A New Methodology to Manage Anthropogenic Sources of Phosphorus Deposition to Lakes: Lake Simcoe Case Study

by

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ABSTRACT

A NEW METHODOLOGY TO MANAGE ANTHROPOGENIC SOURCES OF PHOSPHORUS DEPOSITION TO LAKES: LAKE SIMCOE CASE STUDY

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Excessive phosphorus loading to inland freshwater lakes around the globe has resulted in nuisance plant growth along water fronts, degraded habitat for cold water fisheries, and impaired beaches, marinas and waterfront property. The direct atmospheric deposition of phosphorus can be a significant contributing source to inland lakes. The atmospheric deposition monitoring program for Lake Simcoe, Ontario indicates roughly 20% of the annual total phosphorus load (2010 to 2014 period) is due to direct atmospheric deposition (both wet and dry deposition) on the lake. Bare soil exposure in the spring due to lack of vegetative cover, along with soil disturbance related to agricultural activities, results in higher susceptibility to wind erosion and dust emission.

The objectives of this study were to develop a methodology to model the anthropogenic sources of atmospheric phosphorus deposition to an inland lake and provide land management guidance to reduce loading to the lake. The methodology was then implemented for Lake Simcoe. This was accomplished using the following research milestones: 1) quantifying seasonal variability of atmospheric TP deposition on Lake Simcoe and identifying spatial distribution patterns of atmospheric TP deposition on Lake Simcoe, 2) introducing the new concept of Dust Response Units (DRUs), which combine soil type and land use to determine the dust emission susceptibility based on the hourly variation of wind speed and monthly changes in soil cover due to crop growth, 3) developing an integrated PM10 emission, transport and deposition model which has been validated using monitored data, and 4) Developing a first-time application of the Genetic Algorithm (GA) methodology to optimize the application of best management practices (BMPs) related to agriculture and mobile sources to achieve atmospheric phosphorus reduction targets and restore the ecological health of the lake. The geospatial aspect to the optimization (i.e. proximity and location with respect to the lake) will help land managers to encourage the use of these targeted BMPs in areas that will most benefit from the phosphorus reduction approach.
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1 Introduction

1.1 Sources of Atmospheric Phosphorus

The decline in water quality has been attributed to the loading of the macronutrients phosphorus and nitrogen (Evans et al., 1996; Winter et al., 2007). Of these two nutrients essential for both terrestrial and aquatic ecosystems, phosphorus has been acknowledged as the primary limiting nutrient for lakes (Schindler, 1977; Anderson and Downing, 2006). The source from which this phosphorus is emitted must be identified and managed to improve water quality. Atmospheric deposition of phosphorus is considered a non-point source. Unlike nitrogen, phosphorus does not have a gas phase, and therefore, this nutrient cycle is tied to phosphorus enriched sediment transport in the form of dust particles. There have been several studies that have shown that the contribution of atmospheric nutrient loads to lakes is significant (Psenner, 1984; Likens et al., 1985; Jassby et al., 1994).

Modelling results have shown that windblown or atmospheric dust, defined as particles of size 10 µm or less (PM10), generated by agricultural processes constitute the majority of dust loading globally (Tegen and Fung, 1995; Sokolik and Toon, 1996; Ginoux et al., 2001). Agricultural lands and practices associated with agricultural production are a major source of dust, particularly during high wind events or during ‘disturbance activities’, such as tilling (Kjelgaard et al, 2004). Dust generated by these processes has been directly related to nutrient/chemical loading on regional ecological systems (Leys, 1999; Leys and McTainsh, 1999). A study by Watson and Chow (2000) outlined the typical presence of chemicals and nutrients at various particle sizes and showed that PM10 or fugitive dust encompasses most particle sizes found in the atmosphere (Figure 1). From the figure below, it is apparent that PM10 also contains many of the nutrients frequently applied by anthropogenic land uses, namely nitrate and salt. For this reason, this study focuses on the movement of PM10 as a surrogate for atmospheric phosphorus movement.
A study by Sundram, et al. (2003) of wind-driven soil erosion addressed the loss of nutrient rich soil by developing a dust emission and transport model specific to the study area (Sundram et al., 2003). Data collected by Fryrear (1981) showed a direct relationship between increased dust emission and transport and a decline in soil nutrients. A more recent study by Koren et al. (2006) found that approximately 40 Mt of dust is emitted from the Saharan Bodele depression and transported by wind to the Amazonian Rainforest Basin annually; this dust is the principal source of nutrients for the large and vibrant ecosystem. Agricultural crops can reduce dust emissions due to wind erosion compared to bare soil conditions (Mansell et al., 2003).

1.2 Research Motivation

Over the past decades, excessive phosphorus (P) loading to Lake Simcoe (Ontario, Canada) has resulted in the loss of key self-sustaining cold-water fish populations and excessive macrophyte growth and algal blooms, which have impaired beaches, marinas, and waterfront property (Palmer et al. 2011). Atmospheric deposition is believed to be responsible for 20–50% of the total P entering the lake, based on estimates from 15 years of bulk deposition monitoring from 1990 to 2005 (Winter et al. 2007, Ramkellawan et al. 2009, Brown et al. 2011). Agriculture and agricultural practices may contribute significantly to atmospheric P deposition to Lake Simcoe.
Building on the research problem outlined, the purpose of this research is to develop a new and effective methodology to map and support the management of anthropogenic atmospheric phosphorus deposition to inland lakes. Lake Simcoe’s airshed was used to validate the methodology developed through this research. The motivation behind this research and the basis of the assumptions made herein stem from the work completed to date by the Ontario Ministry of the Environment and Climate Change (MOECC) and the Lake Simcoe and Region Conservation Authority (LSRCA). This has been published in several works cited above and most recently in the Lake Simcoe Phosphorus Reduction Strategy (https://www.ontario.ca/page/lake-simcoe-phosphorus-reduction-strategy). The monitoring efforts conducted by these bodies indicates that the atmospheric component makes up about 20% of the total phosphorus contribution to the lake. The following sections will provide a background on the most common dust emission, transport and deposition modelling as well as review of previous work in the field.

1.3 Dust Emission, Transport and Deposition Modelling

Wind erosion occurs when a shear force from wind initiates soil movement on the ground. Depending on soil type and surface conditions, a minimum force is required to initiate movement, which is termed the threshold (shear) velocity. Once this minimum force is obtained, soil movement is initiated, and the movement occurs as either suspension, saltation and creep, as outlined in the figure below.

Figure 2 - Soil movement types (USDA, 1994)

Particle suspension occurs when smaller particles are directly entrained by the airstream and will generally be transported over longer distances. Saltation applies to slightly larger particles that are too large for full suspension but become partially suspended and display a ‘jumping’ behaviour. Creep occurs in larger particles and are simply moved close to the surface. The primary mechanisms that drive most stochastic
dust emission models consists of aerodynamic entrainment, saltation bombardment and aggregate disintegration, as outlined in the figure below (Shao, 2008).

![Mechanism for dust emission](image)

**Figure 3 - Mechanism for dust emission.** (a) By aerodynamic lift, (b) saltation bombardment, (c) disaggregation (Shao, 2008)

Anthropogenic disturbance of land can increase emission by breaking up soil aggregates, making smaller particles more susceptible to entrainment. Managing wind erosion is based on reducing the magnitude of shear force on the soil surface and modifying the soil surface to resist soil movement. Adding vegetation or any other type of surface cover or roughness can act as mitigation techniques. Gillette and Passi (1988) quantified the effects on the threshold shear velocity from agricultural management practices, such as vegetation residue and soil moisture, among others.

The current application of dust models to compute windblown emissions, atmospheric transport, and deposition to water bodies contain a great deal of uncertainty due to low spatial resolution (Lu and Shao, 1999), limiting its usefulness in regional environmental management. The United States Department of Agriculture (USDA) has developed windblown emissions models, such the Wind Erosion Equation (WEQ) and later the Wind Erosion Prediction System (WEPS; Hagen, 2004; Feng and Sharratt, 2007, 2009) to estimate the impact of dust emission from agricultural land use.
1.3.1 Wind Erosion Equation (WEQ) and the Wind Erosion Prediction System (WEPS)

The Wind Erosion Equation (WEQ) was originally developed by the United States Department of Agriculture (USDA) and relates the total suspended particulate (TSP) fraction, \( E \) in t/acre/year of wind erosion losses of tilled fields with six independent variables, as follows:

\[
E = A \cdot C \cdot I \cdot K \cdot L' \cdot V'
\]  

(1)

where \( A \) is the portion of total wind erosion loss that would be measured as total suspended particulate, expressed as a percentage, \( C \) is the dimensionless climatic factor, \( I \) is soil erodibility (t/acre/year), \( K \) is the surface roughness factor (dimensionless), \( L' \) is the unsheltered field width factor (dimensionless) and \( V' \) is the vegetative cover factor (dimensionless).

The Wind Erosion Prediction System or WEPS is a process-based, daily time-step model approach to simulate wind erosion, intended to update and replace the Wind Erosion Equation or WEQ (Skidmore and Tatarko, 1997) and is based on soil and residue decomposition relationships studied over the past 60 years (Zobeck T., 1991). Buschiazzo and Zobeck (2008) correlated WEPS and WEQ with 28 measured dust events as part of their study and found that both models fit the data consistently, but the WEPS slope and intercept were better correlated.

1.3.2 Regional Scale Dust Modelling

Both WEPS and WEQ models have been shown to be somewhat inaccurate due to the broad estimation of shear velocity across local and regional scales. Marticorena and Bergametti (1995) developed models to represent the mechanics of soil entrainment which use relationships between soil parameters with vertical and horizontal dust fluxes to estimate dust emissions. Although the parameters for the Marticorena and Bergametti (1995) models were independently verified, limitations related to characterizing dust emissions over more local scales still exist. As a result, various researchers employ field dust emissions measurements (Gillette et al., 2004; Nickling and Gillies, 1993; Rooney and White, 2006; King et al., 2011) in order to obtain more accurate field level results. One of the critical sources of uncertainty associated with estimating these emissions is the friction velocity, which acts as a surrogate to represent the shear stress causing the suspension of particulates (Lu and Shao, 1999).

The US National Oceanic and Atmospheric Administration (NOAA) coordinated the development of a continental scale dust model, embedded in the Weather Research and Forecasting (WRF) model and integrated with chemical modules (Grell et al., 2005). The windblown emissions model, Global Ozone Chemistry Aerosol Radiation and
Transport or GOCART, generates emissions in the WRF model. The grid cells are relatively large in size and all emissions modeled are instantly mixed within the grid cell. This makes identifying the main contributors of dust events virtually impossible for small parcels of land.

CALPUFF is a non-steady state Lagrangian Gaussian puff long-range transport model that includes algorithms for chemical transformations and wet/dry deposition. The CALPUFF Modelling System, which includes the CALPUFF, CALMET, and CALPOST components, is the recommended long-range transport model, as outlined by (FLAG 2010).

CALMET is the meteorological pre-processor for CALPUFF and is a diagnostic meteorological model that produces a high resolution three-dimensional windfield and temperature field and two-dimensional fields of other meteorological parameters (Scire et al., 2000). For the Lake Simcoe case study, a finer resolution and more accurate windfield of the airshed would be required with inputs from the Mesoscale Meteorological Model (MM5; Grell et al., 1994) model and meteorological stations. The MM5 weather model produces gridded prognostic meteorological output fields used as inputs to CALMET.

1.4 Existing Methodologies and Research Gaps

There have been several atmospheric phosphorus loading monitoring and management studies performed for freshwater lakes that use a variety of methodologies. Jassby et al. (1994) collated the bulk collector and meteorological data gathered to determine pollutant loading trends to Lake Tahoe, U.S.A. and deduce the major contributors based on trends in the monitoring data. A follow-up study by Dolislager et al. (2012) updated the monitoring trends and also determined the major sources of emissions using default profiles in their existing emission inventory, analyzing the air quality and meteorology data to better identify sources and installed new aerometric monitoring sites upwind of the basin to assess potential for transport. Similarly, Luo, et al. (2007) used a similar approach with wet deposition to Lake Taihu in eastern China and determined that atmospheric deposition may be a major contributor. A similar sampling and deduction methodology was conducted by Camarero and Catalan (2012) using a similar network of monitoring data in the Pyrenean lake district between France and Spain, to determine whether the lake was moving from phosphorus to nitrogen limited. A recent study by Tipping et al. (2014) compiled sampling and monitoring data from 250 sites globally between 1954-2012 to determine an overall trend in phosphorus deposition and concluded that local transfers of phosphorus from fertilized farmland can have a significant impact on atmospheric loading to lakes; however it does require more research. Meyer (2008) developed a model to simulate field-level dust emission from agricultural fields but was only validated at the field level; it was not tied to a larger area to determine regional impacts.
The major gap in the works outlined above is the fine resolution required to guide effective management at the field scale to reduce regional impacts. Monitoring and sampling data will reveal clues regarding major point-source contributors; however in the development of a broader airshed-scale management strategy, a more detailed understanding is required to determine sources and management options.

1.5 Research Objectives

The primary purpose of the research is to accurately model the emission, transport and deposition of dust from agricultural and roads to provide management insights on a field-scale that will have a measurable impact on reducing nutrient loading to an inland lake. The methodology was developed and applied as a case study to Lake Simcoe in Ontario, Canada. The following section provides greater detail into the fulfilment of the research objectives.

1.5.1 Spatial and Temporal Dust Characterization

Estimates of bulk atmospheric nutrient deposition, for Lake Simcoe, ON, were calculated using a methodology described in detail by Winter et al. (2007). In brief, average bulk deposition chemistry (μg/L) data were combined with average daily precipitation volume over the lake to derive total phosphorus (TP) loads. These TP chemistry data were gathered from continuously open 0.25 m$^2$ bulk deposition collectors, topped with Teflon-coated funnels that are screened with 80 μm Nitex mesh to reduce contamination by insects and vegetative debris. Bulk deposition collectors, or bulk precipitation collectors, do not differentiate between wet and dry deposition. These collectors were deployed at two sites, Scanlon and Ramara from 1995 with the addition of a third site, Hawkstone, in 2001 (Figure 4).
This approach provides average atmospheric TP loads for the lake as a whole; however, any spatial variability in deposition concentrations captured by the bulk collectors is lost using this methodology. It is this spatial variability in deposition rates that may provide insight into local anthropogenic activities that may drive deposition 'hot spots', or discrete areas of high atmospheric contributions to the total phosphorus load of the Lake. Not only is the spatial variability of TP deposition lost using the averaging technique, but the spatial variability in precipitation rates is also lost when average precipitation volumes are calculated, even though the volume measured by each
individual rain gauge may vary greatly. Several researchers have found that radar-based precipitation has improved the aerial coverage and associated spatial variability of precipitation when used in hydrologic simulations (Quirmbach and Schultz, 2002; Velasco-Forero et al., 2005).

1.5.2 Emission Inventory Characterization

Agriculture and agricultural practices are major contributors to phosphorus (P) loading to freshwater systems and may contribute significantly to P deposition to Lake Simcoe. Agriculture is the dominant land use in the Lake Simcoe watershed and may be a major source of dust, particularly during high wind events or “disturbance activities” such as tilling (Kjelgaard et al. 2004a). To prepare for the modelling work and to determine the appropriate emission models, an emission inventory that characterizes the dust related land use activities, such as agriculture, paved and unpaved roads, etc. is required. Once an inventory is generated, the respective emission models are developed for each emission type. Emission inventories are developed by regulatory agencies to determine the relative dust potential contributions from various land uses.

1.5.3 Transport and Deposition Characterization

Windblown dust simulations are one of the most uncertain types of atmospheric transport models. This study presents an integrated PM10, or dust, emission, transport and deposition model to be validated using monitored and meteorological data. The purpose of this is to characterize the airshed to the appropriate resolution to identify sources and propose management practices at a field scale.

1.5.4 Land Management Using Best Management Practices

Genetic algorithm is an optimization methodology that uses the evolutionary process of survival of the fittest to find optimal solutions to problems involving large amounts of data. The components of a GA include the population, which is composed of chromosomes and genes that represent the various solutions possible and randomly set. The fitness (or optimization) of these possible solutions is determined using a fitness function, which optimizes a parameter based on a set of criteria or constraints. Each possible solution is evaluated and the fit or optimized solutions that meet the criteria best are duplicated, while those that do not are discarded from further analysis through selection (Maringanti et al., 2009). Most GAs will, however, retain a set of unfit solutions to retain diversity in the population with the hopes that latent desirable genes will later manifest. Crossover and mutation steps are genetic operators that work to introduce new options into the population. The number of times this process is repeated is called generations and with increasing generations comes increasing accuracy of results.
Soil erosion and subsequent atmospheric deposition of soil-related nutrients can be reduced by effective and practical best management practices (BMPs) related to agriculture and roads. Several studies have used genetic algorithm methodology specifically to optimize the placement of BMPs over a large area, in order to facilitate cost-effective watershed management decision-making. Gitau, et al. (2004) incorporated three existing tools: a genetic algorithm (GA), a watershed-level nonpoint-source model SWAT, and a BMP tool, similar to this study. The costs of the BMPs were used to determine cost-effective BMP applications within the watershed. Maringanti et al. (2009) used similar BMP cost and efficiency data in their optimization to determine the placement of BMPs within their watershed. They also employed two objective functions, reducing pollutant load and net cost reduction, as part of their optimization setup and discussed this approach in their 2011 publication (Maringanti et al., 2011). Chen et al. (2015) described the benefits of using the genetic algorithm optimization methodology when incorporating preference-based criteria, using indicator-based optimization principles.

Although BMPs to reduce atmospheric deposition have been widely promoted in most airsheds experiencing atmospheric phosphorus loading, a more precise identification of the sources of atmospheric P loading is needed to implement BMPs with a targeted approach. In the Lake Simcoe airshed, research to date has evaluated dust containing P from four primary sources: agricultural areas, unpaved roads, aggregate extraction, and construction sites (OMOE 2010). While BMPs are currently being applied within the case study airshed, there is a need to develop a targeted approach, using a GA approach, to promoting and funding BMPs that can have a greater impact on reducing dust deposition to lake.

1.6 Thesis Organization

This thesis is organized in a manuscript format according to the University of Guelph 2013-2014 Graduate Calendar "Thesis Format" section. Chapters 2 through 5 are separate articles and the chapters are outlined as follows:

Chapter 1 – Introduction

This chapter provides an overview of the research and describes the connections between the different thesis chapters.

Chapter 2 – Seasonal and spatial distribution patterns of atmospheric phosphorus deposition to Lake Simcoe, ON

Chapter 2 consists of a characterization study that delineated the study limits, termed the airshed, and defined the geospatial and seasonal deposition trends within the airshed. In addition to defining study limits and trends, the study also performed a desktop inventory of where the soils that contain the highest vulnerability to wind events
are located in the airshed, with respect to the predominant wind and proximity to the lake. It was published in the peer-reviewed Journal of Great Lakes Research. The Brown et al. (2011) work developed a baseline understanding of the seasonal TP trend observed in Lake Simcoe. This knowledge obtained of the study site through this paper provided the researchers and stakeholders greater confidence in the management methodology that was subsequently developed in later chapters.

The study is summarized in this thesis document and not provided in full text format. I am listed as the fourth author and my novel contributions to this study include synthesizing the results into a coherent, publishable document, completing various GIS analyses and organizing the flow of the research. The two lead authors of the study had left the project and my efforts were required to complete the study for publication and prepare the work for subsequent research delivery items. The paper is summarized in Chapter 2 and not provided in full text.


Chapter 3 – Mapping key agricultural sources of dust emissions within the Lake Simcoe airshed

Chapter 3 built on the trends and inventory developed in Brown et al. (2011) to map the modelling units that will be required to quantify dust emission in the airshed. The study introduced the new concept of Dust Response Units (DRUs), which is a modelling unit developed by combining soil type and land use. A susceptibility map was developed using the DRUs in a dust model developed by the United States Department of Agriculture (USDA). This map was used to quantify, at a high level, the relative dust contributions within the airshed.


Chapter 4 – A new dust transport approach to quantify anthropogenic sources of atmospheric PM$_{10}$ deposition on lakes

The key sources of dust emissions and trends observed in the airshed are applied to develop an integrated PM10 emission, transport and deposition model in this chapter. The model focuses on major local sources within the airshed including paved and unpaved roads, agricultural sources, construction sites and aggregate mining sources. The overall model consisted of an emission component, which estimated dust emissions from the sources above, and long-range transport and deposition model to determine deposition to the lake.

Chapter 5 – Optimizing best management practices to control anthropogenic sources of atmospheric phosphorus deposition to inland lakes

Using the modelling results developed in Chapter 4, Chapter 5 goes further to develop an optimization methodology for the application of best management practices (BMPs) within the airshed. The optimization takes into account the location of major dust sources and the transport and deposition processes within the airshed from Chapter 4 and adds cost and efficiency of the popular management practices and social constraints related to the adoption of BMPs. The end result is intended to help land managers develop a targeted and prioritized approach to atmospheric phosphorus deposition control.


Chapter 6 – Conclusion

The final conclusions chapter of this thesis provides an overview of the research contributions of this research and provides recommendations for future work. Authors note: Appendix A contains permission forms for including previously published manuscripts in this thesis.
Transition to Chapter 2

A decline in the water quality of Lake Simcoe, Ontario has been observed over the past few decades. This decline has been attributed to excessive loading of the limiting nutrient phosphorus. Atmospheric deposition of phosphorus is a major non-point source contributing 25–50% of the total phosphorus (TP) load entering Lake Simcoe between the years of 1990 – 2005 (Winter et al., 2007). The objectives of this study were to quantify seasonal variability of atmospheric TP deposition on Lake Simcoe and to estimate spatial distribution patterns of atmospheric TP deposition on Lake Simcoe. Based on the 1995–2007 period of records, on average 35% of the annual bulk atmospheric TP load occurs in the spring, while the summer, autumn and winter account for 45%, 13% and 7%, respectively. The autumn and winter loads are more or less consistent and exhibit little change much from year to year; however, the summer load can vary greatly. Spatially, the Northwest and Southeast quadrants of the lake show the highest atmospheric TP deposition during the spring and summer months. Most of the soils with the highest vulnerability for wind erosion are located in these quadrants and the dominant winds blow in the NW–SE direction.

2 Seasonal and spatial distribution patterns of atmospheric phosphorus deposition to Lake Simcoe, ON

2.1 Introduction

The decline in water quality has been attributed to the loading of the macronutrients phosphorus and nitrogen (Evans et al., 1996; Winter et al., 2007) and phosphorus has been acknowledged as the primary limiting nutrient for lakes (Schindler, 1977; Anderson and Downing, 2006). Atmospheric phosphorus is produced by both anthropogenic and natural processes where anthropogenic sources include quarry operations, industrial processes, construction activities, vehicular traffic on unpaved roads, and agriculture. Entrained dust carry nutrients, such as phosphorus, and are returned to ground or water surfaces by wet (event based) or dry (continual) deposition processes. Previous studies identify atmospheric deposition as a main source of phosphorus input to Lake Simcoe. The atmospheric contribution of phosphorus was estimated at 25–50% of total load from 1990 to 2005 (Winter et al., 2007). The importance of atmospheric deposition of phosphorus in aquatic environments has been reported by many authors for various locations (Scheider et al., 1979; Sober and Bates, 1979; Jassby et al., 1994; Redfield, 1998; Anderson and Downing, 2006; Morales-Baquero et al., 2006).

Estimates of bulk atmospheric nutrient deposition, for Lake Simcoe, ON, have been calculated previously using a methodology described in detail by Winter et al. (2007) where the average bulk deposition chemistry (μg/L) data are combined with average daily precipitation volume over the lake to derive total phosphorus (TP) loads. These TP chemistry data were gathered from Teflon-coated bulk deposition collectors situated around the lake (Figure 4).

While this approach provides average atmospheric TP load estimates for the lake, spatial variability in deposition concentrations are not captured, which may provide insight into local ‘hot spots’ of activity or areas that are contributing nutrient loads disproportionately to the lake. To this end, radar-based precipitation has improved the areal coverage and associated spatial variability of precipitation when used in hydrologic simulations (Smith et al., 1996; Quirmbach and Schultz, 2002; Yang et al., 2004; Velasco-Forero et al., 2005). The approach used in this study produces spatially distributed TP deposition loads and employs both Geographic Information System (GIS) and remote sensing (RADAR) technology. The objectives of this study are 1) to assess the spatial distribution of precipitation, 2) to estimate the temporal variability and spatial distribution of bulk atmospheric (TP) deposition, and 3) to identify the high deposition areas for Lake Simcoe. The time periods of interest are the hydrologic years of 2004/05, 2005/06 and 2006/07 and three data types are used in this study, radar and rain gauge precipitation, and total phosphorus (TP) bulk deposition chemistry obtained from
collectors positioned within the study area. Lake Simcoe (Figure 4) is the largest lake in southern Ontario, excluding the Great Lakes, with a surface area of approximately 722 km$^2$.

### 2.2 Methods

The Ramkellawan (2008) approach was used, which recognized that bulk deposition loads could be spatially distributed over the lake by using radar precipitation data which already incorporates spatial distribution within its data set (Ramkellawan et al., 2009). Bulk deposition is estimated using remotely sensed precipitation rates (from radar images), precipitation depths from rain gauges within the study area and TP chemistry from the bulk collectors. Brief descriptions of each of these data sets are provided followed by an explanation of the three-step process used to compute atmospheric deposition TP loads for Lake Simcoe:

1. pre-processing and GIS processing of the radar precipitation data;
2. calibration of radar data with surface rain gauges; and
3. calculating bulk atmospheric phosphorus loading over Lake Simcoe.

The radar precipitation data sets used in this study are part of the (NEXRAD) Next Generation RADAR produced by the National Oceanic Atmospheric Administration (NOAA) and the closest available station to the Lake Simcoe study area is located in Buffalo, NY, at a distance of 165 Km. Of the several radar products available, the Digital Precipitation Array (DPA) was selected for this study because it provides estimated precipitation accumulation in inches per hour or rainfall intensity. The Digital Precipitation Array (DPA) data from the Buffalo station covers a range of 240 km and includes Lake Simcoe. NEXRAD scans every 10 min during clear conditions and every 1–6 min during precipitation events. Borga (2002) proposed that radar derived precipitation estimates can be calibrated for a specific location by applying a mean-field bias (MFB):

$$
MFB = \frac{\sum_{i=1}^{N_S} G_i}{\sum_{i=1}^{N_S} R_i}
$$

where $G$ and $R$ are the rain gauge and radar estimated precipitation depths for gauge $i$, and $N_S$ is the number of stations used.

This study used a collection of rain gauges within the Lake Simcoe study area to calibrate and quantify the error between measured rain gauge and radar precipitation estimates. Twelve (12) rain gauges cover the study period and are located within the
study area, 9 of which are Environment Canada (EC) gauges including Aurora, Barrie ORO, Cold Water, Egbert, Lagoon City, Orangeville, Orillia Brian, Shanty Bay, and Udora. Two (2) of these gauges are co-located with the bulk deposition sensors (Ramara and Scalon, Figure 4). In the event of missing precipitation values for a particular gauge, that gauge's data was excluded from subsequent analysis related to the effected time period.

Atmospheric bulk TP samples were collected at the three stations surrounding Lake Simcoe, Ramara, Scanlon and Hawkestone (Figure 4). These collectors were visited, and samples were gathered by Lake Simcoe Region Conservation Authority personnel at two-week intervals during the spring, summer, and autumn and every 3 weeks during the winter. For the three (3) hydrologic years between 2004 and 2007, a total of 70 sets of bulk concentration samples were collected. Field observations recorded during sample collection noted the possible sources of contamination observed at the time of collection and some individual samples were discarded on site at the time of collection due to obvious contamination. These contamination sources primarily include bird feces, insects and vegetative matter, such as leaves, or twigs and pollen found on or in the bulk collector's funnel or within the water sample. Once the water samples were collected they were sent for chemical analysis to determine the concentration of total phosphorus (TP μg/L). These chemistry data sets were then pre-screened before use in subsequent analysis by comparing the TP concentration values with the field notes for each sample collection date to identify and remove any outliers in the data set due to sample contamination. Between the hydrologic years of June 2004–May 2007 two (2) sample collection intervals were discarded due to contamination of all three bulk collector samples. Figure 5 shows both the pre-screened and post-screened chemistry data for each of the three bulk collectors.
The chemistry data shows a strong seasonal trend between high deposition periods, namely of the late spring, summer and early autumn, and low deposition periods, in the late autumn, winter and early spring (Figure 5). The figure above also demonstrates the similarity between test sites and the relative impact of wind events where total phosphorus levels can increase by several orders of magnitude. The data sets with radar precipitation on the lake were used as inputs for the automated GIS processing program developed for this study, which produced hourly precipitation depths (mm) that were aggregated to produce daily depths (mm). The radar estimated daily precipitation data sets were then calibrated by calculating and applying the MFB value (EQ. 3) using a 5 km buffer around the surface rain gauges. Ramkellawan et al. (2009) assessed

Figure 5 – Pre-screened (a) and post-screened (b) chemistry data sets from the three bulk
several buffer zone sizes for the rain gauge data in this region and found 5 km to be an optimum size for this type of analysis.

The precipitation radar data was calibrated and combined with the phosphorus concentration data to derive the spatial distribution and atmospheric TP loading values (Figure 8). TP concentration data from each bulk collector station used to interpolate coverage for the entire lake surface using inverse–distance–weighted (IDW) interpolation method. Other studies (Lawrence et al., 2000; Reinstorf et al., 2005) have used this deterministic method to calculate atmospheric deposition of nutrients. The phosphorus deposition distribution over the lake (Figure 6) is generated by the ARCGIS 9.2 algorithm that converts the radar data from a depth (mm) measurement to a volume (L) measurement for each pixel cell. It then combines it with the IDW phosphorus (μg/L) by multiplying the two GIS images together. Areal deposition rates can then be estimated be dividing the TP load by the area of the lake (722 km^2), and can further be aggregated to produce, monthly, seasonal and annual TP loads.

![Figure 6](image)

**Figure 6** – Example of the three components used to estimate TP load to Lake Simcoe. (a) Calibrated precipitation (mm). (b) Interpolated (IDW) phosphorus concentration (μg/L). (c) The final TP load (kg/km²) for September 8–20, 2004.

### 2.3 Results and discussion

#### 2.3.1 Radar precipitation estimates

The precipitation data provided by the radar method was generally underestimated as the MFB values were generally greater than 1 (Figure 77) and this deviation occurs for a variety of known issues. An MFB greater than 3 means that no radar precipitation was observed for 1 or more days during the time interval of interest.
As an example, Smith et al. (1996) observed that range dependent biases exist and when the study area is greater than 100 km away from the radar station (as is the case for Lake Simcoe, ON) may manifest itself in an up to 100% underestimation of precipitation. Anagnostou and Krajewski (1998) concluded that the four step system relies on a series of default parameters that do not incorporate differences in precipitation regimes and raindrop size and hence increase the uncertainty in the estimated precipitation products like the DPA. Ulbrich and Lee (1999) suggested that NEXRAD consistently underestimates the reflectivity factor as a result of a constant radar parameter, thereby underestimating the reflectivity-to-rainfall relationship.

Most of these poor MFB values occurred in the low TP deposition seasons and as a result, the overall impact is likely negligible (Figure 7). The range of MFB values for this study is greater than that previously reported by Ramkellawan et al. (2009), 0.07–1.95, for Lake Simcoe; however, that study was targeting selected high deposition events only, which did not include any of the late autumn through to early spring events, corresponding to the low TP deposition periods.
### 2.3.2 Seasonal variability of atmospheric TP deposition on Lake Simcoe

Table 1 summarizes the seasonal variation associated with TP loads to the lake by three-month season.

<table>
<thead>
<tr>
<th>Season</th>
<th>Bulk atmospheric TP deposition (kg)</th>
<th>Bulk atmospheric TP deposition (kg/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 2004</td>
<td>12,821</td>
<td>18</td>
</tr>
<tr>
<td>Autumn 2004</td>
<td>1,895</td>
<td>3</td>
</tr>
<tr>
<td>Winter 2004-2005</td>
<td>713</td>
<td>1</td>
</tr>
<tr>
<td>Spring 2005</td>
<td>7,096</td>
<td>10</td>
</tr>
<tr>
<td>Summer 2005</td>
<td>15,479</td>
<td>21</td>
</tr>
<tr>
<td>Autumn 2005</td>
<td>2,863</td>
<td>4</td>
</tr>
<tr>
<td>Winter 2005-2006</td>
<td>727</td>
<td>1</td>
</tr>
<tr>
<td>Spring 2006</td>
<td>14,741</td>
<td>20</td>
</tr>
<tr>
<td>Summer 2006</td>
<td>21,963</td>
<td>30</td>
</tr>
<tr>
<td>Autumn 2006</td>
<td>2,232</td>
<td>3</td>
</tr>
<tr>
<td>Winter 2006-2007</td>
<td>429</td>
<td>1</td>
</tr>
<tr>
<td>Spring 2007</td>
<td>12,784</td>
<td>18</td>
</tr>
</tbody>
</table>

Temporally, there was a cyclical trend observed regarding deposition loading to the lake where the lowest rates were observed in the winter season, followed by increasing loads in the spring and continued increases in the summer with a decline in loads in the autumn season. Average monthly TP bulk deposition loads to Lake Simcoe, along with 95% confidence intervals for the 1995–2007 period of record, are presented in Figure 8. May and June have maximum loadings, while TP loads in autumn and winter months are low.
Figure 8 - Average TP deposition loads to Lake Simcoe with 95% confidence intervals based on the 1995-2007 period of record

In late spring and early summer, bare soil exposure due to the lack of vegetative cover along with soil disturbance caused by farming operations result in higher susceptibility to wind erosion and dust emission in the summer months. Figure 9 shows a typical dust storm, captured on May 5, 2010 at the University of Guelph Muck Research Station in the Holland Marsh, and shows the susceptibility of soils to wind erosion at this time of the year.
2.3.3 Spatial distribution of atmospheric TP deposition on Lake Simcoe

The spatial patterns of atmospheric TP deposition to the lake over four seasons is shown in Figure 10. The figures show Lake Simcoe and the surrounding land area; however, the range of values reported in the following description and interpretations of these figures pertains to TP load calculations for the lake only. During the spring season, the spatial loading pattern varies with the higher loads occurring in the North-West quadrant of the lake in 2005, shifting slightly south but on the same western side of the lake in 2006 and transferring to the North-Eastern side of the lake in 2007 (Figure 10).
All three years show a decline in loads as it extends into the lake from the shore. This trend of decreasing deposition load with increasing distance from the shoreline has been previously observed by Cole et al. (1990) using samplers located both on the...
shoreline and floating within a lake. The spring 2006 results show greater TP load values that range from 8.76 to 42.02 kg/km$^2$, while 2005 has the lowest values ranging from 1.87 to 16.18 kg/km$^2$, and 2007 has a range of 4.30–30.04 kg/km$^2$.

The summer spatial load patterns illustrated in Figure 10 also reflect the same decrease in TP loads moving from the shore to the lake's centre. The range of values for the summer TP load in 2005 (5.63–40.37 kg/km$^2$) almost triples from those of the spring. For 2006, the range of TP values is similar (6.38–42.85 kg/km$^2$) to those of the previous year and is quite close to those for the spring of 2006. The summer of 2004 has a lower range of TP load values (6.84–32.38 kg/km$^2$) and shows a different summer spatial pattern when compared with the other two years and the highest loading occurring in the north-east quadrant of the lake. The spatial distribution of TP for the winter seasons (Figure 10) is the most similar to each other with higher loads on the southern and eastern shores of the lake and decreasing loads extending across to the north-west shore.

### 2.3.4 Wind erosion susceptibility of the soils surrounding Lake Simcoe

To identify local source areas of atmospheric phosphorus, an inventory of potential sources of dust emission within the airshed must be developed. Previous studies have used the ‘wind erosion index’ (Table 2) to quantify the susceptibility of soils to wind erosion. This index is based on work done in the U.S. Great Plains by Hayes (1972) and Lyles (1975) for the United States Department of Agriculture (USDA).

<table>
<thead>
<tr>
<th>Wind erodibility group</th>
<th>Predominant soil texture class</th>
<th>Soil erodibility (tonne/ha/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMAFRA</td>
<td>USDA</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Loamy sand; loamy fine sand</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Very fine sandy loam; fine sandy loam; sandy loam</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>Clay; silty clay; noncalcareous clay loam and silty clay loam with more than 35% clay content</td>
</tr>
</tbody>
</table>
The seven wind erodibility groups (WEG) were generalized into four classes by soil scientists at the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) where the lower the WEG number, the higher the susceptibility of wind erosion. OMAFRA has supplied a file with WEG codes associated with the Soils in the airshed (Figure 11).

| 4 | 4 L | Calcaneous loam and silt loam; calcaneous clay loam and sily clay loam with less than 35% clay content | 216 |
| 4 | 5   | Noncalcareous loam and silt loam with less than 20% clay content; sandy clay loam; sandy clay | 141 |
| 4 | 6   | Noncalcareous loam and silt loam with more than 20% clay content; non calcaneous clay loam with less than 35% clay content | 121 |
| 4 | 7   | Silt; noncalcareous sily clay loam with less than 35% clay content | 95 |
Figure 11 - The wind erosion susceptibility map (based on soil texture only) for the Lake Simcoe study area

The key deposition areas of the north-west and south-east quadrants of the lake correspond to the highly susceptible to wind erosion soils (Figure 11). Figure 12 illustrates the wind roses for the summer season at the Toronto Buttonville, Barrie-Oro and Lagoon City stations, while Figure 13 shows the season average wind roses at the Barrie-Oro station alone. This data, together with the soil classification map, can be used as a preliminary guide to identifying major sources.
Figure 12 - Wind roses for the summer season for Toronto Buttonville, Barrie-Oro and Lagoon City stations for the 2004-2007 period of record
As shown in Figure 13, the dominant winds blow from the north-west (about 50% of the time) and from the southeast (about 30% of the time) for the high deposition seasons of spring and summer (Figure 10). Identifying high TP deposition areas, upwind land use and anthropogenic activities can be investigated to assess their respective contribution to the TP load to the lake. Further studies are needed to investigate the link between atmospheric TP deposition and identifying the local source areas of TP laden dust emissions.

### 2.3.5 Advantages of revised radar method and comparison with historical methods

Several studies around the globe have shown that wet deposition is the dominant process and constitutes 85–90% of the total bulk atmospheric TP deposition load (Yang et al. 1996; Chen et al. 1985). Consequently, this study has used GIS and remote sensing technologies to better estimate the spatial distribution of atmospheric TP.
deposition to Lake Simcoe. The main advantage of the revised method compared to historical methods is higher spatial resolution of rainfall over Lake Simcoe and therefore, a more accurate method of estimation of atmospheric TP load. The historical methods are simpler and can provide reasonable estimates of total load, if sufficient number of rain gauges and bulk collectors were available.

TP deposition loads were calculated using the historical method (Winter et al., 2007; Ramkellawan et al., 2009) to compare with the total loads estimated using the methodology presented in this paper (Table 3).

<table>
<thead>
<tr>
<th>Season</th>
<th>Revised method TP load (kg)</th>
<th>Historic method TP load (kg)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 2004</td>
<td>12,821</td>
<td>10,799</td>
<td>-15.8</td>
</tr>
<tr>
<td>Autumn 2004</td>
<td>1,895</td>
<td>2,404</td>
<td>26.8</td>
</tr>
<tr>
<td>Winter 2004-2005</td>
<td>713</td>
<td>1,236</td>
<td>73.3</td>
</tr>
<tr>
<td>Spring 2005</td>
<td>7,096</td>
<td>4,166</td>
<td>-41.3</td>
</tr>
<tr>
<td>Summer 2005</td>
<td>15,479</td>
<td>14,098</td>
<td>-8.9</td>
</tr>
<tr>
<td>Autumn 2005</td>
<td>2,863</td>
<td>5,266</td>
<td>83.9</td>
</tr>
<tr>
<td>Winter 2005-2006</td>
<td>727</td>
<td>2,748</td>
<td>278.2</td>
</tr>
<tr>
<td>Spring 2006</td>
<td>14,742</td>
<td>16,400</td>
<td>11.2</td>
</tr>
<tr>
<td>Summer 2006</td>
<td>21,963</td>
<td>17,005</td>
<td>-22.6</td>
</tr>
<tr>
<td>Autumn 2006</td>
<td>2,232</td>
<td>5,008</td>
<td>124.4</td>
</tr>
<tr>
<td>Winter 2006-2007</td>
<td>429</td>
<td>977</td>
<td>127.8</td>
</tr>
<tr>
<td>Spring 2007</td>
<td>12,784</td>
<td>13,442</td>
<td>5.1</td>
</tr>
</tbody>
</table>

A comparison of seasonal loads indicates that, in general, the historical method tends to overestimate TP deposition loads during the fall and winter seasons and underestimates the loads in the spring and summer months. Annual atmospheric TP deposition estimates for Lake Simcoe are within the range of published atmospheric TP deposition loads for the Great Lakes in Ontario and other locations around the world, as outlined in Table 4.
Table 4 - Summary of published bulk atmospheric TP deposition loads.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Site location</th>
<th>Atmospheric TP load (kg/km²/year)</th>
<th>Period of record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramkellawan et al., 2009</td>
<td>Ontario, Canada</td>
<td>17–58</td>
<td>1995–2006</td>
</tr>
<tr>
<td>Winter et al., 2007</td>
<td>Ontario, Canada</td>
<td>21–43</td>
<td>1995–2003</td>
</tr>
<tr>
<td>Ahl, 1988</td>
<td>Ontario, Canada</td>
<td>24–53</td>
<td>-</td>
</tr>
<tr>
<td>Shaw et al., 1989</td>
<td>Alberta, Canada</td>
<td>20</td>
<td>1983–1986</td>
</tr>
<tr>
<td>Anderson and Downing, 2006</td>
<td>Iowa, USA</td>
<td>30</td>
<td>2003–2004</td>
</tr>
<tr>
<td>Linker et al., 1993</td>
<td>Chesapeake Bay, USA</td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>McMahon and Woodside, 1997</td>
<td>North Carolina, USA</td>
<td>78</td>
<td>1990</td>
</tr>
<tr>
<td>Chen et al., 1985</td>
<td>New Zealand</td>
<td>15</td>
<td>1983</td>
</tr>
<tr>
<td>Gibson et al., 1995</td>
<td>North Ireland</td>
<td>5–60</td>
<td>1968-1993</td>
</tr>
</tbody>
</table>

As of 2008 three additional bulk collectors have been deployed, which will help mitigate some of the uncertainty inherent with chemistry data sets. The additional stations will facilitate improved spatial representation in the resultant interpolated surface and allow for more refined spatial interpolation techniques to be applied.

2.4 Conclusions

The atmospheric TP load to Lake Simcoe follows a distinct seasonal pattern; from October to March, atmospheric TP loads are typically below 2 kg/km²/month, while May and June typically have the highest loads of near 8 kg/km²/month. The main reason for low atmospheric TP loads in the autumn and winter months is the excess soil moisture, frozen ground or snow cover conditions that minimizes dust emission from exposed soils. Following the peak load in late spring early/summer months, the
atmospheric TP load tends to subside as the vegetation cover grows and the risk of wind erosion and dust emission diminishes. The spatial distributions of atmospheric TP deposition were higher in either the north-west or the south-east quadrants of Lake Simcoe. Most of the soils with the highest vulnerability for wind erosion are located in these quadrants and the dominant winds blow in the NW–SE direction. Further research is needed to confirm the local sources of TP and to apportion likely sources of dust emission and associated phosphorus.
A decline in water quality attributed to excessive inputs of phosphorus has been observed in Lake Simcoe over the past few decades. Various studies have estimated that 25–50% of the total phosphorus entering the lake is from atmospheric deposition, based on estimates from 15 years of bulk deposition monitoring from 1990 to 2005 (Winter et al. 2007). Bare soil exposure in the spring due to lack of vegetative cover, along with soil disturbance related to agricultural activities, results in higher susceptibility to wind erosion and dust emission. This study introduces the new concept of Dust Response Units (DRUs), which combine soil type and land use to determine the dust emission susceptibility based on the hourly variation of wind speed and monthly changes in soil cover due to crop growth. The Wind Erosion Prediction System (WEPS) was used to determine dust emission suppression factors for a combination of 11 different soils and 6 dominant agricultural land uses, totalling 66 different DRUs in the Lake Simcoe airshed. Employing a widely used dust emission model and applying these dust emission suppression factors resulted in the identification of high risk DRUs. Twelve of the potential 66 DRUs were determined to contribute 85% of the total crop dust emissions within the Lake Simcoe airshed, including sand, loam, sandy loam, and loamy sand soils combined with row crop, mixed, and hay and pasture land management operations. This study demonstrates a new method to map high priority areas for targeted implementation of dust control best management practices that could be useful in agricultural areas both within and beyond the Lake Simcoe airshed.

3 Mapping Key Agricultural Sources of Dust Emissions within the Lake Simcoe Airshed

3.1 Introduction

Over the past decades, excessive phosphorus (P) loading to Lake Simcoe, Ontario, Canada, has resulted in the loss of key self-sustaining cold-water fish populations and excessive macrophyte growth and algal blooms, which have impaired beaches, marinas, and waterfront property (Palmer et al. 2011). Atmospheric deposition is believed to be responsible for 25–50% of the total P entering the lake, based on estimates from 15 years of bulk deposition monitoring from 1990 to 2005 (Winter et al. 2007, Brown et al. 2011). Agriculture and agricultural practices may contribute significantly to atmospheric P deposition to Lake Simcoe. Agriculture is the dominant land use in the Lake Simcoe watershed and may be a major source of dust, particularly during high wind events or ‘disturbance activities’ such as tilling (Kjelgaard et al. 2004a). Modelling results have shown that windblown or atmospheric dust, defined as particles of size 10 µm or less (PM$_{10}$), generated by agricultural processes constitute the majority of dust loading globally (Tegen and Fung 1995, Sokolik and Toon 1996, Ginoux et al. 2001), and agricultural dust has been directly linked to nutrient loading to rivers and lakes (Leys 1999, Leys and McTainsh 1999). Nutrient loading from dust can be significant, as shown by Koren et al. (2006) who found that approximately 40 metric tonnes of dust is emitted from the Saharan Bodele depression and transported by wind to the Amazonian Rainforest Basin annually, this dust is the principal source of nutrients for the large and vibrant ecosystem. Increased dust emission and transport can even result in a decline in soil nutrient levels (Fryrear 1981).

Soil erosion and subsequent atmospheric deposition of soil-related nutrients can be reduced by effective and practical best management practices (BMPs). Although BMPs to reduce atmospheric deposition have been widely promoted in the Lake Simcoe watershed, there is a pressing need to more precisely identify the sources of atmospheric P loading to inform the implementation of BMPs. Research to date indicates that dust containing P is generated by four primary sources: agricultural areas, unpaved roads, and aggregate extraction and construction sites (OMOE 2010). The objective of this study was to identify and map key agricultural sources of PM$_{10}$ emission within the Lake Simcoe airshed to determine high priority areas for adoption of dust control BMPs. This study builds upon work by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) to rank soil susceptibility to wind erosion and identify high risk soils within the Lake Simcoe airshed (Figure 14; Brown et al. 2011).
Here, we evaluate soil susceptibility combined with crop land use to develop a map of key agricultural sources of PM$_{10}$ emissions. Crops can reduce dust emissions due to wind erosion compared to dust emissions on bare soil conditions (CARB 1997, Mansell et al. 2003); conversely, agricultural activities such as tilling may enhance dust emissions. We used dust emission and wind erosion models to estimate PM$_{10}$ emissions for various combinations of soil types and crops. Site-specific dust emission and transport models have previously been shown to be useful for studying wind-driven soil erosion and loss of nutrient rich soil (Sundram et al. 2003), and PM$_{10}$ or fugitive dust (i.e. small atmospheric dust particles that originate from non-point sources) encompasses atmospheric P (Watson and Chow 2000), making it an ideal surrogate parameter for modelling atmospheric P loading.
3.2 Study Site

Lake Simcoe (44°25’N; 79°20’W) is the largest inland lake in Southern Ontario and the watershed supports an estimated population of 400,000 residents (MOE 2010) with an additional 50,000 cottagers (LSRCA and OMOE 2009). Although there is little commercial industry located near the lake, it is a major recreational destination for local residents and tourists. Declines in native cold-water fish populations in the lake triggered the onset of several major monitoring programs and collected data indicated eutrophication from excess P loading was the major cause of ecological impairment (Palmer et al. 2011). Approximately 47% of the Lake Simcoe watershed is used for agriculture and an estimated 25% of the total P load to the lake is from hay, pasture, and cropland alone (OMOE 2010). Agriculture also contributes to atmospheric deposition of P to Lake Simcoe but detailed estimates are lacking.

3.3 Methods

Agricultural sources of PM$_{10}$ emission within the Lake Simcoe airshed were identified using 2 models: a modified GP88 (Gillette and Passi 1988) dust emission model and the Wind Erosion Prediction System (WEPS) model.

3.3.1 Modified GP88 dust emission model (MGP88)

The GP88 model has been widely used to predict regional and local dust emission rates as a function of hourly wind shear velocity time series data, and the critical shear velocity of the soil and its corresponding dust emission factor (Gillies et al. 1996, Ginoux 2004). While the GP88 is a mechanistic model, predictions have been validated using wind tunnel results of soil and land use data from the U.S. Department of Agriculture (Gillette and Passi 1988). The GP88 model was modified for application in the Lake Simcoe airshed by developing crop reduction and climate factors specific to Lake Simcoe and is hereafter referred to as the MGP88 model. The MGP88 model was used to determine the annual PM$_{10}$ emission from combinations of different soil types and crop land uses for the Lake Simcoe airshed.

Hourly wind speed and wind shear velocity data for the MGP88 model were calculated for the 2005–2008 period at a 1 km grid spacing for the study area using surface meteorological data from 10 climatic stations maintained by Environment Canada: Barrie-Oro, Toronto Buttonville Airport, Collingwood, Egbert, LagoonCity, Mount Forest, Muskoka, Toronto Pearson Airport, Waterloo, and Wiarton. The MGP88 predicts dust flux, $F$ (µg m$^{-2}$s$^{-1}$), converted to annual emission for this study, and is expressed as

$$F = c_0 u^* (1 - \frac{u_{cr}}{u^*}) \times CRF \times C_m,$$

(4)
where $c_0$ is a proportionality constant ($\mu g m^{-6} s^3$), $u^*$ is the shear velocity ($ms^{-1}$), and $u_{cr}$ is the critical or threshold shear velocity ($ms^{-1}$); the crop reduction factor ($CRF$; dimensionless), and the climatic reduction factor ($C_m$; dimensionless), were developed for the Lake Simcoe airshed. The $CRF$ incorporates the impact of land management on dust emission potential by comparing the ratio of dust emission rates for a given crop management operation versus a bare soil control. WEPS was used to determine the various CRF factors for different crops. $C_m$ modifies the predicted dust emission to correct for the suppression of dust by moisture in the soil.

The $c_0$ and $u_{cr}$ were calculated for each of the 11 dominant soil types commonly found in the Lake Simcoe airshed (Table 5) by calibrating the MGP88 model with the Single-event Wind Erosion Evaluation Program as described by Hagen (1995) with measured PM$_{10}$ dust emission data obtained for the Lake Simcoe soils using the Portable In-Situ Wind Erosion Laboratory equipment (PI-SWERL) developed by the Desert Research Institute in Nevada, USA.

Table 5 - Constants ($c_0$) and critical shear velocities ($u_{cr}$) generated from SWEEP results for the MGP88 dust emission model and average PM$_{10}$ emission and annual soil loss estimates for bare soil from WEPS.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>$c_0$</th>
<th>$u_{cr}$</th>
<th>PM$_{10}$ Emission</th>
<th>Soil Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($\mu g m^{-6} s^3$)</td>
<td>($ms^{-1}$)</td>
<td>(t ha$^{-1}$ yr$^{-1}$)</td>
<td>(t ha$^{-1}$ yr$^{-1}$)</td>
</tr>
<tr>
<td>Clay</td>
<td>336</td>
<td>0.68</td>
<td>Trace</td>
<td>1.7</td>
</tr>
<tr>
<td>Clay loam</td>
<td>211</td>
<td>0.65</td>
<td>0.02</td>
<td>3.4</td>
</tr>
<tr>
<td>Fine sandy loam</td>
<td>1,409</td>
<td>0.6</td>
<td>0.46</td>
<td>9.5</td>
</tr>
<tr>
<td>Loam</td>
<td>437</td>
<td>0.63</td>
<td>0.04</td>
<td>10.8</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>4,109</td>
<td>0.56</td>
<td>9.2</td>
<td>652.4</td>
</tr>
<tr>
<td>Organic soil</td>
<td>710</td>
<td>0.54</td>
<td>0.47</td>
<td>109.3</td>
</tr>
<tr>
<td>Sand</td>
<td>4,367</td>
<td>0.53</td>
<td>9.9</td>
<td>760.5</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>1,162</td>
<td>0.6</td>
<td>0.34</td>
<td>80.6</td>
</tr>
<tr>
<td>Silt</td>
<td>4,898</td>
<td>0.64</td>
<td>0.63</td>
<td>44.5</td>
</tr>
<tr>
<td>Silt loam</td>
<td>849</td>
<td>0.64</td>
<td>0.05</td>
<td>10.9</td>
</tr>
</tbody>
</table>
Soil samples were collected throughout the Lake Simcoe airshed at 16 locations (Figure 14) and analyzed in a lab using the PI-SWERL. The lab analysis was performed as ramp tests similar to the procedure outlined by Sweeney et al. (2008). For each soil sample, the PI-SWERL system was positioned over a tray containing the sample, which had been wetted and left to air dry for 5–6 days to recreate an undisturbed surface. In order to determine the \( u_{cr} \), the fan was engaged at a very low speed and slowly increased or ramped to a high wind speed to determine the onset of dust emission and the associated wind shear at the surface.

Additional “step tests” were run to determine PM\(_{10}\) concentrations and dust fluxes from bare, dry soils at successively increasing wind speeds. Ramp and step tests were repeated on soil samples that were rewetted and dried for 2–3 days to assess the effect of soil texture, soil moisture, and wind speed on dust emission rates. Three tests were performed at each site and each test consisted of a ramped wind speed test starting from 3,000 RPM, increasing to 5,000 RPM for a duration of 6.5 min. These measurements were used to validate bare, dry soil predictions using the MGP88 model and were compared to published results.

Atmospheric loading of PM\(_{10}\) to Lake Simcoe is a wind driven process, which is the primary focus of this study. Agricultural processes, such as tilling, disturb soils and contribute to PM\(_{10}\) emission. Conversely, crop cover can reduce dust emission. This dynamic process was captured in the emission reduction factors. The crop PM\(_{10}\) emission reduction factors were calculated by the WEPS model that specifically includes agricultural practices, such as tilling and harvest for each crop development stage, and land disturbance processes. The CRFs were determined for each soil type and crop type combination, or DRU, by comparing cropland versus bare soil PM\(_{10}\) emissions. This was developed using the standard suite of agricultural practices in WEPS and comparing them to a bare soil scenario. For example, a bare loam soil scenario would yield a certain dust emission regime. This would then be compared with a loam soil and row crop regime in WEPS and the ratio between the two would be the resulting CRF for that specific DRU. Once this was completed for all DRUs, the results were then incorporated in the MGP88 model to calculate hourly dust emissions from each of the Dust Response Units (DRUs) within the study area.

DRUs, which are introduced in this study, are a basic computational unit used to assess homogeneous dust emission susceptibility analogous to Hydrologic Response Units used for assessing soil, land use, and management impacts on water quantity and quality (Flugel 1995). Using GIS map files provided by research stakeholders, DRUs were developed by combining soil type and land use to determine dust emission using the MGP88 model by considering the hourly variation of wind speed along with monthly changes in soil cover due to crop growth through crop dust emission reduction factors. The WEPS model, discussed further below, was used to determine the CRF for a
combination of 11 different soils (Table 5) and 6 dominant agricultural land uses: row crops (modeled as soy followed by corn), mixed (alfalfa/hay/barley), hay and pasture, sod, vegetable (potato), and idle agricultural land; for a total of 66 different DRUs within the Lake Simcoe airshed.

A DRU grid map (100 m resolution) to determine PM\textsubscript{10} emission potential for the Lake Simcoe airshed was developed using Geographical Information Systems (GIS) data (in vector-based format) obtained from the Lake Simcoe Region Conservation Authority and GIS Spatial Analysis tools to overlay soils (Figure 15) and land use (Figure 16) grid maps.

Figure 15 - Soil type map of the study area around Lake Simcoe, Ontario (data provided by the Lake Simcoe Region Conservation Authority).
These maps were converted into raster format grid maps at 100 m resolution for DRU mapping. Both soil type and land use, and hence dust emission response, was assumed to be uniform within each DRU.

### 3.3.2 The Wind Erosion Prediction System (WEPS)

WEPS is a process-based, daily time-step model based on soil and residue decomposition relationships and is used to predict dust emissions. It is a field-scale wind erosion model and, for this study, simulations assumed a 1 ha field with non-erodible boundaries, similar to the methodology used by Hagen (2004). The erosion
sub-model of WEPS was developed into a standalone application called the Single-event Wind Erosion Evaluation Program (SWEEP). To quantify dust emission from various agricultural sources, DRUs were generated by pairing the land use (crop type) with soil type using GIS data. This approach also quantified the respective area of each DRU within the Lake Simcoe airshed. Each unique DRU was modeled using WEPS to obtain continuous daily PM$_{10}$ data per unit area for each crop cycle.

The 6 crop land uses used in this study were developed by modifying the relevant National Resource Conservation Service (NRCS) crop cycles for New York and Michigan (USA) with input from OMAFRA staff to represent Lake Simcoe-specific crop cycles. The majority of modifications made to the crop cycles were related to the timing of planting and harvesting, as well as the type of seed used. The WEPS model simulated the growth and harvest cycle for 8 years for row crops and vegetable crops based on 2 year cycles; other crop types were run for 4 years, based on a single year cycle. Daily predicted dust emissions from WEPS were averaged to determine a monthly dust emission from each DRU for the simulated period.

Modelling scenarios were conducted using WEPS for both bare and managed land. The dust emission for each crop type was compared to the emission from bare soil to generate a crop emission factor for each of the 66 DRUs. The monthly crop emission factors were calculated by dividing the average monthly emission from the managed soil by the average monthly emission from the bare soil WEPS run over the same cycle period. Monthly values were averaged to determine an annual CRF for each DRU. While WEPS could have been used to simulate overall annual emissions, it was necessary to use the MGP88 model, which isolates shear velocity, for use in future regional long-range transport and deposition modelling using US EPA CALPUFF model.

WEPS modelling results for soil loss and PM$_{10}$ emission from bare soils are presented in Table 5. While the WEPS model incorporates soil moisture and climatic conditions as part of the soil loss and PM$_{10}$ emission calculations, the climate and soil moisture values for both the bare and managed scenarios were maintained to isolate the impact of crop type on dust emissions. As a result, the varying monthly impact of soil moisture had to be incorporated into the MGP88 dust emission model. The monthly climatic factor, $C_m$, was calculated using the following relationship (Woodruff and Armbrust 1968):

$$C_m = 0.345 \frac{W_m^3}{PEI_a},$$

where $W_m$ is the average monthly wind velocity and $PEI_a$ is the annual Thornthwaite precipitation-evaporation index, which is a measure of soil aridity calculated as the ratio of precipitation to evapotranspiration. The precipitation-evaporation index was calculated using monthly evapotranspiration relationships for each subwatershed in the Lake Simcoe airshed, where the $PEI_a$ is the monthly ratio of precipitation to evaporation effectiveness. While climate factors were calculated for each month for each
subwatershed, they remained consistent among subwatersheds due to the relatively small size of the Lake Simcoe airshed and the absence of any major geological variability. The mean monthly climate factors (Table 6) were used to distribute the predicted annual dust flux over each month in the year and reflected the impact of the hydrologic cycle and corresponding effects of soil moisture on dust emission.

Table 6 - Mean monthly climatic moisture values for the Lake Simcoe airshed

<table>
<thead>
<tr>
<th>Month</th>
<th>Climate moisture value</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.00</td>
</tr>
<tr>
<td>February</td>
<td>0.00</td>
</tr>
<tr>
<td>March</td>
<td>0.00</td>
</tr>
<tr>
<td>April</td>
<td>0.15</td>
</tr>
<tr>
<td>May</td>
<td>0.95</td>
</tr>
<tr>
<td>June</td>
<td>1.73</td>
</tr>
<tr>
<td>July</td>
<td>2.58</td>
</tr>
<tr>
<td>August</td>
<td>1.54</td>
</tr>
<tr>
<td>September</td>
<td>0.72</td>
</tr>
<tr>
<td>October</td>
<td>0.18</td>
</tr>
<tr>
<td>November</td>
<td>0.01</td>
</tr>
<tr>
<td>December</td>
<td>0.00</td>
</tr>
</tbody>
</table>

3.4 Results

There was good agreement between MGP88 model predictions for a variety of bare, dry soils and shear velocities and measured PM$_{10}$ emission rates (Figure 17).
Figure 17 - Comparison of PM10 emission rates among measured Lake Simcoe PI-SWERL field data, published research, and the MGP88 dust emission model

Results from previously published wind tunnel studies (Lopez 1998, Rajot et al. 2003, Rooney and White 2006) were also consistent with the PI-SWERL results obtained. Rooney and White (2006) obtained their soil samples from Owen's Lake, California, USA, and tested them in a wind tunnel. Rajot et al (2003) obtained their data in-situ in the Sahel Desert, Niger, and Lopez et al. (1998) obtained their data in an agricultural field of Central Aragón in north eastern Spain. Overall the dust emission data in this study agree well with the GP88 model, which is a theoretical model based on the 'Law of the Wall' logarithmic–linear relationship between dust emission and shear velocity (Figure 17).

The WEPS models estimated soil loss to be <11 tha⁻¹ yr⁻¹ from all soil types except loamy sand, sand, and silt (Table 5). Higher soil loss was predicted for loamy sand and sand. One possible explanation for this discrepancy is that WEPS was validated for erosive crop land use sites and the application of WEPS to bare soils can yield higher than expected emissions (L. Wagner, USDA, March 2012, pers. comm.). It is important to note that published values of mean annual soil loss due to wind erosion from agricultural fields range from ~1 to almost 300 tha⁻¹ depending on soil susceptibility (Table 7).
Table 7 - Summary of recent published values for mean annual soil loss from agricultural fields

<table>
<thead>
<tr>
<th>Reference</th>
<th>Site location</th>
<th>Soil loss (t ha⁻¹)</th>
<th>Period of record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coen et al. (2004)</td>
<td>Alberta, Canada</td>
<td>0–286</td>
<td>30-yr WEPS simulation</td>
</tr>
<tr>
<td>Van Donk and Skidmore (2003)</td>
<td>Colorado, USA</td>
<td>0.6</td>
<td>unknown</td>
</tr>
<tr>
<td>Zobeck et al. (2001)</td>
<td>Washington, USA</td>
<td>1.5</td>
<td>unknown</td>
</tr>
<tr>
<td>Larney et al. (1995)</td>
<td>Alberta, Canada</td>
<td>30</td>
<td>single event</td>
</tr>
<tr>
<td>Van Pelt and Zobeck (2004)</td>
<td>Various, USA</td>
<td>3.2–287.8</td>
<td>2 average years</td>
</tr>
</tbody>
</table>

The WEPS and SWEEP erosion submodel specify a minimum 0.35 ms⁻¹ threshold friction velocity in order to generate soil loss and/or PM₁₀ emission (Sharratt and Vadella 2012). The average dry critical shear velocities generated from the SWEEP simulations was approximately 0.6 ms⁻¹. While WEPS and SWEEP have been known to underestimate dust emission and overestimate threshold shear velocity values (Van Donk and Skidmore 2003, Hagen 2004, Feng and Sharratt 2009), the results of the bare soil SWEEP runs yielded similar results to those of Gillette and Passi (1988) where dry threshold shear velocity values for various soil types ranged from 0.25 to 0.75 ms⁻¹. Our results were also consistent with the upper limit of the range of threshold shear velocity values reported by Shao (2004) for various soils. However, work by Kjelgaard et al. (2004b) and Sharratt et al. (2007) found that the critical shear velocity can be less than 0.3 ms⁻¹ when particles are perched on the soil surface after tillage.

Climate moisture values signalled the impact of snow cover, with values of zero over the winter months followed by increasing values through the spring (Table 6). The climate moisture factor peaked in July, which is the driest month resulting in the highest bare soil PM₁₀ emission susceptibility, and then declined through the autumn. These
results are consistent with the work of Brown et al. (2011) who showed that the highest bulk atmospheric deposition to Lake Simcoe occurs in the summer months.

The monthly CRFs were used to evaluate the impact of agricultural land use on PM$_{10}$ emission by soil type producing 66 evaluations. An example of six of the monthly PM$_{10}$ emission reduction factors for loamy sand soils is presented here (Figure 18).

![Figure 18 - Crop emission reduction factors (dimensionless) for loamy sand soil combined with different crop types](image)

In each case, the CRF was calculated by comparing the monthly emission from the agricultural land use from WEPS to the monthly emission from bare soils also calculated by WEPS. The CRF was the ratio between the managed and the bare soil emission; thus, CRF values below 1.0 indicated that PM$_{10}$ emission from crop land use was less than emission from bare soils while CRF values above 1.0 indicated that emission from crop land use was greater than emission from bare soils. As demonstrated in Figure 18, crop land use tended to reduce PM$_{10}$ emissions in comparison to bare soils. Farming practice for vegetables produced higher PM$_{10}$ emissions in March compared to bare soils but emission dropped below that for bare soil in April–May as the crop began to grow and cover the land thereby reducing PM$_{10}$
There was a smaller peak in PM$_{10}$ emission relative to bare soil for vegetable crops in October, although emission was still less than that from bare soil, followed by a substantially decline in November. Row crops tended to emit approximately 80% of the PM$_{10}$ emitted from bare soils from March to November; emission from row crops was negligible compared to bare soil for December–February. Mixed growth crops had a similar pattern to row crops but emissions relative to bare soil were negligible until peaking in April followed by a decrease in May then a generally increase to a second peak in November. Emission from hay crops was negligible compared to bare soil throughout the year except in April and May. Idle lands completely suppressed (< 10%) emission when compared to bare soils. The crop reduction factor for sod was bimodal with emission relative to bare soil increasing after February to peak in April–May while the crop was seeded and the soil was exposed, and then declining to zero from July–September when the crop grew followed by a second peak in October–November when the sod was harvested. These results are consistent with reported seasonal P deposition trends that showed PM$_{10}$ emission generally peaks in the spring and summer and then declines in the fall and winter (Brown et al. 2011). Similar monthly patterns for crop reduction factors were obtained for each of the agricultural land use practices for each of the soil types (data not shown), although in some cases patterns were slightly shifted earlier or later in the year.

When annual mean crop PM$_{10}$ emission reduction factors were compared for each soil type, the highest emissions compared to bare soils were for vegetable crops on loam soils (63%), row crops on loamy sand soils (62%), and mixed crops on loam soils (60%; Table 8).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Row</th>
<th>Mix</th>
<th>Hay</th>
<th>Sod</th>
<th>Vegetable</th>
<th>Idle</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay loam</td>
<td>26%</td>
<td>14%</td>
<td>3%</td>
<td>14%</td>
<td>20%</td>
<td>0%</td>
<td>13%</td>
</tr>
<tr>
<td>Fine sandy loam</td>
<td>32%</td>
<td>14%</td>
<td>2%</td>
<td>22%</td>
<td>21%</td>
<td>0%</td>
<td>15%</td>
</tr>
<tr>
<td>Loam</td>
<td>28%</td>
<td>60%</td>
<td>38%</td>
<td>48%</td>
<td>63%</td>
<td>0%</td>
<td>40%</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>62%</td>
<td>42%</td>
<td>9%</td>
<td>32%</td>
<td>41%</td>
<td>1%</td>
<td>31%</td>
</tr>
<tr>
<td>Organic</td>
<td>19%</td>
<td>13%</td>
<td>1%</td>
<td>22%</td>
<td>18%</td>
<td>0%</td>
<td>12%</td>
</tr>
<tr>
<td>Sand</td>
<td>52%</td>
<td>37%</td>
<td>9%</td>
<td>30%</td>
<td>30%</td>
<td>1%</td>
<td>27%</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>27%</td>
<td>14%</td>
<td>2%</td>
<td>17%</td>
<td>22%</td>
<td>0%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Table 8 - Annual average crop PM$_{10}$ emission factors expressed as the percent of emission from crop land use relative to bare soil for 6 crop types and 10 soil types; values for clay soils are not included as all emission reduction factors were 0%.
Only one of the highest 11 CRFs was from hay crops when combined with loam soils. The other values were distributed between row and mixed crops (3 soil types each), and vegetable and sod crops (2 soil types each). When averaged across soil types, row crops produced the highest emissions of all agricultural land uses at 37% that from bare soil. Mixed crops, sod and vegetable crops had similar average crop reduction factors at ~30% while hay reduced emissions to an average of 9% of emission levels from bare soil. The most effective land use for reducing PM$_{10}$ emission was idle land, which had an average CRF of zero. The annual average CRFs also differed by soil type (Table 8). On average, PM$_{10}$ emission was most reduced by agricultural land uses on silty clay loam soil where emission was 8% that of bare soil. Emissions were least reduced by crop land use on loam soil where, on average, emission was 40% that from bare soil.

An analysis of how much PM$_{10}$ is emitted by each DRU after taking into account how much of the land area is made up by a particular DRU revealed that the high emitting soil types were the sandy soils (loamy sand, sandy loam, and sand), while the lowest emitting soils were silts and clays (Table 9).

Table 9 - Relative mean annual PM$_{10}$ emission for each DRU (soil type combined with crop type) within the Lake Simcoe airshed. Bold-face values correspond to high emitting DRUs. Soil-crop combinations that do not occur in the Lake Simcoe airshed are indicated as NA (not applicable)
Organic | 0.04% | 0.02% | 0.00% | 0.00% | 0.72% | NA | 0.8%  
Sand    | **10.18%** | **4.28%** | **2.93%** | 0.42% | 2.55% | 0.21% | **20.6%**  
Sandy loam | **15.88%** | **6.79%** | **1.36%** | 0.57% | 0.94% | NA | **25.5%**  
Silt    | 0.26% | 0.22% | 0.09% | 0.03% | 1.22% | NA | **1.8%**  
Silt loam | 0.30% | 0.34% | 0.02% | 0.17% | 0.03% | NA | **0.9%**  
Silty clay loam | 0.09% | 0.09% | 0.01% | 0.00% | 0.00% | NA | **0.2%**  
**Total** | 47.9% | 29.6% | 10.9% | 1.5% | 9.6% | 0.6%  

Row crops yielded the highest contribution (48%) of the total PM$_{10}$ produced in the Lake Simcoe airshed, followed by mixed crops at 30%. Hay and vegetable crops produced 11 and 10% of the total PM$_{10}$, respectively. It is important to note that not all DRUs were found within the Lake Simcoe watershed. For example, sod was not farmed on clay loam soil, which is reflected by NA (not applicable) in Table 9.

An evaluation of the relative mean annual PM$_{10}$ dust emissions indicated that 12 of the 66 DRUs contributed just over 85% of the total PM$_{10}$ emitted in the Lake Simcoe airshed (Table 9). The highest contributions came from row, mixed, and hay crops on loamy sand, sand, sandy loam, and fine sandy loam soils. Mapping the spatial distribution of these 12 high PM$_{10}$ emitting DRUs revealed that the high risk areas are dominant to the northwest and southeast of Lake Simcoe (Figure 19).
Figure 19 - Spatial distribution (shown in red) of the 12 (out of 66) highest potential for dust emitting agricultural DRUs, including sand, loam, sandy loam, and loamy sand soils combined with row crop, mixed, and hay and pasture land management operations.

3.5 Discussion

The modelling results of this study indicate that crops on a given surface reduce PM$_{10}$ emissions compared to bare soil conditions. In addition, the modelling exercise identified and mapped the crop and soil type combinations that best reduce dust emission. Similarly, high risk crop and soil type combinations were also identified and mapped around the airshed.

As part of this study, dust response units were developed to facilitate the analysis of different soil and land use combinations. The new concept of DRUs can be used in both Lake Simcoe airshed as well as other similar inland lakes airsheds dominated by agricultural land uses to determine the optimal type and location of various BMPs
throughout the airshed. Estimates of the amount of dust reduced by the BMP can also be made.

Current GIS data indicates that a considerable amount of the land area in the Lake Simcoe airshed is classified as DRUs capable of emitting high amounts of PM$_{10}$. Based on the results shown in Figure 19, many of the high emitting DRUs are located on the west side of the lake, which has been identified as an area of interest, due to the prevailing wind direction. Analysis of wind direction in the Lake Simcoe watershed by Brown et al. (2011) indicated the dominant winds blow from northwest about 50% of the time and from the southeast about 30% of the time during the high deposition seasons of spring and summer.

The analysis of the spatial distribution of high risk DRUs refines our understanding of potential wind erosion by reflecting smaller areas with high dust emission potential allowing for targeted BMP action on the ground. Using the modelling results obtained in this study, the type and location of BMP that should be applied to best reduce dust emission can be determined and mapped accordingly. In addition, dust emission reduction estimates can also be estimated. As PM$_{10}$ deposition is a reasonable surrogate for P loading, reduction of dust emissions through BMPs will result in reduced P loading to Lake Simcoe and potential water quality improvements. Our analysis revealed that many high emitting DRUs are located on the northwest and southeast portion of the airshed. Given that the dominant wind directions are also from these areas (Brown et al. 2011), particular attention should be paid to these DRUs for targeted stewardship activities such as the implementation of BMPs for row crops, mixed crops and hay crops. These crops emit more PM$_{10}$ than other agricultural land uses, such as sod and idle land because they are subjected to more soil disturbance activities (such as tilling). Detailed resolution studies and modelling should be focussed on these areas to determine optimal stewardship activities to reduce PM$_{10}$ emissions. Based on the wind characterization work by Brown et al. (2011) in conjunction with our high risk DRU map, particular attention should be placed in the northwest area of Lake Simcoe close to the shoreline.

General stewardship activities in the Lake Simcoe airshed should focus best management opportunities on row crops as the highest contributor to emissions in the Lake Simcoe airshed. Additional focus on best management practices suitable for mixed crops could address just over 77% of the total PM$_{10}$ emissions from agricultural sources.

While characterizing and mapping agricultural emissions within the Lake Simcoe airshed is an important step to reduce PM$_{10}$ emission, there can be many other sources of PM$_{10}$ that should be considered. Future work includes extending the delineation of the DRU system to include other PM$_{10}$ emitters within the airshed, such as aggregate pits and quarries, active construction sites and unpaved roads. Using the complete DRU delineation analysis, a meteorological model that includes PM$_{10}$ transport and
deposition should be developed to determine wet and dry deposition from sources close to the lake and from the overall airshed. Further limitations are outlined below.

3.5.1 Limitations to the Modelling Approach

The results presented as part of this study do not include PM$_{10}$ contributions from non-agricultural sources, such as unpaved roads or construction sites, which also exist within the subject airshed. In order to develop customized PM$_{10}$ emission, transport and deposition models for the Lake Simcoe airshed, a variety of factors were individually developed. In particular, the MGP88 model used to determine emission contained individual factors that required input from precipitation, wind speed, soil type and land use. The data used and assumption made to determine many of these factors contain a high degree of variability. In addition, the relations used, while previously verified through studies, have been typically used as standalone parameters, as opposed to as part of a broader dust emission relation, as used in this study.

While the modeled results have not been validated with field data, there was a good agreement between the MGP88 model results, PI-SWERL data and published data for PM$_{10}$ emissions. This introduced a level of complexity to the study that was required in order to develop a shear velocity – based dust emission model.

3.6 Conclusions

The main goal of this study was to develop a more accurate method to identify and quantify key local agricultural sources of dust emissions within the Lake Simcoe airshed and opportunities for management and control of these local pollution sources.

Soil samples were taken from 16 sites around Lake Simcoe and were subjected to tests that measured the potential dust emission rates for a range of wind speed and soil moisture content using PI-SWERL tests. These measurements were used to validate bare, dry soil predictions using the GP88 model and compared to published results. The modeled results indicated that increased surface roughness, in the form of crops, can reduce dust emission within the airshed.

This study introduces the concept of DRUs which combine soil type and land use to determine the dust emission susceptibility based on the hourly variation of wind speed and monthly changes in soil cover due to crop growth. The DRU grid map was developed by using GIS Spatial Analysis tools to overlay soils and land use grid maps. Various dominant crop and soil type combinations were identified. The MGP88 model was used to evaluate the dust emission potential map for DRUs in the Lake Simcoe airshed. Of the 66 DRUs, 12 were determined to contribute 85% of the total dust emissions within the Lake Simcoe airshed. The new map (Figure 19) highlights areas with the highest potential for dust emission, including sand, loam, sandy loam, and
loamy sand soils with row crop, mixed, and hay and pasture land management operations.

Using the risk map developed, an efficient and targeted approach to BMP application can be pursued. In addition, the amount of dust emission reduced through BMP application can be estimated. Previous to this study, the originating locations of atmospheric P entering Lake Simcoe were unclear but through this project, the areas with highest potential for dust emission can be targeted. This can help educate landowners to adopt wind erosion control and dust emission agricultural BMPs. This study provides key information for the development and implementation of BMPs by providing the ability to distinguish where BMPs should be used and where specifically, at a field level, atmospheric nutrients are coming from. This should also include comprehensive follow-up research and monitoring, which is essential for community engagement and assessing BMP effectiveness.

The novel and customized dust emission model described in this paper can be used to calculate hourly PM$_{10}$ dust emission as input data for the USEPA CALPUFF long-range air dispersion and transport model for the Lake Simcoe airshed. As a result, this study has provided the necessary foundation for greater insights into the contribution of various sources of dust within the airshed and atmospheric sources of P loading to the lake.
Transition to Chapter 4

Windblown dust simulations are one of the most uncertain types of atmospheric transport models. This study presents an integrated PM$_{10}$ emission, transport and deposition model which has been validated using monitored data. This model characterizes the atmospheric phosphorus load focusing on the major local sources within the Lake Simcoe airshed including paved and unpaved roads, agricultural sources, construction sites and aggregate mining sources. This new approach substantially reduces uncertainty by providing improved estimates of the friction velocities than those developed previously. Modelling improvements were also made by generating and validating an hourly windfield using detailed meteorology, topography and land use data for the study area. The model was used to estimate dust emissions generated in the airshed and to simulate the long-range transport and deposition of PM$_{10}$ to Lake Simcoe. The deposition results from the model were verified against observed bulk collector phosphorus concentration data for both wet and dry deposition. Bulk collector data from stations situated outside the airshed in a remote, undeveloped area were also compared to determine the background contribution from distant sources.

4 A new dust transport approach to quantify anthropogenic sources of atmospheric PM$_{10}$ deposition on lakes

4.1 Introduction

The current application of dust models to compute windblown emissions, atmospheric transport, and deposition to water bodies contains a great deal of uncertainty (Lu and Shao, 1999), limiting its usefulness in regional environmental management. Dust can contain nutrients, which add to eutrophication processes when dust is deposited on the surfaces of lakes and ponds (Weiss et al., 2013). A study by Watson and Chow (2000) outlined the typical presence of chemicals and nutrients at various particle sizes and showed that PM$_{10}$ or fugitive dust encompasses most particle sizes found in the atmosphere.

Agricultural lands and practices associated with agricultural production are a major source of dust, particularly during high wind events or during ‘disturbance activities’, such as tilling (Kjelgaard et al., 2004). Modelling results have shown that windblown or atmospheric dust, defined as particles of size 10 µm or less (PM$_{10}$), generated by agricultural processes constitute the majority of dust loading globally (Tegen and Fung, 1995; Sokolik and Toon, 1996; Ginoux et al., 2001; Amodio et al. 2014). Dust generated by these processes has been directly related to nutrient/chemical loading (Leys, 1999; Leys and McTainsh, 1999; Salvador et al. 2014). The United States Department of Agriculture (USDA) has developed windblown emissions models, such the Wind Erosion Equation (WEQ) and later the Wind Erosion Prediction System (WEPS; Fryrear et al., 2001; Hagen, 2004) to estimate the impact of dust emissions from agricultural land use. However, both models have been shown to be somewhat inaccurate due to the broad estimation of shear velocity across local and regional scales. Alfaro et al. (1997) and Marticorena and Bergametti (1995) developed models to represent the mechanics of soil entrainment which use relationships between soil parameters with vertical and horizontal dust fluxes to estimate dust emissions. Although the parameters for these models were independently verified, limitations related to characterizing dust emissions over more local scales still exist. As a result, various researchers employ field dust emissions measurements (Gillette et al., 2004; Nickling and Gillies, 1993; King et al., 2011). One of the critical sources of uncertainty associated with estimating these emissions is the friction velocity, which acts as a surrogate to represent the shear stress causing the suspension of particulates (Lu and Shao, 1999).

The US National Oceanic and Atmospheric Administration (NOAA) coordinated the development of a continental scale dust model, embedded in the Weather Research and Forecasting (WRF) model and integrated with chemical modules (WRF/CHEm; Grell et al., 2005). The windblown emissions model, GOCART, generates emissions in the WRF model. The grid cells are large in size and all emissions modeled are instantly
mixed within the grid cell. This makes identifying the main contributors of dust events virtually impossible for small parcels of land.

The goal of this study was to quantify long range versus local source contributions of the atmospheric phosphorus load to a large lake. Specific emission sources by land use were also quantified through the development of a customized and integrated model. Long-range transport and deposition contributions were then mapped within the airshed, to enable resource managers to design a cost-effective and targeted dust control Best Management Practice (BMP) implementation plan as part of an overall phosphorus reduction strategy.

This study presents a new approach to more accurately estimate dust loading. The algorithm used a precise windfield model to generate the hourly spatial distribution of winds for input into the dust emission model. This distribution was used as input to a windblown emissions estimation process to create individual dust sources within the airshed. An air dispersion model was then employed to advect, diffuse, and deposit dust over the water bodies. Extensive dust deposition monitoring data were used to validate the new model.

The model was developed for Lake Simcoe, the largest inland lake in Southern Ontario, Canada. Its watershed supports an estimated population of 400,000 residents (MOE 2010) with an additional 50,000 cottagers (LSRCA, 2009). A decline in water quality attributed to excessive inputs of phosphorus has been observed over the past few decades (LSRCA, 2009). Various studies have estimated 25-50% of the total phosphorus entering the lake is from atmospheric deposition (Winter et al, 2007). Lack of vegetative cover, along with soil disturbance related primarily to agricultural activities, results in higher susceptibility to wind erosion and dust emission of soil particles loaded with phosphorus from fertilizers. Other sources include paved and unpaved roads, pits and quarries and construction sites. Recently, phosphorus loading to Lake Simcoe from atmospheric sources accounted for an estimated 19 tonnes per year on average, based on Lake Simcoe Region Conservation Authority and Ministry of the Environment data sets on phosphorus loading for 2002 to 2007 (LSRCA, 2009).

Earlier work by Ramkellawan et al. (2009) and Brown et al. (2011) provided various TP deposition estimates for Lake Simcoe. Ramkellawan et al (2009) used weather data to estimate the bulk deposition to the lake and Brown et al (2011) analyzed the bulk collector data in conjunction with a high-level analysis of the meteorological landscape within the airshed.

Weiss et al. (2013) continues this work and goes further to characterize one of the major atmospheric sources to the lake. Weiss et al. (2013) outlines the agricultural emission summary within the airshed, which includes a modified form of the Gillette and Passi (1988) dust emission model (MGP88), updated to reflect local climate and crop behaviour. The key benefit of using the MGP88 model is the independent parameterization of shear velocity, making it more accurate than standard regional
models. In urban environments vehicular traffic on paved and unpaved roads is the primary mechanism for dust emissions (Watson and Chow, 2000). An extension of the Weiss et al. (2013) study is the addition of paved and unpaved roads, pits and quarries and construction within the airshed.

4.2 Objectives

The main objective of this study is to develop more accurate methods and estimates of both wet and dry atmospheric deposition of nutrients to Lake Simcoe. To accomplish this, an integrated modelling approach was developed to incorporate widely accepted dust emission models with models based on real-time geophysical data. The specific objectives are to calculate the atmospheric loading of nutrients on Lake Simcoe due to: (1) wet deposition based on detailed analysis of spatial distribution of rainfall intensity data and rain water quality data; and (2) dry deposition based on detailed analysis of wind velocity and direction data and air quality data. Special attention was given to identify the location and magnitude of local sources of air pollution near the lake’s shoreline.

Agricultural emissions were modeled using a modified form of the GP88 dust emission model (Gillette and Passi, 1988; Weiss et al., 2013) and unpaved road emissions were calculated using the AP-42 emission equation developed by the USEPA (USEPA AP-42, 1995). An accurate windfield of the Lake Simcoe airshed was developed with simultaneous input from the Mesoscale Meteorological Model (MM5; Grell, et al., 1994) model and meteorological stations. The MM5 weather model produces gridded prognostic meteorological output fields used as inputs to CALMET. CALMET is the meteorological preprocessor for CALPUFF and is a diagnostic meteorological model that produces the final higher resolution three-dimensional wind and temperature fields and two-dimensional fields of other meteorological parameters (Scire et al., 2000). The purpose of the CALMET wind modelling exercise was to precisely characterize the Lake Simcoe airshed’s windfield in order to accurately model the windblown dust emissions, dispersion, and deposition of PM$_{10}$. Using inputs from CALMET, the CALPUFF model was used to model transport and deposition of PM$_{10}$ within the airshed and specifically Lake Simcoe. The model was verified using observed data from bulk collectors, located both in the airshed and outside, to distinguish between nearshore and background sources. To determine background contributions, bulk collector data from a station situated outside the airshed in a remote and undeveloped area were compared to nearshore station data.
4.3 **Material and methods**

4.3.1 **Dust emission estimates**

A widely used dust emission model for both regional and local dust emission is the GP88 dust emission model (Gillette & Passi, 1988). It was developed using a wind tunnel and validated using agricultural dust emission data, making it ideal for this study. The dust flux, \( F \) (\( \mu g/m^2 \cdot s \)) is expressed as:

\[
F = c_0 u^4 \left( 1 - \frac{u_{*cr}}{u_*} \right)
\]

where

- \( c_0 \) = Proportionality constant (\( \mu g/m^6 \cdot s^3 \))
- \( u_* \) = Friction velocity (m/s)
- \( u_{*cr} \) = Critical or threshold friction velocity (m/s).

Estimation of the friction velocity, consistent with the method used by Gillette & Passi (1988), uses the following relationship between wind velocity and the drag coefficient:

\[
u_* = \sqrt{c_d U}
\]

where

- \( U \) = Wind speed (m/s)
- \( c_d \) = Drag coefficient, Gillette & Passi (1988) expresses as:

\[
c_d = \left( \frac{0.23}{\ln z_{ref}} \right)^2
\]

where \( z_{ref} \) is the reference anemometer height.

Typically the height of the anemometer is 10 m. This way, equations (7) and (8) assumes that the friction velocity will always be 10% of the wind speed, which is a crude approximation. This approach ignores the effect of surface roughness and convective turbulence effects of the ground boundary layer. Since windblown dust emissions are dependent on the friction velocity raised to the power of four (\( u^4 \)), any error on its estimation is greatly amplified. Therefore, a better approach, suggested by Panofsky and Dutton (1984) for convective atmosphere is presented below:
\[ u_* = \frac{k \cdot u_{ref}}{\ln\left(\frac{z_{ref}}{z_o}\right) - \Psi_m\left\{\frac{z_{ref}}{L_*}\right\} + \Psi_m\left\{\frac{z_o}{L_*}\right\}} \]  

where

- \( k \) = von Karman constant = 0.4
- \( u_{ref} \) = wind speed at reference height [m/s]
- \( z_o \) = Surface roughness height [m]
- \( L_* \) = Monin-Obhukov length [m]
- \( \Psi_m \) = Stability term expressed as:

\[
\Psi_m\left\{\frac{z_o}{L_*}\right\} = 2 \ln\left(\frac{1 + \mu}{2}\right) + \ln\left(\frac{1 + \mu^2}{2}\right) - 2 \tan^{-1} \mu + \pi/2
\]

\[ \mu = \left(1 - 16 \frac{z}{L_*}\right)^{1/4} \]  

The Monin-Obhukov formula is presented below (Venkatram, 2004)

\[
L_* = -\frac{\rho \cdot c_p \cdot T_{ref} \cdot u_*^3}{H \cdot g \cdot k}
\]

where:

- \( g \) = acceleration due to gravity [m/s²]
- \( c_p \) = specific heat of air at constant pressure [J/g°K]
- \( \rho \) = density of air [kg/m³]
- \( T_{ref} \) = Reference Temperature of the surface layer [K]
- \( H \) = Sensible heat flux [W/m²]
Procedure steps for the calculations of u* under convective conditions are as follows:

1. Calculate assuming neutral conditions (Ψ_m = 0)
2. Calculate initial estimate of L*
3. Recalculate using equations for u*, Ψ_m and L*
4. Continue until the value of L* changes by less than 1%.

A 56-cell gridded polygon was developed for the airshed to function as point sources for dust emission within the airshed. Grid cells were sized based on soil type and the predominant wind direction, where areas with more erodible soils in the upwind direction contain smaller cells and areas of lower risk have larger cells.

### 4.3.2 Unpaved and Paved Road Emissions

Dust emissions from paved and unpaved roads were calculated using the AP-42 equation, as outlined in the Emissions Inventory 2002 Guidebook (Pollution Data Division of Environment Canada, 2006). The following relationship was used to determine the emissions from unpaved roads per vehicle kilometer traveled (VKT) as follows:

\[
E = 1.7k \left( \frac{s}{12} \right) \left( \frac{S}{48} \right)^{0.7} \left( \frac{W}{2.7} \right)^{0.05} \frac{365 - (p + \text{snow})}{365}
\]

where \( k \) is the base emission factor for the particle size range (dimensionless) and is 0.36 for PM_{10}, \( s \) is the silt content of the road material (%), \( S \) is the mean vehicle speed (km/h), \( W \) is the average weight of the vehicles travelling the road (t), \( w \) is the mean number of wheels, \( p \) is the number of days per year with at least 0.254 mm of precipitation and snow is the number of days per year on which snow covers the road. Using equation (13) above, the unpaved road emission rate was calculated to be 0.088 kg/VKT using the following parameters: \( s = 10\% \), \( S = 50 \text{ km/h} \), \( W = 2t \), \( w = 4 \) wheels, \( p = 140 \) days and \( \text{snow} = 150 \) days.

All unpaved roads within the Lake Simcoe airshed were analyzed spatially in GIS and the total length of unpaved roads within the airshed was calculated to be approximately 2,500 km. This translates into a road density of approximately 0.2 km/km².

Based on the 2011 Annual Daily traffic map generated by County of Simcoe, approximately 350 vehicles travel on local/unpaved roads in the vicinity of Lake Simcoe every day. The study assumed 125,000 vehicles per year frequent the unpaved roads around Lake Simcoe in order to estimate the total annual unpaved road dust emission. In addition, municipalities responsible for local, unpaved roads within the County of
Simcoe routinely apply oil to the unpaved roads as a dust suppression technique. A study by Flocchini et al. (1994) observed a dust suppression of up to 70% using this technique depending on the timing and frequency of application. Local to the Lake Simcoe watershed, road maintenance staff in the Township of Oro-Medonte indicate a dust suppression of approximately 30-50% (Brian Roubos, pers. comm.). Based on the literature, a 50% suppression value or BMPF was applied to the unpaved road dust emission estimate. Using this dust suppression assumption, the resulting emissions from unpaved roads is approximately 25,000 tonnes per year, consistent with the values reported by XCG Consultants Ltd. (2013).

The estimated unpaved road emission summary was developed by summarizing the total number of kilometers of unpaved roads in each grid cell, as shown in red using a GIS unpaved road shapefile supplied by the Lake Simcoe Conservation Authority (Figure 20) created in 2009.

![Figure 20 - Unpaved roads and grid numbers map](image-url)
The paved road emissions were calculated using the corresponding AP-42 equation, as follows:

\[ E = k \left( \frac{sL}{2} \right)^{0.65} \left( \frac{W}{3} \right)^{1.5} \left( \frac{365 - \text{snow}}{365} \right) \]  

(14)

where \( k \) is the base emission factor for the particle size range (g/VKT), \( sL \) is the road silt loading (g/m²), \( W \) is the average weight (t) of the vehicles travelling the road and snow is the number of days per year on which snow covers the road. For this analysis \( k = 4.6 \) g/VKT, \( sL = 0.002 \), snow = 150 days and \( W = 2 \) t. Based on the County of Simcoe Traffic Count Program, approximately 250,000 cars use the paved roads in the Lake Simcoe airshed daily resulting in 60,000 t/year of dust emitted.

### 4.3.3 Extraction Pits and Quarries

The dust emitted from extraction pits and quarries was calculated in accordance with the US EPA AP-42 Aggregate Sites standard (USEPA AP-42, 2006). The emission factor per ton of material transferred, \( E \) (kg/Mg) is calculated as follows:

\[ E = k(0.0016) \left( \frac{U}{22} \right)^{1.3} \left( \frac{M}{2} \right)^{-1.4} \]  

(15)

where \( k \) is a dimensionless particle size multiplier, \( U \) is the mean wind speed (m/s) and \( M \) is the material moisture content (%). According to the AP-42 standard, the particle size multiplier for various particle sizes is as follows: 0.35 (<10 µm), 0.2 (<5 µm) and 0.053 (<2.5 µm). Extraction pits in the Lake Simcoe airshed have been assigned a particle size multiplier of 0.35 for particles smaller than 10 µm and a moisture content of 0.25%. Using these parameters, the emission factor for extraction pits is 0.044 kg/Mg of extracted material. With regards to quarries, a crushed limestone operation provides the largest range of values for both moisture and silt content. The average moisture content of 0.7% for a crushed limestone operation was used (USEPA AP-42, 2006). Using these parameters, the emission factor for quarries is 0.011 kg/Mg of extracted material. Based on GIS data for the Lake Simcoe airshed, the allowable tonnages for pits and quarries in the Lake Simcoe airshed range from 20,000 to 12,827,900 t/year and are granted by regulatory permits. The locations are shown in the Figure 21. The climate factors outlined in Weiss et al. (2013) were also applied to emissions associated with pits and quarries.
4.3.4 Construction Sites

Several areas within the Lake Simcoe airshed are experiencing rapid urban development. The Places to Grow Greater Golden Horseshoe Growth Plan (2006) estimates a 184% growth in population by 2031 within the constituent municipalities of the Lake Simcoe region from a current population of 400,000 to 642,000 by 2031. This is an increase of approximately 8,000 people per year or 2,000 new homes per year. The PM$_{10}$ emission factor for housing construction sites, according to the USEPA AP-42 Guide is approximately 0.032 tons PM$_{10}$/acre/month. The emission (t/yr) generated from residential construction is calculated using the following relation:
\[
PM10\ Emission = \left( \frac{0.011\ tons\ PM10}{acre\ month} \right) \times B \times f \times m + \left( \frac{0.059\ tons\ PM10}{1000\ cubic\ yards\ dirt\ moved} \right) \times B \times d \quad (16)
\]

Where \( B \) is the number of single or two-family houses constructed, \( f \) is the buildings-to-acre conversion factor (estimated at 20 houses/acre), \( m \) is the duration of the construction activity in years and \( d \) is the cubic yards of dirt moved per house, typically 652 cubic yards (USEPA AP-42, 2006).

### 4.3.5 Emission Reduction Factors

The Best Management Reduction Factors (BMPFs) are factors by which each BMP is effective at suppressing dust emission. The MGP88 model incorporates the influences of ground cover, moisture, and other management factors, as shown below:

\[
F = c_0 u_s^4 \left( 1 - \frac{u_c}{u_s} \right) * CRF * C_m * BMPF \quad (17)
\]

where \( CRF \) is the crop reduction factor and \( C_m \) is the climate factor. The BMPF is expressed as follows:

\[
BMPF = \%PM10\ reduction \quad (18)
\]

The BMPF is defined for each practice type and is defined by township/municipality within the census data. Since each grid cell can potentially have several townships/municipalities, the area weighted average (based on % area coverage) for each township is calculated for each grid cell.

### Table 10 - BMP participation by township for the Lake Simcoe airshed (Statistics Canada, 2006)

<table>
<thead>
<tr>
<th>Township/Municipality</th>
<th>Crop residue</th>
<th>No-till</th>
<th>Cover crop</th>
<th>Windbreak</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRADFORD WEST Gwillimbury</td>
<td>84%</td>
<td>18%</td>
<td>14%</td>
<td>31%</td>
</tr>
<tr>
<td>Innisfil</td>
<td>88%</td>
<td>35%</td>
<td>12%</td>
<td>30%</td>
</tr>
<tr>
<td>New Tecumseth</td>
<td>81%</td>
<td>29%</td>
<td>20%</td>
<td>33%</td>
</tr>
<tr>
<td>Adjala-Tosorontio</td>
<td>67%</td>
<td>20%</td>
<td>17%</td>
<td>33%</td>
</tr>
<tr>
<td>Clearview</td>
<td>83%</td>
<td>14%</td>
<td>21%</td>
<td>31%</td>
</tr>
<tr>
<td>Essa</td>
<td>88%</td>
<td>29%</td>
<td>20%</td>
<td>38%</td>
</tr>
<tr>
<td>Township</td>
<td>% Township Coverage</td>
<td>% PM10 Reduction</td>
<td>% Crop Residue</td>
<td>% No-Till</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------------</td>
<td>------------------</td>
<td>----------------</td>
<td>-----------</td>
</tr>
<tr>
<td>ORO-MEDONTE</td>
<td>66%</td>
<td>18%</td>
<td>8%</td>
<td>38%</td>
</tr>
<tr>
<td>RAMARA</td>
<td>65%</td>
<td>24%</td>
<td>4%</td>
<td>25%</td>
</tr>
<tr>
<td>SEVERN</td>
<td>51%</td>
<td>13%</td>
<td>6%</td>
<td>23%</td>
</tr>
<tr>
<td>SPRINGWATER</td>
<td>90%</td>
<td>27%</td>
<td>16%</td>
<td>28%</td>
</tr>
<tr>
<td>TAY</td>
<td>66%</td>
<td>10%</td>
<td>7%</td>
<td>35%</td>
</tr>
<tr>
<td>TINY</td>
<td>61%</td>
<td>14%</td>
<td>11%</td>
<td>26%</td>
</tr>
</tbody>
</table>

**Average BMP Participation**

|                | 74%   | 21%   | 13%   | 31% |

The % township coverage combined with the % PM$_{10}$ reduction provides the overall BMPF for each practice. The effectiveness of the crop residue, no-till and windbreaks was calculated at 40% while the effectiveness of the cover crop BMP was calculated at 90%, consistent with the rates of effectiveness documented in Schnepf and Cox (2006). The agricultural BMPFs were obtained using the data above, applying each of the BMPs concurrently within each applicable grid cell. They range from 46% to 71% with the average BMPF being 60%.

### 4.4 Windfield Model Setup

Windfields can be generated using a variety of widely tested models such as diagnostic processors, including CALMET (Scire, et al., 2000) and SCIMET (Elmer, 2009), or more precise but computationally expensive prognostic processors such as MM5 (Grell et al., 1994) and WRF (Grell et al., 2005). To test and validate the model an approach was selected that increases accuracy and reduces computer requirements when compared to a very high resolution prognostic windfield. Datasets from the prognostic MM5 model and 10 meteorological stations were used as inputs to the high resolution diagnostic CALMET wind field modelling system. *Lakes Environmental* developed the first dataset for the MM5 hourly Lake Simcoe windfield, here denoted as the “MM5 Dataset”, which included wind estimations for both on and offshore areas. The following surface meteorological station data was used as the second dataset and are available through the Environment Canada website:

1. Barrie-Oro
2. Collingwood
3. Egbert
4. Lagoon City
5. Muskoka
6. Mount Forest  
7. Toronto-Buttonville  
8. Toronto-Pearson Airport  
9. Waterloo  
10. Wiarton

The following upper air met stations are also available:

1. Buffalo, NY  
2. Maniwaki, QC

The MM5 Dataset includes 3-D output from the MM5 prognostic model and observed meteorological data for surface, upper air, precipitation, and the offshore buoy located on Lake Simcoe. The time period covered in the MM5 and Stations datasets is 2005-2008. The CALMET model included the meteorological stations above, which were included after quality assurance was performed on the data prior to the final CALMET modelling runs. It is important to note that the number of stations included were those available within the 50 km modelling domain with an additional 50 km buffer. In each year, there were eight meteorological stations, one upper air station and one overwater station. The data from these sources were used to develop the windfield model.

4.4.1 Windfield Meteorological Grid

In order to develop the windfield, the study site was divided into finite areas or meteorological grid cells. A critical component of the windfield development is terrain and land use data. This study employed digitized terrain maps to assess the ground elevations at various locations within the modelling domain. The terrain pre-processor for CALMET extracted the terrain elevation from the most refined terrain data set to estimate the elevation point data for the objects within the modelling domain.

The USGS 200-meter Composite Theme Grid (CTG) data files were used as the input for the surface properties windfield computations. The study also attempted to use the new OMAFRA Ontario land use dataset, but this information did not contain sufficient data records for CALMET.

Surface measurement stations provide hourly meteorological information to the modelling grid domain plus a 50 km buffer. The two upper air meteorological stations are located outside the proposed meteorological grid domain plus a 50 km buffer but are within the acceptable range for these data. Precipitation stations are within the
CALMET meteorological grid domain plus a 50 km buffer. Additionally, data from one buoy station was located within the CALMET grid domain plus buffer.

4.5 Windfield Model Validation

The number of modelling runs required to accurately calibrate the model was determined using a customized statistical tool based on the parameters used to develop the windfield. The wind field modelling runs were produced using a CRAY supercomputer and verified to match bulk collector dust results around the lake. To ensure that the model results match the observed data, dust emission estimates were developed using the emission methodology outlined in Weiss et al. (2013) and were used to guide the CALMET model validation. The hourly wind field was used to produce friction velocity squared ($U^2$) results.

Additional statistical validation was performed on each aspect of the windfield model results, including temperature, wind speed and wind direction for a one year period. Each station was validated using X-Y and Q-Q plots on meteorological data from Jan 1 – Dec 31, 2007, as shown in Figure 22 and Figure 23.

![Figure 22 - Quantile-quantile plot comparing measured wind direction versus modeled for station 5.](image_url)
Figure 23 - Quantile-quantile plot comparing measured wind speed versus modeled for station 1.

The statistical analyses showed a good relationship between modeled and measured data at all three stations. Figure 24 outlines the methodology used to evaluate the accuracy of the modeled windfield.
4.6 Transport and deposition model setup using CALPUFF

The dust transport model uses the windfield modelling results as input. While the methodology used in this study employed the CALPUFF modelling system approved by the US EPA (FLAG, 2010), future work can use more modern transport models, such as SCIPUFF/SCICHEM (Sykes et al., 1997). CALPUFF is a Lagrangian Gaussian long-range transport puff model that includes algorithms and wet/dry deposition. CALMET, the meteorological pre-processor for CALPUFF, is a diagnostic meteorological model that produces three-dimensional fields of wind and temperature and two-dimensional fields of other meteorological parameters. Lastly, CALPOST is the postprocessor for CALPUFF. This study employed version 6.4 of the model, instead of version 5.8, in order to carry out the modelling analysis according to the latest FLAG (2010) methodology:

1. The model reads the CALMET.DAT wind field data file to obtain the hourly values of the friction velocity
2. The following tables were inserted into the database:
a. The critical friction velocity \((U_{cr})\), by soil type. If the wind speed \((U^*)\) predicted by the model is greater than \((U_{cr})\), particles are suspended generating dust.
b. The soil constant \((c_0)\) for each of the eleven soil types which is used in the dust emissions equation.
c. The Crop Reduction Factor (CRF) which varies according to soil type, by month, and by crop type (6 different crop types).

3. Two following two shapefiles were developed for this study:
   a. Land use and soil type (11 different soil types and 6 different crop types)
   b. 56 area sources, denoted Dust Reduction Units (DRUs)

4. The CALPUFF model evaluates the wind field, based on the CALMET cell location and the associated Dust Response Unit (DRU).

5. The model then evaluates the dust emissions formula for each cell to determine the hourly emission rate of dust for each DRU.

4.6.1 Lake Simcoe Surface Area Receptors

Receptors are locations where model results are calculated. In order to calculate the amount of PM\(_{10}\) and phosphorus deposited to Lake Simcoe, discrete receptors were used to cover the extent of the lake. The model used 22,500 receptors distributed over approximately 22,500 km\(^2\). There were 738 receptors over the surface of the lake. Figure 25 presents the distribution of modelling receptors over Lake Simcoe. Only “lake” receptors were used to compute deposition that contribute directly to the Lake Simcoe phosphorus load.
These receptors, denoted as green crosses, were assigned to a 1km by 1km grid over the area of the lake. This way, each receptor cell is 1 km² in surface area with the grid node receptor located at its geometric center. Receptor grid nodes are located at the windfield grid nodes to eliminate the necessity of interpolations on the computation of dust transport by CALPUFF. The final model included several discrete receptor points over land to assess potential deposition locations for bulk collector monitoring stations.

4.6.2 Methodology for Dust Emission

In order to generate the variable emission rates for each DRU, a dust emissions software utility was developed. This utility used hourly meteorological results from the windfield model and calculated the total dust emissions for each DRU for every hour for the entire year. To compute these hourly emissions, average hourly friction velocity (u*) over each DRU were first obtained. Once the average hourly friction velocity was calculated, the utility established the total hourly dust emission rate taking into account the critical friction velocities (u*,cr) for each of the soil types found within the DRU. Next,
the utility created variable hourly emissions dust area source files for each of the 56 grid cell point sources used as input for the CALPUFF model.

Using measured bulk collector data obtained through the monitoring program (Brown et al., 2011), it was possible to define approximate benchmarks for deposition values for the modelling exercise. These benchmarks include PM$_{10}$ emission of approximately 20 g/year/m$^2$, an overall atmospheric deposition of approximately 19,000 t/year and measured estimates from local dust sources of approximately 12,000 t/year. The bounding analysis was then used to calibrate the dust transport model by defining the lake polygon to assess total deposition and preparing the source contribution analysis.

Dust emission estimates require collection of surface parameters, such as the critical friction velocity, throughout the Lake Simcoe airshed. These data were obtained using the Portable In-Situ Wind Erosion Laboratory (PI-SWERL), as well as other published dust emission soil data. In addition, the field data collected relates to the GP88 dust emission model, which is based on the theoretical relationship of the ‘Law of the Wall’ and further verified using wind tunnel studies on agricultural fields. Based on these results, the friction velocity corrected GP88 model is an appropriate model to use within the Lake Simcoe airshed for agricultural sources.

### 4.6.3 CALPOST Modelling Options

CALPOST version 6.4 was used to post-process the CALPUFF output by obtaining the results for hourly and annual deposition fluxes of PM$_{10}$ to Lake Simcoe. A separate utility was developed to calculate the final CALPOST results by using the binary output files from CALPUFF to generate the total deposition values per month, adding all the lake receptors for each source. The CALPUFF model simulated multiple source contribution in order to calculate the deposition independently for each DRU.

Output from CALPOST provided the total deposition results per month and per emission source in text files. These files included X-Y locations relative to the modelling domain (latitude and longitude) and deposition fluxes and were processed using SURFER™ commercial plotting software, version 8 (Golden Software Inc., Golden, Colorado). One file for each DRU was created containing the center point of each grid cell and the corresponding deposition values. Three files were then generated: percent contribution of emissions deposited on the surface of Lake Simcoe, total dust emission from each DRU and total wet and dry deposition in the airshed to the surface of Lake Simcoe.

### 4.7 Model results and Validation

The monthly emissions trend computed by the model is similar to the observed deposition data measured by the bulk collectors sampling sites surrounding Lake
Simcoe, as shown in Brown et al. (2011). Figure 26 displays the monthly Total Phosphorus (TP) deposition on Lake Simcoe, as modeled by this study and compares these data to the observed TP deposition calculated by Brown et al (2011). However, the largest discrepancy between observed and model predicted TP deposition occurs during the April-June period. Banks and Nighswander (2000) measured the contribution of Pollen to atmospheric TP deposition on Clear Lake – located about 50 km north-east of Lake Simcoe - to be approximately 9 mg/m\(^2\)/yr or 6 tonnes/yr over Lake Simcoe that primarily happens in the months of April-June; however, this study mainly focused on anthropogenic sources (including paved and unpaved roads, agricultural sources, construction sites and aggregate mining sources) and did not include the contribution of pollen and other contaminants, such as feces, that might explain the difference between bulk collector data and the model predicted TP deposition in Figure 26. While outliers were removed from the bulk collector analysis as an integral step in the methodology, some events which can dramatically increase the apparently TP load, such as pollen or feces, may have been included in the results.

![Figure 26 - TP monthly deposition to Lake Simcoe](image)

The total model deposition of phosphorus to Lake Simcoe is approximately 11.5 t/year. This modeled deposition estimate favourably compares with the estimated 13.2 t/year from the OMOE monitoring program outlined in Brown et al. (2011).
4.8 Dust Measurements

Phosphorus loading data were continuously gathered in bulk collectors around Lake Simcoe (Brown et al., 2011) and reported regularly as a partnership between the Ontario Ministry of the Environment and the Lake Simcoe and Region Conservation Authority. Background phosphorus deposition data was also collected at bulk collector stations located outside the airshed in Dorset, Ontario. It is managed by the Ontario Ministry of the Environment using the same methodology for gathering the bulk collector data at Lake Simcoe. While the Lake Simcoe data is published regularly, the deposition rates in the Dorset are have not been recently published, so were calculated using bulk collector data using a similar methodology to that outlined in Winter et al. (2002). An analysis of the TP deposition at Dorset, Ontario showed that TP deposition at Dorset remained consistent over the last decade and is on average 50% less than TP deposition to Lake Simcoe. The Dorset station is a good indicator of background levels of TP deposition; it is located on the Canadian Shield where there are significantly fewer agricultural areas generating PM$_{10}$. Comparisons between the two locations indicated that there is an opportunity to reduce atmospheric deposition, based on the understanding that approximately 10 t/year of PM$_{10}$ will always be present in the form of background dust deposition.

The dust source emission rates to be evaluated in the analysis were located offshore and adjacent to Lake Simcoe at 44.44° north latitude and 79.35° west longitude. These sources formed a modelling domain around the lake area of approximately 50 km and it is in this area that particulate emissions generated by wind were evaluated.

Weiss et al. (2013) developed Dust Response Units (DRUs) by combining soil type and land use to determine dust emission using a modified form of the Gillette and Passi (1988) dust emission model (MGP88). Emission rates for each land use were developed within each grid cell and an area-weighted average of the DRUs was developed for 56 grid cells within the airshed (Figure 25) and incorporated into the model as point sources.

4.9 Deposition results

The model results were evaluated to determine:

1. Areas with the highest emissions in the airshed
2. Dust deposition impacts of PM$_{10}$ and its associated phosphorus to Lake Simcoe
3. Contribution from each of the DRUs surrounding Lake Simcoe
4. Segregate contributions from different source categories, such as agricultural sources, to total deposition of PM$_{10}$ and Phosphorus to Lake Simcoe
Total deposition flux (g/m²/s) was calculated from dry and wet flux components. The total annual PM₁₀ deposition to the surface of the lake was calculated by integrating all the deposition on the lake receptors over each month.

4.9.1 Distribution of Emissions from Emission Sources

The normalized emissions modeled by CALPUFF are shown in the Figure 27, by grid cell. They are effective in assessing the source of dust emissions.

Figure 27 - CALPUFF Normalized PM₁₀ Emission by Grid Cell Area (t/km²)

Similar to the results in Brown et al. (2011), the major emission 'hot spot' is identified at the north-west quadrant of the lake. Other hot spots within the airshed have been identified through a combination of soil type, land use, topography and orientation to the lake in relation to the prevailing wind direction.
4.9.2 DRU Contribution to Lake Simcoe Deposition

Due to preferential wind directions coming from the west and emission source distance from Lake Simcoe, areas with the highest emissions are not necessarily the ones that will have the highest deposition of phosphorus on Lake Simcoe. The contour plot in Figure 28 illustrates phosphorus total deposition (dry and wet) contributions from each of the emission sources to Lake Simcoe. The contour plot is an effective tool in assessing and analyzing the estimated PM$\text{_{10}}$ reduction from potential controls.

![Figure 28 - Deposition contribution of phosphorus to Lake Simcoe - all sources](image)

The Kriging interpolation method used to develop the plot above.
4.10 Discussion

To date, much of the dust emission modelling performed from agricultural sources has assumed that the detachment and transport capacity of wind is a function of the friction velocity to the power of 3 or 4 (Lu and Shao, 1999). However, in many cases the friction velocity is a crude approximation based on an approximation of the wind profile. Although this assumption has been somewhat verified experimentally, there are errors associated with it which are magnified exponentially when dust emission is considered constant on a regional scale. As a result, tailor-made regional models developed for a certain area or 'airshed' are required (Gong, et al., 2003).

Emission rates are far more accurate if the friction velocity is more accurately developed through real-time modelling of the wind profile and surface characteristics (Marticorena and Bergametti, 1995). The friction velocity developed through this study reduces error, which develops more accurate emission, transport and deposition results that closely align with observed field results. In doing so, this study has uniquely developed a regional atmospheric deposition model related to the major land uses within the airshed, namely agriculture, paved and unpaved roads, pits and quarries and construction sites. Is it also particularly tuned for northern climate impacts on an inland lake, such as snow, and the impacts of local topographical features on wind direction and speed.

In addition, the model includes a 1 km² resolution for DRUs that is then area-weighted within each grid cell. The meteorological model performed well compared to climate stations within the airshed. This analysis showed that near-shore sources have a far greater percentage contribution to atmospheric deposition on the lake than sources farther than 10 km away. There was a significant drop in deposition contribution in various locations around the lake, primarily in the south-east and north-west quadrants.

Based on the integrated model results, a targeted BMP approach can be taken to further reduce TP deposition to the lake. The historical tracking of TP deposition versus background TP from the Dorset station shows that the airshed is well on its way to improving the health of the lake. TP deposition has significantly declined in the past 10 years and the census data for the lake shows that most residents are employing multiple BMPs on their properties (Statistics Canada, 2006). Using the integrated model developed for the Lake Simcoe airshed, the optimum BMP can be selected DRUs within the airshed based on emission reduction efficiency, percentage contribution and implementation cost.
4.11 Conclusions

Over the past decades, excessive phosphorus loading to Lake Simcoe has resulted in nuisance plant growth along the waterfront, degraded habitat for cold water fisheries, and impaired beaches, marinas and waterfront property. Atmospheric deposition of phosphorus is reported to be responsible for 25-50% of the total phosphorus load. The main sources were dust from agricultural fields, unpaved roads, construction sites, aggregate pits and quarries. This research demonstrated that the new methodology improves dust modelling accuracy compared to previous modelling approaches.

The calibrated windfield and dust transport model was used to quantify the contribution of local air pollution sources including agricultural fields, construction sites, unpaved roads, and aggregate operations, and included the effects of seasonal wind patterns and land uses. The integrated model results showed that the nearshore sources play a major role in PM$_{10}$ and therefore associated phosphorus loading to the lake. Similarly, sources located upwind of the lake in the northwest and west quadrant of the airshed are more important than sources located downwind of the lake.

This study revealed that a considerable proportion of the atmospheric phosphorus entering Lake Simcoe is local in origin. As a result we can introduce control measures that are targeted for areas where the majority of airborne phosphorus to the lake originates. Decision-makers will be able to encourage the use of these targeted BMPs in those areas and/or sectors, as part of a targeted Phosphorus Reduction Strategy. The next steps of this study will include using more sources (grid cells) to increase the resolution of the results and provide an even more targeted approach for BMP application in areas around the lake.
Excessive phosphorus loading to inland freshwater lakes around the globe has resulted in nuisance plant growth along the waterfronts, degraded habitat for cold water fisheries, and impaired beaches, marinas and waterfront property (Environment Canada 2018). The direct atmospheric deposition of phosphorus can be a significant contributing source to inland lakes. The atmospheric deposition monitoring program for Lake Simcoe, Ontario indicates roughly 20% of the annual total phosphorus load (2010 to 2014 period) is due to direct atmospheric deposition (both wet and dry deposition) on the lake. To address this growing problem, this novel study presents a first-time application of the Genetic Algorithm (GA) methodology to optimize the application of best management practices (BMPs) related to agriculture and mobile sources to achieve atmospheric phosphorus reduction targets and restore the ecological health of the lake. The novel methodology considers the spatial distribution of the emission sources in the airshed, the complex atmospheric long-range transport and deposition processes, cost and efficiency of the representative management practices and social constraints related to the adoption of BMPs. The optimization scenarios suggest that the optimal overall capital investment of approximately $2M, $4M, and $10M annually can achieve roughly 3, 4 and 5 tonnes reduction in atmospheric P load to the lake, respectively. The exponential trend indicates diminishing returns for the investment beyond roughly $3M per year and that focusing much of this investment in the upwind, nearshore area will significantly impact deposition to the lake. The optimization is based on a combination of the lowest-cost, most-beneficial and socially-acceptable management practices that develops a science-informed promotion of implementation/BMP adoption strategy. The geospatial aspect to the optimization (i.e. proximity and location with respect to the lake) will help land managers to encourage the use of these targeted best practices in areas that will most benefit from the phosphorus reduction approach.
5 Optimizing best management practices to control anthropogenic sources of atmospheric phosphorus deposition to inland lakes

5.1 Introduction

Genetic Algorithms (GAs) are uniquely suited to optimizing Best Management Practices selection and placement over a spatial region, since multiple objective functions can be defined that can incorporate a variety of different optimization criteria (Arabi et al., 2006; Bekele and Nicklow, 2005; Gitau et al., 2004; Maringanti et al., 2009; Srivastava et al., 2002; Rabotyagov et al., 2010). Several studies have used genetic algorithm specifically to optimize the placement of BMPs over a large area, in order to facilitate cost-effective watershed management decision-making. This technique can be appropriately applied to the Lake Simcoe airshed, which has experienced a decline in water quality attributed to excessive inputs of phosphorus over the past few decades. The Lake Simcoe Region Conservation Authority and the Ontario Ministry of the Environment and Climate Change have reported that phosphorus loading to Lake Simcoe from atmospheric sources accounts for an estimated 20% of the total phosphorus entering the watershed; approximately 16 t/year (LSRCA, 2009; LSRCA, 2017). Previous studies have analyzed the airshed and effectively mapped the major atmospheric sources both spatially and temporally (Brown et al. 2011). Building on these studies and applying a GA optimization can ensure that effective and practical Best Management Practices (BMPs) are promoted and implemented within the airshed to reduce soil erosion and address some of the atmospheric deposition at the lake.

GA procedures follow evolutionary processes that search for optimal solutions for diverse and complex problems. For this reason, GAs are one of the most widely used techniques for the selection and placement of BMPs (Deb, 1999; Deb et al., 2002). The evolutionary nature of the selection of possible solutions ensures that a healthy diversity of possible outcomes that fit the specified objective functions (Zitzler & Thiele, 1999). Evolutionary algorithms applied to BMP placement can incorporate the interaction of BMPs with each other and can produce near-optimal solutions that comply with a specified objective function, which can be based on meeting a pollutant threshold or a cost-effective criteria or both. Gitau et al. (2004) incorporated three existing tools: a genetic algorithm (GA), a watershed-level nonpoint-source model SWAT, and a BMP tool, similar to this study. The costs of the BMPs were used to determine cost-effective BMP applications within the watershed. Maringanti et al. (2009) used similar BMP cost and efficiency data in their optimization to determine the placement of BMPs within their watershed. They also employed two objective functions, reducing pollutant load and net cost reduction, as part of their optimization setup and discussed this approach in their 2011 publication (Maringanti et al., 2011). Chen et al. (2015) described the benefits of
using the genetic algorithm optimization methodology when incorporating preference-based criteria, using indicator-based optimization principles. Loonen et al. (2006) conducted a similar study where atmospheric nitrogen deposition was modeled, due to excess loading to various nature reserves using a linear programming technique. Loonen et al. (2006) extended this study and used a genetic algorithm approach to determine various emission-deposition processes and distributions and found that it performed similarly to their linear programming technique.

Dust, defined as particles of size 10 µm or less (PM$_{10}$), generated from practices associated with agricultural production and unpaved roads, are directly related to nutrient/chemical loading on regional ecological systems (Leys, 1999; Leys and McTainsh, 1999). Dust emission susceptibility was determined by combining soil type and land use into 66 different dust response units (DRUs) in the Lake Simcoe airshed, which are a combination of 11 soil types and 6 land uses. Using a risk-based approach, the airshed was then split into grid cells, varying in size based on the areas that require more attention and greater resolution of detail. Each grid cell contains several DRUs and are generally representative, as the airshed is quite homogenous from a land use and soil type perspective as outlined in Weiss et al. (2014).

Based on the work in Weiss et al. (2014), a considerable proportion (roughly 40%) of the atmospheric phosphorus entering Lake Simcoe originates within the defined airshed. An integrated emission, transport and deposition model related to atmospheric dust was developed and applied to the Lake Simcoe airshed (Weiss et al., 2014), which characterizes the atmospheric phosphorus load focusing on the major local sources within the airshed and is based on an hourly windfield model developed using detailed meteorology, topography and land use data for the study area.

While the BMPs discussed in this study are promoted through Ontario’s Lake Simcoe Protection Plan and associated Phosphorus Reduction Strategy (MOECC, 2017), this study goes further and outlines a cost-effective approach to BMP application as it relates to the current understanding of the spatial and temporal mapping of PM10 emission, transport and deposition within the airshed. This provides a new approach to optimizing the placement of BMPs based on an integrated model to quantify atmospheric deposition to a particular source, in this case an in-land waterbody. Although GAs are widely used, this study represents the first application of using GAs for BMP placement to reduce atmospheric deposition of phosphorus based on results from an integrated emission-transport-deposition model. This study is the continuation of Weiss et al. (2014) and demonstrates a new method to map high priority areas for targeted implementation of dust control best management practices that could be useful in agricultural areas both within and beyond the Lake Simcoe airshed.
5.2 Background

Lake Simcoe is approximately 722 km$^2$ and is the largest inland lake in Southern Ontario. It is located north of Toronto and supports an estimated population of 400,000 residents (MOE, 2010) with an additional 50,000 cottagers (LSRCA and MOE, 2009) and is largely used for recreational purposes. The dominant land use is agricultural with a wide variety of soil types, including sandy soils. The map below outlines the lake and its relation to Southern Ontario.

Figure 29 - Map of Lake Simcoe (Environment Canada, 2017)
The findings from Weiss et al (2013 and 2014) both demonstrate that agricultural sources within the airshed are major contributors to atmospheric phosphorus loads to Lake Simcoe. As a result, this study focuses on prioritizing agricultural BMPs implementation scenarios within the airshed with the goal of producing "quick wins" at minimal cost. For the purpose of this optimization study, the agricultural BMPs used are no-till, crop residue, cover crops and crop rotation. Windbreaks were applied to the unpaved roads in the north-south orientation and are expanded upon below. Field scale resolution was not available in the agricultural land use dataset so this BMP could not be applied to discrete fields. In addition, calcium chloride and street sweeping are applied to both unpaved and paved roads respectively within the airshed. In addition to the benefits to reducing dust emission, the BMPs outlined below also benefit water-based erosion processes.

5.2.1 BMP Adoption Rates

The 2006 census data obtained BMP participation rates for five (5) agricultural Best Management Practices within the airshed, organized by township/municipality. Weiss et al (2013) defines DRUs, explains how they were developed and describes how the airshed (i.e. grid cells) were delineated. An area-weighted average was completed in GIS to determine the percentage of each grid cell that lies within each municipality (Table 11).

Table 11 – Agricultural BMP participation percentages according to 2006 census data (Statistics Canada, 2006)

<table>
<thead>
<tr>
<th>Township/Municipality</th>
<th>Crop residue</th>
<th>No-till</th>
<th>Crop rotation</th>
<th>Cover crop</th>
<th>Windbreak</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRADFORD WEST</td>
<td>84%</td>
<td>18%</td>
<td>65%</td>
<td>14%</td>
<td>31%</td>
</tr>
<tr>
<td>GWILLIMBURY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INNISFIL</td>
<td>88%</td>
<td>35%</td>
<td>61%</td>
<td>12%</td>
<td>30%</td>
</tr>
<tr>
<td>NEW TECUMSETH</td>
<td>81%</td>
<td>29%</td>
<td>62%</td>
<td>20%</td>
<td>33%</td>
</tr>
<tr>
<td>ADJALA-TOSORONTIO</td>
<td>67%</td>
<td>20%</td>
<td>52%</td>
<td>17%</td>
<td>33%</td>
</tr>
<tr>
<td>CLEARVIEW</td>
<td>83%</td>
<td>14%</td>
<td>65%</td>
<td>21%</td>
<td>31%</td>
</tr>
<tr>
<td>ESSA</td>
<td>88%</td>
<td>29%</td>
<td>72%</td>
<td>20%</td>
<td>38%</td>
</tr>
<tr>
<td>ORO-MEDONTE</td>
<td>66%</td>
<td>18%</td>
<td>58%</td>
<td>8%</td>
<td>38%</td>
</tr>
<tr>
<td>RAMARA</td>
<td>65%</td>
<td>24%</td>
<td>61%</td>
<td>4%</td>
<td>25%</td>
</tr>
<tr>
<td>SEVERN</td>
<td>51%</td>
<td>13%</td>
<td>38%</td>
<td>6%</td>
<td>23%</td>
</tr>
</tbody>
</table>
Municipalities located within the airshed that were not included in the census were assigned average participation rates based on the closest known municipal participation rate(s). Similarly, through the LEAP program, the Lake Simcoe Region Authority reported various participation rates within the airshed and the Ontario Soil and Crop Improvement Association have also tracked the number of BMP projects that have been implemented within the airshed between 2005 and 2015.

The potential participation rate for crop residue is lower, on average, than the current participation rate reported in the census. The maximum participation rate was used for each grid cell and the potential participation rate was applied to grid cells that did not participate in the census. For the purpose of this study, the optimization was conducted in an unrestricted fashion and then compared to the adoption rates outlined above for each grid cell. A brief description of each of the BMPs applied in this study is provided below.

### 5.2.2 Crop Residue and No-Till

Crop residue management ensures that organic matter levels in soils are optimal for continued crop production. This technique is considered one of the most commonly used BMPs in Southern Ontario to protect the soil surface from erosion (Greenland International Consulting Ltd., 2010) and is an important part of the crop production system. Crop residue management is defined as “any tillage and planting system that uses no-till, ridge-till, mulch-till or other systems designed to retain all or a portion of the previous crop’s residue on the soil surface. The amount required depends on other conservation practices applied to the field and the farmer’s objectives.” (USDA, 2002). In the absence of residue left on or incorporated in the soil, nutrients will continue to degrade, leading to declining soil structure and increased runoff.

In the Lake Simcoe airshed, approximately 74% of all farms that took part in the 2006 census reported applying some level of crop residue management. Similar to crop residue, no-till management is the ideal application of conservation tillage. While the two types of BMPs are similar, they have been differentiated in the Statistics Canada 2006 census and are therefore considered separate BMPs in this study. The average participation for no-till management is approximately 21%. Greenland International Consulting Ltd. (2010) estimates the PM10 control efficiency to be 40%, which is
consistent with the USDA-NRCS (2002) Handbook of Conservation Practices estimate of 30-90%.

In addition to reducing dust emission, no-till reduces the amount of fuel and equipment usage; however, because soil is being left undisturbed, often with plant residue on top, additional seed treatment, pesticides and spraying is often required. In comparing the costs for no-till and standard tillage for a similar crop type, The 2017 Field Crop Budgets, Publication 60 (a crop budgeting tool to estimate expenses for farmers, developed by the Province of Ontario, URL: http://www.omafra.gov.on.ca/english/busdev/facts/pub60.htm) outlines the following costs: seed treatment: $10/acre; pesticides: $30/acre; spraying: $10/acre; and the total cost of $50/acre or $12,350/km² annually. The BMP cost is the difference in net returns between conventional and no-till practices.

Crop residue covers a wider suite of management techniques – basically any plant residue left on the surface - and was assumed to have a slightly less control efficiency at 20%. Since any organic material can be considered a crop residue, the cost was considered minimal at approximately $200/km². These BMPs can be applied to all active agricultural land uses identified within the study area.

5.2.3 Cover Crops

Cover crops provide cover and protection to both soil and seeds. They are grown close to the production crop and often act as wind breaks to shorter crops within a field. In this way, cover crops can effectively reduce wind erosion and protect production crops from weeds. Some of the major costs associated with establishing cover crops are the seed and planting costs, which for this study, are considered minimal, since we are assuming that this task would have been done by the farmer regardless. Within the Lake Simcoe airshed, approximately 13% of all farms that took part in the recent census reported applying winter cover crops. The PM10 control efficiency is defined as 35% by Greenland International Consulting Ltd. (2010). The Sustainable Agriculture Network (1998) estimates the cost of putting this practice in place to be $4-20/acre, which is consistent with $20/acre figure estimated by Schnitkey, et al. (2017). Schnitkey et al (2017) estimate approximately $8/acre is associated with seeding while $13/acre is for drilling. For the purpose of this study, only the additional cost of seeding is accounted for at $8/acre or $2,000/km². This BMP can be applied to all active agricultural land uses.

5.2.4 Crop Rotation

Crop rotation involves the sequential rotation of a variety of dissimilar crops in the same area. This practice greatly enhances soil nutrients and minimizes the risk of disease to farmers due to the accumulation of pathogens and pests that can often occur on monocultures. At present, approximately 57% of the farms surveyed in the census
reported to participating in regular crop rotation. While the costs associated with crop rotation can be high, due to the need to vary machinery and operation on a more frequent basis, the benefits to soil health, reduced pesticide use and overall greater yield, outweigh the perceived disadvantages of varying the operation more frequently (Bullock, 1992). As a result, a minimal cost of $50/km² was allocated to implementing crop rotation on an annual basis.

5.2.5 Windbreaks

Natural barriers, such as tree lines, can be planted along unpaved roads to reduce wind erosion on the road, as well as adjacent agricultural fields. A windbreak is a row of vegetation, often trees or shrubs, planted adjacent to an agricultural field to break the wind and protect against wind erosion. Other benefits include providing habitat for wildlife and preventing snow from drifting onto roadways. In addition to these benefits, windbreaks are also often used to delineate between two properties. The PM10 control efficiency is 25% according to Greenland International Consulting Ltd. (2010). The capital cost associated with implementing this BMP was $15,000/km and was calculated as a weighted per kilometer average from the costs reported through the 2004 – 2015 The Landowner Environmental Assistance Program (LEAP) initiatives data. While this BMP has a relatively high capital cost, the ongoing maintenance is minimal; however the dust suppression rate is maintained. In order to determine the annual cost of the BMP, to enable a fair comparison with the other BMPs that consist of annual implementation costs alone, equation (19) was adapted from Maringanti et al. (2011) and Arabi et al. (2006) to determine the annual cost over the design life of the windbreak ($c_{td}$):

\[
 c_{td}($/km/year) = c_0 \left( 1 + s \right)^{td} + rm \left( \frac{(1+s)^{td}-1}{s} \right) / td
\]

(19)

where $c_0$ is the one-time capital cost of the BMP ($/km), rm is the ratio of maintenance to implementation cost (in this case, 1% as windbreaks have very low annual maintenance), s if the fixed interest rate (5%) and $td$ is the design life, assumed to be 25 years. The result is an equivalent annual cost of $2,300/km per year to implement windbreaks.

5.2.6 Unpaved Roads

Unpaved roads are made up of well compacted, engineered soils and typically have a coarser, harder surface material as the top layer, such as gravel. Several techniques can be used to reduce dust emission from unpaved roads and in Lake Simcoe, the predominant methods are chemical suppression, using calcium chloride and/or applying vegetable oil to the unpaved road surface. A study performed by Johnson and Olson (2009) in Minnesota looked to evaluate calcium chloride, magnesium chloride and an
organic polymer-plus-binder at various rates of application for two years. They examined the different types of dust suppressants, in concert with their rates of application, their costs and the types of roads being analyzed. They concluded that application frequency needed to increase from the standard application rate (typically once per year) and that the chemical suppressants worked better on roads beds with a higher silt content in contrast with the high-sand road beds that did not work effectively with the suppressants, which is similar to the findings of Gillies et al. (2009) regarding road bed silt loading. Gillies et al. (2009) also analyzed the efficiency of several suppressants and found that the petroleum emulsion with polymer was 73% efficient three months after application but reduced to 49% effective 12 months after application. In contrast, the Wisconsin Transportation Information Center (1997) recommended 1-2 treatments per year for both calcium chloride and oil suppressants and is consistent with the NRC and FCM (2005) assessment for application as well. In addition, both guides suggesting paving a road once the total vehicular traffic per day exceeds 500. Foley et al. (1996) and the Wisconsin Transportation Information Center (1997) do not recommend using chemical suppression techniques on unpaved roads with vehicular traffic of less than 15-50 vehicles per day. The NRC and FCM (2005) assessment estimates an annual cost of $2,800/km to apply calcium chloride to an unpaved road.

On high traffic roads, Walker & Everett (1987) found that road dust has a negative impact on roadside vegetation and recommends chemical suppressants, namely calcium chloride and lignin sulfonate, be used especially if the roads pass through environmentally sensitive areas and also serves to improve drainage. Their study was also consistent with other studies that suggest suppressants should be applied during the snow-free months, which corresponds to the higher emission months, outlined in Brown, et al. (2011). A study by Succarieh (1992) determined that reducing vehicular speed from 40 miles per hour (mph) or 64 kilometers per hour (kmph) to 20 mph (32 kmph) can reduce dust emissions by 65%. This can accomplished through signage and speed bumps, along with law enforcement availability and community cooperation; however road modification can only reduce speed within the limited modified distance.

Strategic and dense planting of trees and shrubs along roads, in the form of a windbreak, have also been studied extensively as a more natural technique to control dust emission from unpaved roads. A recent study by Mao, et al. (2013) modeled and measured the effect of a shelterbelt on an unpaved road and found that due to the small nature of particles emitted from the surface, the shelterbelt did not work to suppress the emission and may even increase the suspension of these particles. Windbreaks have also not been popular control techniques within the airshed and as a result, were not included as part of this study.

Within the Lake Simcoe airshed, the Township or Oro-Medonte and the Town of Innisfil currently use virgin oil for dust suppression, as is the case with several municipalities adjacent to the lake (Figure 30), however Tiny Township has stated that calcium chloride is used and is applied once per year in late June (XCG Environmental
Engineers & Scientists, 2013). This was also confirmed through a personal communication with municipal transportation staff (Roubos, 2011).

Figure 30 - Unpaved roads within the airshed with a 20km buffer around the lake

The existing emission model accounted for a 30% efficiency, based on existing BMP application. For the purpose of this study, a dust suppression factor of 73% was used to correspond with the efficiency rate observed by Gillies et al. (2009) through frequent application during the snow-free months. Unpaved roads within the 20 km nearshore buffer around the lake should be high priority areas for municipalities to implement intensive dust suppression measures.

5.2.7 Paved Roads

Dust emissions from paved roads are also a function of the volume of vehicular traffic on the road. Dust can be generated and emitted from combustion by-products, released through the tailpipe of the car, dust from the application of brake pads and the re-suspension of dust from other sources that deposited on the road and are not re-suspended by the disturbance.
The standard approach to controlling emissions from paved roads includes street sweeping. The EPA (2014) states that an effective street cleaning programs can minimize road pollutants. Finley (1996) estimated a cost of $21 USD/mile associated with street sweeping, which is conservatively converted to approximately $40 CAD/km.

5.3 Methodology

Genetic algorithm (GA) is an optimization methodology that uses the evolutionary process of survival of the fittest to find optimal solutions to problems involving large amounts of data. The components of a GA include the population, which is made up of chromosomes and genes that represent the various sets of random possible solutions. The optimization of these possible solutions is determined using a fitness function, which maximizes (or minimizes) a parameter based on a set of criteria or constraints.

Each possible solution is evaluated in this way and the fit or optimized solutions that meet the criteria best are duplicated while those that do not meet the criteria are discarded from further analysis through selection. Most genetic algorithms will, however, retain a set of unfit solutions to retain diversity in the population with the hopes that latent desirable genes will later manifest. Crossover and mutation steps are genetic operators that work to introduce new options (or possible solutions) into the population. The number of times this process is repeated is called the generations and with increasing generations comes increasing accuracy of results. This process is depicted in Figure 31 below.

![Figure 31 - GA methodology for BMP selection and placement optimization adapted from Maringanti et al. (2009)](image-url)
Using the GA methodology to determine optimized solutions for BMP application for a given watershed and more specifically, agricultural BMP application, is one of the most widely used optimization methodologies (Hsieh et al., 2010; Maringanti et al., 2011; Panagopoulos et al., 2013). A similar approach was taken by Maringanti et al. (2011) where NPS pollution was determined using a SWAT model and the GA was then applied on the results to determine the optimal type and location of the BMP within the watershed.

The GA methodology outlined above progressively evaluates a wide range of solutions, based on various criteria, and as a result is a preferred method for optimizing BMP placement over a large area with various criteria.

5.3.1 BMP Inputs

Since the program investment or cost was unknown, various orders of magnitude of investments were inputted into the algorithm, to determine whether varying the level of investment impacts the level of removal efficiency. The following table summarizes the BMPs proposed within the airshed and the inputs to the optimization exercise with the associated efficiency and cost. For this study, the fitness function was defined using information from the BMP tool in conjunction with the results from the dust modelling results for each grid cell.

<table>
<thead>
<tr>
<th>BMP</th>
<th>Allele set</th>
<th>PM10 suppression</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservation Tillage</td>
<td>Standard and No-till</td>
<td>40%</td>
<td>$12,350/km²</td>
</tr>
<tr>
<td>Residue management</td>
<td>Not present and Present</td>
<td>40%</td>
<td>$200/km²</td>
</tr>
<tr>
<td>Crop rotation</td>
<td>Not present and Present</td>
<td>40%</td>
<td>$50/km²</td>
</tr>
<tr>
<td>Cover crop</td>
<td>Not present and Present</td>
<td>35%</td>
<td>$2,000/km²</td>
</tr>
<tr>
<td>Windbreaks (unpaved roads)</td>
<td>Not present and Present</td>
<td>25%</td>
<td>$2,300/km</td>
</tr>
<tr>
<td>Calcium chloride (unpaved roads)</td>
<td>'Not present' and 'Present'</td>
<td>0%, 60%</td>
<td>$2,800/km</td>
</tr>
<tr>
<td>Street sweeping (paved roads)</td>
<td>Not present' and 'Present'</td>
<td>0%, 30%</td>
<td>$40/km</td>
</tr>
</tbody>
</table>
Through the optimization, the fitness function ensures that only the most optimal solutions are retained with some sub-optimal solutions remaining, to ensure genetic diversity. The optimization uses the deposition data, obtained in Weiss et al. (2014), and performs 50 generations of BMP application within the airshed. Generations that contain sub-optimal solutions are generally discarded and the optimization results in the most favourable scenario for each overall airshed investment.

While many more agricultural BMPs are currently implemented in the airshed, such as fertilizer storage improvement and tree and shrub planting, limitations in data availability made it difficult to model many of them and as a result, they were omitted from this study. Further studies could also be directed to other non-agricultural BMPs, such as dust suppression from aggregate operations and construction sites. Dust emitted from agricultural fields and mobile sources may have greater amounts of phosphorus.

5.3.2 GA Parameters

The objective function defined for this study was applied to the optimization to maximize overall dust suppression by cost to implement BMP in airshed and used the existing BMP application as a baseline. The summary table below (Table 13) outlines the model parameters and objective functions used in the GA process.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Source / Constraints</th>
<th>GA application formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>potential&lt;sub&gt;i,n&lt;/sub&gt;</td>
<td>Maximum achievable coverage for each BMP “n” on grid cell “i”</td>
<td>Fixed value based on potential BMP adoption rates from OMAFRA workshop</td>
<td>potential&lt;sub&gt;i,n&lt;/sub&gt;</td>
</tr>
<tr>
<td>P&lt;sub&gt;i,n&lt;/sub&gt; for i=1 to 56, n=1 to 7</td>
<td>Percentage of each BMP (1 through 7) applied to grid cell “i”</td>
<td>0 ≤ P&lt;sub&gt;i,n&lt;/sub&gt; ≤ potential&lt;sub&gt;i,n&lt;/sub&gt;</td>
<td>P&lt;sub&gt;i,n&lt;/sub&gt;</td>
</tr>
<tr>
<td>A&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Area of each grid cell “i” applicable to agricultural BMP</td>
<td>Fixed based on input data</td>
<td>A&lt;sub&gt;i&lt;/sub&gt;</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>Li</td>
<td>Length of paved or unpaved road applicable to each BMP</td>
<td>Fixed based on input data</td>
<td></td>
</tr>
<tr>
<td>SFn</td>
<td>Suppression factor for BMP “n”</td>
<td>Based on literature</td>
<td></td>
</tr>
<tr>
<td>Ei</td>
<td>Total emission (tons) from grid cell “i”</td>
<td>Based on fixed input data</td>
<td></td>
</tr>
<tr>
<td>SGi</td>
<td>Total suppression (tons) for grid cell “i”</td>
<td>Based on fixed input data</td>
<td></td>
</tr>
</tbody>
</table>

\[
0 \leq \sum_{i=1}^{56} \frac{SG_i}{E_i} \leq 1
\]

\[
SG_i(\text{tons}) = A_i E_i \sum_{n=7}^{4} p_n SF_n
\]

\[
= L_i E_i \sum_{n=5}^{7} p_n SF_n
\]

\[
C_n \ 	ext{Cost ($/km^2) for BMP “n”} \ 	ext{Based on literature}
\]

\[
CG_i \ 	ext{Total cost ($) for grid cell “i”; based on unit costs (Cn) for each BMP and associated area / length.}
\]

\[
\sum_{i=1}^{56} CG_i > 0
\]

\[
CG_i(\$) = A_i \sum_{n=1}^{4} p_n C_n
\]

\[
= L_i \sum_{n=5}^{7} p_n C_n
\]

**Objective Function**

Maximizes total suppression and minimizes cost for highest value of “tons suppressed per dollar”

\[
\text{Objective Function} \quad \max \sum_{i=1}^{56} \frac{SG_i}{CG_i}
\]

A commercially available GA, Evolver 4.0, Palisade, Ithaca, NY was used to solve each optimization. The GA considers possibilities at a system level rather than evaluating individual alternatives. It functions as an optimization add-on for Microsoft Excel. Each optimization run was set for 50 generations and the option to stop the optimization, in the event of an error, was selected.
5.4 Results and Discussion

There was a clear relationship of diminishing returns with increased investment per kilogram of phosphorus removed and greater overall program investment (Figure 32, Table 14).

\[ y = 34626e^{0.0012x} \]

\[ R^2 = 0.9279 \]

The greatest return on investment, in terms of dollars per kilogram of phosphorus removed, stems from the smaller investments. Once the investment exceeds the $3M mark, there appears to be diminishing returns. Outside of the clustered data, the slope on the trend line of return becomes flatter, indicating that the return is less dramatic. This shows a clear diminishing return experienced with greater overall investment.
Table 14 - Summary of all optimization scenario runs

<table>
<thead>
<tr>
<th>Scenario ID</th>
<th>kg P removed</th>
<th>Cost ($)</th>
<th>$/kg P removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,813</td>
<td>174,983</td>
<td>97</td>
</tr>
<tr>
<td>2</td>
<td>1,945</td>
<td>224,868</td>
<td>116</td>
</tr>
<tr>
<td>3</td>
<td>1,960</td>
<td>274,983</td>
<td>140</td>
</tr>
<tr>
<td>4</td>
<td>2,116</td>
<td>374,885</td>
<td>177</td>
</tr>
<tr>
<td>5</td>
<td>2,241</td>
<td>473,627</td>
<td>211</td>
</tr>
<tr>
<td>6</td>
<td>2,396</td>
<td>999,993</td>
<td>417</td>
</tr>
<tr>
<td>7</td>
<td>2,489</td>
<td>1,194,111</td>
<td>480</td>
</tr>
<tr>
<td>8</td>
<td>2,688</td>
<td>1,392,271</td>
<td>518</td>
</tr>
<tr>
<td>9</td>
<td>2,844</td>
<td>1,499,919</td>
<td>527</td>
</tr>
<tr>
<td>10</td>
<td>2,920</td>
<td>1,599,760</td>
<td>548</td>
</tr>
<tr>
<td>11</td>
<td>3,099</td>
<td>1,964,264</td>
<td>634</td>
</tr>
<tr>
<td>12</td>
<td>3,394</td>
<td>2,578,952</td>
<td>760</td>
</tr>
<tr>
<td>13</td>
<td>4,093</td>
<td>3,030,043</td>
<td>740</td>
</tr>
<tr>
<td>14</td>
<td>4,280</td>
<td>5,005,162</td>
<td>1,169</td>
</tr>
<tr>
<td>15</td>
<td>4,405</td>
<td>6,633,903</td>
<td>1,506</td>
</tr>
<tr>
<td>16</td>
<td>4,680</td>
<td>8,476,962</td>
<td>1,811</td>
</tr>
<tr>
<td>17</td>
<td>4,752</td>
<td>9,867,562</td>
<td>2,077</td>
</tr>
</tbody>
</table>

An analysis of the trend indicates that the investment cost rises dramatically after GA scenario 13 and that this scenario represents the optimal investment given the selected criteria for this optimization. Using this scenario for further analysis, the total investment cost was about $3M with an average $740/kg P removal or approximately 4 tonnes of phosphorus removed. Prior scenarios show a dramatic increase in removal with incremental cost. This pattern of diminishing returns has also been observed in
other BMP placement studies that use a GA optimization technique. Perez-Pedini et al. (2005) observed a similar trend in placing infiltration-based BMPs within their watershed and found a diminishing return beyond 600 BMPs applied and the total peak flow reduction achieved.

Subsequent scenarios, such as scenario 15, more than double the overall investment with only a small gain, 405 kg or 10% of the total, in phosphorus removed. For illustrative purposes, scenario 13 was mapped in GIS as investment per kilometer of grid cell, shown in Figure 33.

Figure 33 - Cost per square kilometer ($/km$\(^2\)) per grid cell for GA run 13

The optimization was performed on the airshed with proposed investments for each grid cell, as shown above. Many of the key investment grid cells are located in the “hot spot” areas identified in previous studies, namely up-wind and in the near-shore cells of the lake. The highest ranked investment, grid cells 17-22 and 27-30, have a relatively high number of north-south unpaved roads and the investment in the relatively expensive mobile sources are the primary cause for the increased investment in these cells. Cover crops and crop rotation are also predominant BMPs in these cells. This is also the case for cell 52, which also contains a sizeable investment in both crop rotation and cover crops. The results outlined in Figure 33 are the distribution of the total investment proposed by scenario 13 from the results above; namely an investment of approximately $3 million for an average cost of $740 / kg of phosphorus removed for a total of 4,093 kg of phosphorus prevented from entering the lake.
The pie chart below shows the overall investment, by BMP, that resulted from scenario 13. Crop rotation makes up the bulk of the investment with agricultural BMPs, second to cover crops and followed by crop residue. BMPs related to mobile sources make up approximately 22% of the overall BMPs with the emphasis on unpaved roads. Windbreaks and no-till BMPs had minimal representation at the airshed scale.

![Pie chart showing investment breakdown by BMP](image)

**Figure 34 - GA Scenario 13 - Breakdown by Investment Cost of the BMPs**

The normalized nutrient removal cost estimates (costs per kg P) outlined above compare favourably with the results outlined by Zukovs et al., (2010) for other types of nutrient removal strategies. Zukovs et al (2010) estimated that retrofitting Sewage Treatment Plants to comply with more stringent phosphorus discharge limits to the lake could cost as much as $13,100/kg of phosphorus, installing technology related to storm water runoff to control phosphorus is estimated at $1,800/kg of phosphorus, and agricultural BMPs cost between $170 to $1,700/kg of phosphorus. This study places BMPs consistent with Zukovs et al. (2010) and the inputs to the GA (BMP cost and effectiveness) are consistent with studies cited in previous sections.

### 5.5 Conclusions

This study presents a novel application of the Genetic Algorithm (GA) to optimize for cost when implementing BMP scenarios within the Lake Simcoe airshed. The goal is to
guide strategies to reduce the atmospheric phosphorus loads to Lake Simcoe. A GA optimization for BMP selection was developed using a DRU grid map and an integrated model for PM10 emission, air dispersion, transport and atmospheric deposition to Lake Simcoe (Weiss et al. 2013 and 2014). The GA presented cost-effective BMP implementation scenarios that target the areas with the highest potential for atmospheric phosphorus load reduction to help guide and educate landowners to adopt wind erosion control and dust emission agricultural BMPs within the Lake Simcoe airshed as well as controlling emissions from mobile sources, such as paved and unpaved roads.

The GA methodology was well suited for this application and provided an optimal BMP application for agricultural sources within the airshed. The inclusion of location factors provided further insight into the GA results by incorporating the transport and deposition aspects into the GA optimized results. The GA optimized scenario runs suggest that atmospheric phosphorus loads to Lake Simcoe can be effectively reduced by investing approximately $740/kg P removal at an optimal capital cost investment of approximately $3M annually. The removal cost can be as low as $100/kg phosphorus removal, depending on the size of the overall capital investment. This minimal removal cost corresponds with approximately 1,813 kg of P removed.

The study was conducted for the Lake Simcoe airshed; however, the methodology can be applied to other, similar inland lakes experiencing nuisance nutrient loading from atmospheric sources. This novel approach enables land managers to gain a higher resolution, field-scale view of the airshed and incorporates technical and social factors to deliver an optimized BMP strategy.

The Lake Simcoe Region Conservation Authority (LSRCA), through the Lake Simcoe Protection Plan, has implemented the Lake Simcoe Phosphorus Offset Program to reduce phosphorus loading to the lake in an incremental and cost effective manner. While several studies have determined the effectiveness of water-based erosion BMPs, this study quantifies the benefits from atmospheric BMPs on phosphorus reduction to the lake. The estimates and approach outlined in this study can be used to further improve the cost-effectiveness of investments made to improve Lake Simcoe’s water quality.
6 Conclusions and Recommendations

Nutrient loading to inland lakes from atmospheric sources is an ever-present driver of eutrophication. The predominant methods to estimate atmospheric loading are high level and rely on larger scale models that do not provide field or local level resolution. As a result, understanding field scale interactions and applying an optimization for the purpose of land management is often difficult, due to the high resolution of the modelling analysis. This body of work analyzed spatial and temporal patterns related to atmospheric loading to an inland lake, developed a record of land uses and soil types, a field scale emission, transport and deposition integrated model and an optimization methodology to help land managers prioritize BMP application. The major novel academic contributions of this thesis are:

- A comprehensive analysis of the monitoring data within the Lake Simcoe airshed that identified spatial and temporal trends of atmospheric phosphorus deposition to the lake using various analytical techniques.
- A comprehensive map of the land uses and soil types within the airshed that are the primary contributors of atmospheric nutrient loading to the lake.
- An integrated emission, transport and deposition model that provided field-scale resolution of areas within the airshed that are the main contributors of atmospheric nutrient loads.
- A genetic algorithm-based optimization model for BMPs selection that was developed using a DRU grid map and an integrated model for PM$_{10}$ emission, air dispersion, transport and atmospheric deposition to Lake Simcoe. The optimization model generated cost-effective BMP implementation scenarios that identify key areas for atmospheric phosphorus load reduction.

The details of these contributions were discussed in each chapter. A summary of the research conclusions and recommendations for further work are included below.

6.1 Seasonal and spatial distribution patterns of atmospheric phosphorus deposition to Lake Simcoe, ON

Using a variety of analytical techniques, nutrient loading to Lake Simcoe was found to have both a temporal or seasonal trend, as well as a spatial trend. The spring and summer months yielded four times more deposition than the later fall and winter months, accounting primarily to excess soil moisture and snow cover conditions reducing dust emission during the fall and winter seasons. The peak load was observed in late spring and early summer before adequate vegetation cover was in place to reduce emission rates by late summer and early fall. Spatially, deposition was higher in the northwest quadrant of the airshed, due to the presence of a sandy soil type associated with higher emissions as well as the prevailing wind direction.
This study marked the first time seasonal and spatial trends were linked with phosphorus deposition. The results of this study are able to provide land managers with a comprehensive overall understanding of the dynamics of the airshed from a phosphorus deposition perspective. This enables land managers to target management techniques to optimize in both space and time.

6.2 Mapping key agricultural sources of dust emissions within the Lake Simcoe airshed

Building on the spatial and temporal trends observed above, this chapter analyzed the airshed and identified the key soil and agricultural dust response units (combination of soil type and land use) that are the primary sources of dust to the lake. Once the sources and DRUs were identified, the seasonal changes in wind speed and soil cover were determined and an agricultural dust emission model (MGP88) was used to evaluate the varying dust emission potential within the airshed of each DRU. Areas of higher risk regarding higher erodible soils or more disruptive land uses were identified within the airshed, in the form of a risk map. This helped develop the modelling approach, namely the grid cells that would be used as an input to the integrated emission, transport and deposition model. By using this methodology, BMPs, can be identified at the local or field scale, in order to provide the resolution required to land owners and managers.

This study built on the spatial and temporal trends observed within the airshed and provided an increased field scale resolution to the modelling domain through the introduction of DRUs. This study was the necessary foundation to developing an integrated model for the airshed and provided land managers with a more detailed understanding of high risk erosion areas within the airshed by mapping high risk DRUs. This study also marked the first application of DRUs for dust modelling purposes.

6.3 A new dust transport approach to quantify anthropogenic sources of atmospheric PM$_{10}$ deposition on lakes

The DRUs and risk map developed were used to create an integrated emission, transport and deposition model for nutrient loading to the lake. The dust emissions were previously determined (using the MGP88 model) and a windfield was created to model dust transport across the airshed. The seasonal wind trends observed previously were also included in the transport model developed. From this modelling exercise, it was concluded that this methodology compares favourably with other dust modelling approaches (in terms of accuracy) and that most of the atmospheric phosphorus loads to the lake are local (from within the airshed) and specifically from the nearshore grid cells. The primary contribution of this approach is the quantification of the shear velocity
parameter, which separates this methodology in terms of accuracy and resolution at the field scale.

This study marked the first application of an integrated model using field scale elements; namely the DRU approach, within a discrete airshed. While the methodology was applied to Lake Simcoe, it can be similarly applied to any inland lake irrespective of land uses and soil types. Errors associated with emission determination as well as transport and deposition were counterbalanced by the fact that the overall deposition was validated with the field data observed for over a decade. While the model has field scale resolution through the shear velocity parameter, the integrated modeling exercise was developed to understand the relative contributions of various sources, at various locations, for an inland lake. As a result, the research team is confident that there is minimal bias in the modeled data.

6.4 Optimizing best management practices to control anthropogenic sources of atmospheric phosphorus deposition to inland lakes

Using the field scale resolution modelling results obtained above, a GA optimization was applied to the airshed to identify priority BMP scenarios. While GAs are typically used by land managers for BMP identification in a defined area, this was a first time application of a GA in an airshed (for atmospheric nutrient reduction) with field level resolution. The BMPs were inputted into the GA on the basis of cost, efficiency and rates of participation and included BMPs for agricultural and mobile sources. The results indicate that investments of $740/kg P removal can significantly reduce nutrient loads from atmospheric sources and this rate of investment is comparable with other BMPs proposed in the airshed related to storm water management and wastewater treatment. While the methodology was applied to Lake Simcoe, it can also be applied to other inland lakes with a similar level of information available. Additionally, this study can provide land managers with an understanding of the order of magnitude of funds required to obtain various levels of phosphorus reduction, in addition to a targeted approach to where the BMPs should optimally be placed to obtain these results. This approach ultimately provides a targeted approach to land management that can help managers justify a variety of investments.

6.5 Recommendations for Further Work

1. Lake Simcoe exhibits both spatial and temporal (or seasonal) trends in nutrient loads with the spring and summer months most heavily impacted. Since nutrient loading can be curbed by BMP application (and other behavioural modifications), further work can be done in developing a real time alert system for those in the airshed to respond to conditions from a land management perspective, in real time.
2. The monitoring results obtained end in spring 2007. The modelling results could be further updated with data obtained since this monitoring period.

3. The land use categories could be expanded upon and modelled to provide a more accurate and holistic view of emission sources within the airshed. Further to this, corresponding BMPs can also be identified for each of the land uses not included in this study.

4. Lake Simcoe Phosphorus Offset Program contains benchmark credits for various BMPs applied within the airshed. The Program could be further expanded to include atmospheric sources from a variety of land uses. The proposed credits would require refinement to ensure that the offsets provided are indeed reducing nutrient loads to the lake.


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Roubos, B. (2011, December 14). Aggregate Resources Officer. (L. Weiss, Interviewer)


