7.5
	Fall	16.3	344.8	18.5	460.9	17.6	223.6
2093	Winter	5.7	260.7	7.4	367.4	6.8	237.2
	Spring	31.3	127.9	27.6	75.0	31.8	116.0
	Summer	42.8	22.7	37.8	1.6	42.3	2.0
	Fall	17.6	158.6	19.3	182.6	18.7	151.9
2094	Winter	6.3	265.9	8.1	271.8	7.9	227.9
	Spring	29.2	142.2	26.5	91.9	30.2	109.0
	Summer	42.1	69.3	36.7	5.5	41.8	8.1
	Fall	17.8	311.8	19.7	265.2	19.2	114.6
2095	Winter	7.6	294.7	9.4	287.8	8.8	221.4
	Spring	31.2	93.7	27.9	53.5	31.7	102.2
	Summer	43.8	26.2	38.9	0.4	44.4	8.5
	Fall	16.3	117.7	18.9	163.5	17.7	83.9
2096	Winter	9.2	185.1	10.5	248.9	10.5	208.9
	Spring	33.7	111.2	29.5	62.0	34.0	101.7
	Summer	43.2	44.8	37.6	1.1	42.8	6.6
	Fall	17.2	177.1	19.3	192.8	18.5	137.1
2097	Winter	12.6	195.7	13.4	151.4	13.8	100.6
	Spring	31.7	134.6	28.3	78.4	33.1	49.5
	Summer	42.2	52.9	37.3	15.2	42.5	30.0
	Fall	15.2	311.7	17.6	292.9	16.8	328.2

Year	Season	Temperature (°C)			Precipitation (mm)		
		Toronto	Cobourg	Grimsby	Toronto	Cobourg	Grimsby
2098	Winter	6.0	247.2	8.1	246.0	7.3	289.9
	Spring	28.0	183.9	24.9	102.8	28.6	90.8
	Summer	42.7	28.9	37.8	6.2	42.5	7.8
	Fall	15.8	247.6	18.0	378.4	16.6	220.3
2099	Winter	6.1	171.8	7.7	199.5	7.2	144.7
	Spring	27.7	165.8	25.1	131.2	28.3	48.4
	Summer	43.0	51.9	37.9	6.9	42.7	7.3
	Fall	22.7	117.5	23.7	108.6	24.1	121.2

Appendix B: The developed code in MATLAB for modeling the atmospheric deposition quality in Toronto region

The developed code in MATLAB for modeling the atmospheric deposition quality in the Toronto region is presented below. The other codes for atmospheric deposition and water quality models in the other regions are the same and just the inputs and output should be defined again.

```
% Solve an Input-Output Fitting problem with a Neural Network
% Script generated by Neural Fitting app
% This script assumes these variables are defined:
%   Inputs_Norm - input data.
%   Output_Norm - target data.
x = Seasonal_Inputs';
t = Seasonal_Output';

I=200000;
j=0;
for i=1:I
% Choose a Training Function
trainFcn = 'trainlm';  % Levenberg-Marquardt backpropagation.
% Create a Fitting Network
hiddenLayerSize = [8 8];
net = fitnet(hiddenLayerSize,trainFcn);
% Setup Division of Data for Training, Validation, Testing
net.divideParam.trainRatio = 70/100;
net.divideParam.valRatio = 15/100;
net.divideParam.testRatio = 15/100;
% Choose a Performance Function
% For a list of all performance functions type: help nnperformance
net.performFcn = 'mse';  % Mean Squared Error
```

```
%loop ANN
% Train the Network
[net,tr] = train(net,x,t);
% Test the Network
y = net(x);
e = gsubtract(t,y);
performance = perform(net,t,y);
%Model_outputs(:,i)=y;
% Recalculate Training, Validation and Test Performance
trainTargets = t .* tr.trainMask{1};
valTargets = t .* tr.valMask{1};
testTargets = t .* tr.testMask{1};
%trainPerformance(:,i) = perform(net,trainTargets,y)
%valPerformance (:,i)= perform(net,valTargets,y)
%testPerformance (:,i)= perform(net,testTargets,y)
trainR(:,i) = regression(trainTargets,y)
valR (:,i)= regression(valTargets,y)
testR (:,i)= regression(testTargets,y)
TotalR (:,i)= regression(t,y)
MSE(:,i)=performance

 if j==100
    break
 end
if trainR(:,i)>0.8 && testR (:,i)>0.8 && valR(:,i)>0.8

 j=j+1;
 efficient_runs(:,j)=i;
 efficient_Outputs(:,j)=y;
 efficient_trainR(:,j)=trainR(:,i),
 efficient_testR(:,j)=testR(:,i),
```

```
   efficient_valR(:,j)=valR(:,i),
   efficient_MSE(:,j)=MSE(:,i)

   New_X1=Toronto_CC_CanESM2_Input_2030_2099';
   New_Y1=net(New_X1);
   Toronto_Output_2030_2099(:,j)=New_Y1;

   New_X2=Toronto_Input_2030_2099_50reduction';
   New_Y2=net(New_X2);
   Toronto_Output_2030_2099_50reduction(:,j)=New_Y2;

   New_X3=Toronto_Input_2030_2099_50increasing';
   New_Y3=net(New_X3);
   Toronto_Output_2030_2099_50increasing(:,j)=New_Y3;

   New_X4=Toronto_Input_2030_2099_100increasing';
   New_Y4=net(New_X4);
   Toronto_Output_2030_2099_100increasing(:,j)=New_Y4;

   efficient_nets{j}=net;
  end
 end
```