A Regional Probabilistic Dust Emission Management Model for Construction Activities

By

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A Thesis

Presented to

The University of Guelph

In partial fulfilment of requirements

For the degree of

Master of Applied Science

In

Engineering

Guelph, Ontario, Canada

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ABSTRACT

A REGIONAL PROBABILISTIC DUST EMISSION MANAGEMENT MODEL FOR CONSTRUCTION ACTIVITIES

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Fugitive dust emissions from active construction sites, without wind erosion and dust suppression controls, can be orders of magnitude higher than pre-development background values. As the exact location, size, and timing of construction activities within a region are difficult to forecast, a new probabilistic dust emission management tool is proposed. This proposed Construction Induced Dust Emission Management (CIDEM) probabilistic model incorporates both the spatial and temporal variation of construction activities. Characterization of the construction phases provides the basis for the dust emission calculations and for the selection/sizing of the wind erosion and dust suppression control measures commonly used on construction sites, including watering, mulching, unpaved road dust suppressants, and revegetation. The cost-optimization of the Best Management Practices (BMPs) is performed using a genetic algorithm and linear programming called Evolver. However, to keep the cost reasonable, contractors applying the wind erosion and dust suppression controls should target highly susceptible areas, prioritizing unpaved roads, followed by areas with little-to-no boundary obstructions and flat bare soil surfaces that would remain exposed for extended periods. This study highlights that construction sites should consider modelling maximum daily dust emissions and use wind erosion and dust suppression controls if the site footprint is larger than 5 ha or if the soil is of sandy nature as those soils have significantly higher dust emission potential when disturbed and exposed for extended period of time than others.

ACKNOWLEDGEMENTS

I would like to thank the Ontario Ministry of Environment Conservation and Parks (MOECP), the Lake Simcoe Conservation Authority (LSRCA), and the Natural Science and Engineering Research Council of Canada (NSERC) for providing me with the opportunity to pursue this work through their financial contributions and constant support. Additionally, I thank Larry Wagner and John Tatarko, for helping me in the early stages of WEPS development and troubleshooting. I am indebted to Lee Weiss for her continual support in this work and providing me essential guidance in the early stages of this project.

I am grateful to Dr. Bahram Gharabaghi for high energy and continuous passion for my success throughout these two years. Bahram knew how to keep me focused and engaged, especially when difficulties arose, an invaluable skill that few possess. I thank Dr. Amir Aliabadi for contributions to my development as a critical thinker throughout my university years and his incredible patience throughout this process. I would not be the problem solver I am today without his leadership. I am grateful to Dr. Jesse Thé, Jennifer Mackey, and Jeff Madge for their various contributions.

To my fellow graduate students: Patrick McGrath, Ahmad Kia, Ryan Byerlay, Amir Nazim, and the many others along the way. The last two years have been an exponential learning experience for me, and without your kind words of inspiration and motivation, I do not think I would have reached where I am today.

I finally give my most sincere gratitude to my family and friends: Mom, Dad, Scott, Jitka, my five sisters, two brothers, and all others (especially Geoff, Martin, & Emma). These people have seen a light in me since day one. They are always there to support me with everything I accomplish in life, listening to my thoughts, and providing me sound advice throughout. I am so glad to be surrounded by such well-rounded people, shaping me into the individual I am today. I seriously would not have been able to finish my graduate studies without them. Thank you all so much,

Denis Clement

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Table of Nomenclature and Commonly-Used Terms

AT%: Percent Area of Treatment [%] **BMP: Best Management Practice BMPF: Best Management Practice Factor BMRF: Blanket Mulch Reduction Factor CF:** Construction Factor CIDEM: Construction Induced Dust Emissions Management C_{bm}: Cost of blanket/mulch incurred by the contractor [\$] C_w: Cost of water incurred by the contractor [\$] CM: Cover-to-mass ratio D: Depth of water applied [mm] f: Frequency [d⁻¹] GA: Genetic Algorithm GIS: Geographic Information System MOECC: Ministry of the Environment and Climate Change NRCS: Natural Resources Conservation Services **P:** Phosphorus PM₁₀: Particulate matter with a particle diameter of $\leq 10 \,\mu m$ P_{bm}: Price of blanket/mulch [\$ kg⁻¹ha⁻¹] P_w : Price of water [\$ mm⁻¹ ha⁻¹] **RRF:** Revegetation Reduction Factor **TSP: Total Suspended Particles** USEPA: United States Environmental Protection Agency VKT: Vehicle Kilometer Travelled VMT: Vehicle Mile Travelled WEPS: Wind Erosion Prediction System WRF: Watering Reduction Factor

CHAPTER 1 - INTRODUCTION

It is vital for modern society to carefully evaluate the impact of anthropogenic activities on the environment as these activities can cause irreversible damage that are unlikely to be completely mitigated using remediation techniques. By focusing on the minimization of anthropogenic activities and the prevention of their adverse effects, conservation of a healthy local and global environment is more likely (Ehrlick & Mooney, 1983). Due to the global population increase, it is inevitable that anthropogenic activities, like urban development, will continue to impact the environment. Ontario, the most southern and populated province in Canada, has seen a 4.6% increase in population from 2011 to 2016 and will continue to experience urban development for years to come due to it's continually increasing population (Statistics Canada, 2018). Construction, an integral part of urban development, can be considered one of the most environmentally degrading anthropogenic activities as processes cause land to be more vulnerable to erosion by means of the removal of natural vegetation, displacement of soil, and change in drainage features (Toronto and Region Conservation, 2009).

By modelling construction activities around Lake Simcoe, a freshwater body found in southern Ontario and predicting the rate of construction annually; this research will develop a tool to estimate dust emissions from construction sites in the area and optimize the relationship between dust emission reduction and future investments in dust emission management practices on-site.

The degradation of lakes, rivers, and other natural inland water bodies can be attributed to excessive nutrient loading, specifically phosphorus (Brown et al., 2011; Weiss et al., 2017). Agriculture, construction, and transportation are examples of anthropogenic activities that contribute to phosphorus loading through wind erosion and dust emissions (Tatarko et al., 2016;

Liu et al., 2017). Airborne dust, which can be defined as particles of size $\leq 10 \ \mu m$ (PM₁₀), contributes to an excess of nutrient loading in surrounding water body loading from particulate phosphorus in dry deposition and dissolved phosphorus in wet deposition (Leys, 1999).

ONTARIO, LAKE SIMCOE, AND PHOSPHORUS LOADING

Lake Simcoe, one of Ontario's largest freshwater bodies excluding the great lakes is found 60 km north of Toronto and serves as a great socio-economic asset to the province due to it's an attraction to cottagers, fishers, and boaters alike (ILEC, 2019). The lake hosts many boating and fishing events in the Summer. Lake Simcoe is well known for the annual Canadian Ice Fishing Championship as its surface completely freezes during the Winter months (Town of Georgina, 2013). Many communities border the lake, including Barrie, Orillia, Durham, and others. The surface area of the lake, at 725 km², only represents about 25% of the catchment area, at 2840 km². The lake's catchment basin has 35 rivers that drain into the lake, five of which drain 60% of the catchment area into Lake Simcoe with an approximate volume of 11.6 km³ (ILEC, 2019).

By monitoring cold-water fish communities, conservation authorities around Lake Simcoe can get a reasonable sense of the overall health and water quality of the lake. As authorities have seen a significant decrease in cold-water fish populations, including lake trout, herring, and whitefish, the water quality of the lake has been declining over time (LSEMS, 2008). The deteriorating water quality has been attributed to excessive nutrient loading, including phosphorus (Ramkellawan et al., 2009; Brown et al., 2011). With an increase in phosphorus loading, the lake experiences excessive algae growth, resulting in a decrease of dissolved oxygen concentrations in

the water which ultimately diminishes the abundance and diversity of the fish population in the lake (Ramkellawan et al., 2009).



Figure 1: The Lake Simcoe watershed (Evans et al., 1996)

Due to Lake Simcoe's large surface area, atmospheric deposition of dust, both wet and dry, is estimated to contribute 25-50% of phosphorus loading in the lake annually; phosphorus loading

is fairly stable every year during the Fall and Winter months but variant during the Summer and Spring months (Brown et al., 2011). Agricultural operations, especially in areas consisting of soils with high erosion susceptability, have shown to emit dust due to wind erosion from operations that disturb the soil and expose bare soils due to diminished vegetation in the Spring and Summer months (Weiss et al., 2013). Similar to agricultural operations, construction projects have multiple phases in which soils are disturbed or left exposed to the air, resulting in the potential for wind erosion and dust emissions.

Anthropogenic activities have affected the Lake Simcoe watershed for over 200 years; urbanization has changed the natural landscape of the water shed, altered the composition of vegetative cover, caused excessive nutrient loading, and imposed other environmental impacts. Other human-induced pressures that have been compromising the integrity of the lake include the introduction of the invasive zebra mussel species, which alter the natural equilibrium of the lake and its ability to resist stress, climate change, which introduces longer droughts during the Summer months, harsher Winters, and larger storms that cause heavy erosion and sedimentation, and alteration of shorelines and other marine habitats (Ontario Ministry of the Environment, 2009).

The increase in anthropogenic pressures on Lake Simcoe over recent years could be primarily attributed to the dense population in southern Ontario that continues to grow each year. Over the next 24 years, the population of Ontario is expected to grow by 30.2 percent by July 1st, 2041, to 18.5 million. In 2006, 12.7 million Ontarians accounted for 40% of the Canadian population, with nearly 98% of the population of Ontario found in the Grake Lakes Basin in southern Ontario (Ontario Ministry of the Environment, 2009; Ontario Ministry of Finance, 2018).



Figure 2: Historic land use in the Lake Simcoe Region (Evans et al., 1996)

With the increasing population in southern Ontario, it will be important to develop larger communities to accommodate the extra residents. Net migration is expected to contribute 76% of the total increase in population in Ontario, requiring even more new dwellings and complexes. The population of seniors in Ontario is also expected to double from 2.4 million to 4.6 million over the next 24 years (Ontario Ministry of Finance, 2018). As Lake Simcoe and its surrounding communities are mostly rural areas, it can be expected that many of these seniors will migrate towards the lake and invest their life's earnings on new dwellings or dream homes, ultimately increasing the overall rate of development in the area.

Due to the declining health of the lake, Ontarians have been on-board for a comprehensive plan to rejuvinate Lake Simcoe's watershed and begin recovering the natural state of health that once was. In 1990, the Lake Simcoe Environmnetal Management Strategy (LSEMS) program began in an effort to restore the lakes ecological health and return the water body to a selfsustaining cold water fishery (Ontario Ministry of the Environment, 2009).

CONSTRUCTION SITES IN LAKE SIMCOE

Construction activity is inevitable toward urban development. It is a major environmentally degrading anthropogenic activity since its processes increase soil erosion susceptibility including natural vegetation stripping, altercation to soil structures, and changes to drainage features (Flagg et al., 2014; Payus et al., 2017; Xing et al., 2018). Construction projects can be challenging to summarize as each project is unique concerning the time of year it starts, the proposed building or structure being worked on, unforeseen delays including weather, the physical properties of the site, and others.

Generally, the three processes that are most dust emission-intensive are the preliminary phases of construction: grubbing, leveling, and servicing. Later phases in construction, such as the building phases, can be considered insignificant concerning dust emissions as most of the earthworks have been completed, so there are minimal soil disturbances, buildings and roads cover exposed soils, and the revegetation of exposed soils has been well underway.

Grubbing, the first phase of construction, is the removal of rocks, stumps, trees, and other pre-existing vegetation (Government of Manitoba, 2003). This is performed using heavy machinary, causing significant disturbances in the soil and resulting in exposed soils. The leveling

phase of construction comes after grubbing. Leveling is performed by moving around pre-existing or additional soils, depending on the project, to create and prepare a landscape for the upcoming construction. Similar to grubbing, leveling uses heavy machinery to move and alter soil structures, ultimately creating frequent soil disturbances and exposed soils. The servicing phase of construction occurs after all leveling has been finished. This phase consists of implementing foundations, water piping systems, electrical systems, and other objects that can be found below grade level. Excavation of the soils is performed during this phase to put objects underground. These excavation activities result in the disturbance of soils and exposed soils, increasing the susceptability of wind erosion and fugitive emissions on a construction site.

During the three phases mentioned above, frequently exposed soils generally result in unacceptable rates of erosion (Benik et al., 2003). Soil erosion is a re-occuring problem with construction sites and the increase in the rate of erosion can cause the equivalent of decades of natural erosion to occur in a single year from construction activities (Wolman & Schick, 1967; Kaufman, 2000). As soil erosion is a significant contributor of non-point source pollution in many countries, it is important to consider ways that we can incorporate science-informed policy into construction activities in an effective manner (Faucette et al., 2006).

EROSION AND SEDIMENT CONTROL REGULATIONS

Because of the negative environmental impacts of construction over time, many regulations and legislations have been enacted to mitigate these impacts. The Constitution Act, established in 1867, gave the federal government total jurisdiction over the protection of Canada's coasts, inland water bodies, and fisheries under section 91, the Fisheries Act (Government of Canada, 2013). The main function of this Act, with respect to construction, is to protect fish and fish habitats from the negative impacts of construction activities (Toronto and Region Conservation, 2009). The Act also restricts the emission of deleterious substances, a substance that degrades water quality affecting fish and fish habitats, and requires the owner of that substance to report it to officials (Toronto and Region Conservation, 2009). When a contractor wishes to perform construction activities that may violate the Fisheries Act in Ontario, the Department of Fisheries and Oceans Canada (DFO) must be contacted. Inspections can be performed by Fishery Officers and other DFO officials to ensure compliance with the Fisheries Act is warranted (Toronto and Region Conservation, 2009). The Canadian Environmental Assessment Act (CEAA), first passed in 1992, also pertains to construction activities as it requires that potential environmental threats are identified and mitigated appropriately (Government of Canada, 2016). The Act permits the Canadian Environmental Agency to review the evaluation of projects from other agencies to decide if the project can proceed as is, proceed with additional conditions to mitigate environmental impacts further, or cease work on the project altogether (Toronto and Region Conservation, 2009). It is essential, then, that contractors planning on conducting any work that may damage fish habitats seek guidance or approval from the appropriate agencies about the nature of their work, and its potential impacts as not to violate these Acts (Fisheries and Oceans Canada, 2019).

Provincially, the Ministry of the Environment, Conservation and Parks (MOECP) and the Ministry of Natural Resources (MNR) are the regulatory bodies for different acts and legislation that may pertain to construction activities. The Lakes and Rivers Improvement Act, established in 1990 and regulated by the MNR, was created to help manage and protect the water and land under lakes and rivers in Ontario (Government of Ontario, 2017). The Ontario Water Resources Act, established in 1990 and regulated by the MOECP, aims to protect and manage ground and surface water quality. Similar to the Fisheries Act, the Ontario Water Resources Act prohibits the release of substances that may degrade surface or groundwater (Toronto and Region Conservation, 2009).

Municipal regulations are mandated by two groups: Conservation Authorities and respective municipal workers. Conservation Authorities in the Greater Golden Horseshoe Area, where Lake Simcoe can be found, have signed into a memorandum of understanding (MOU) with their respective municipalities to allow their staff to review site plans and Erosion and Sediment Control plans (ESCs) while providing municipalities the oppurtunity to officially approve ESCs. The Planning Act, mandated by municipalities, passes "Sediment and Erosion Control" bylaws, which regulate activities that affect soil profiles or other natural ground conditions (Toronto and Region Conservation, 2009).

RESIDENT EXPOSURE AND ENVIRONMENTAL COMPLIANCE

Particulate Matter (PM) air-quality standards in Ontario are only based on a 24-hour averaging time. The Ambient Air Quality Criteria (AAQC) for PM_{2.5} and PM₁₀ are 30 and 50 μ g m⁻³, respectively (MOECP, 2012). The value for PM_{2.5} is the Canada-Wide Standard (CWS). It was developed in collaboration with other provinces and the Federal government as a long-term blanket goal to reduce exposure to Canadian residents and the environment. To try and achieve this CWS, single sources should not release more than 25 μ g m⁻³ (24 hr) to try and reduce ambient concentrations. There is less information on the AAQC for PM₁₀, other than that "This value of 50 μ g m⁻³ (24 hr) is an interim AAQC and is provided here as a guide for decision making (with no conversion to other averaging times)" (MOECP, 2012).

In the United States of America, the United States Environmental Protection Agency (USEPA) first developed general air quality standards for PM in 1971, but were thoroughly revised in 1987 to change the indicator to PM₁₀, which are particles equal to or smaller than 10 microns;

these particles were considered "inhalable particles" (USEPA, 2019). After various amendments in 1997, 2006, 2009, and 2012, the USEPA finalized their Ambient Air Quality Standards to an annual standard of 12 μ g m⁻³ for PM_{2.5} and a 24-hour standard of 35 μ g m⁻³ and 150 μ g m⁻³ for PM_{2.5} and PM₁₀, respectively. There is no annual PM₁₀ standard as the USEPA deemed there was "a lack of evidence establishing a link between long-term exposure to coarse particles and health problems" (USEPA, 2019).

CHAPTER 2 – OBJECTIVES

The primary purpose of this research, and the case study on Lake Simcoe, is to develop a simple design tool that can be used by contractors to calculate an estimate of potential dust emissions from construction sites. Then, using this tool, a probabilistic model, and a transport model, generate a prediction of how much dust will be deposited into Lake Simcoe annually from these construction sites and identify where investments can be made to more effectively manage dust emissions, as well as identifying key factors to reduce emissions for nearby residents. Four primary objectives are identified below with several associated goals. These objectives are summarized below:

1) Conduct a critical literature review on proposed tools for completing the research project, tools used to quantify the performance of common best management practices, and published research projects which have explored parts of the proposed itinerary. This includes:

A) Critiquing published research works that pertain to the negative impacts of dust emissions, phosphorus loading in water bodies, and others.

B) Discussing published tools and methodologies that are currently being used to quantify dust emissions from construction sites and evaluate the performance of best management practices.

C) Identifying probabilistic models, optimization models, spatial computer programs which can be used to complete the Lake Simcoe focused case-study portion of this project.

2) Develop a simple tool that can be used by anyone that wishes to estimate dust emissions from any construction site found in the Greater Golden Horseshoe area. This includes:

A) Characterizing construction so that all construction projects around Lake Simcoe can fall into representative categories to be modelled. This includes identifying standard best management practices used in the area and modelling them appropriately.

B) Identify tools that can be used to create the model based on construction processes and best management practices, then developing the new simple tool for estimating dust emissions from construction sites by integrating results into a pre-existing model.

3) Generate an estimate of projected deposition of dust from construction sites onto Lake Simcoe using a pre-existing transport model.

A) Develop a spatially accurate probabilistic model for projected urban development rates in the area of interest.

B) Use the simple estimation tool, in conjunction with the transport model and probabilistic model, to generate an estimate for the annual deposition of dust from construction sites onto Lake Simcoe.

4) Determine where future investments are most valuable for managing dust emissions from construction sites using best management practices.

A) Accumulate costs associated with each best management practice

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B) Using an optimization tool, the Lake Simcoe case study, and the costs of each best management practice, determine where making investments in best management practice technology is most effective for contractors and regulatory authorities.

CHAPTER 3 – CRITICAL REVIEW AND DISCUSSION OF PUBLISHED RESEARCH WORKS THAT PERTAIN TO IMPACTS OF DUST EMISSIONS AND PHOSPHORUS LOADING

As mentioned in the introduction, construction activities are a major concern when it comes to sediment deposition into water bodies because of their negative impacts on water quality and aquatic life habitats. Significant damage is brought upon the environment from neglected water and wind erosion due to construction activities as the effluent sediment pollutes water bodies and alters the natural state of streams, rivers, lakes, and others (Clyde, et al., 1978). Dust emissions not only negatively impact surrounding water bodies, but they also generate health concerns to humans, safety issues, and generate excessive on- and off-site costs (Hagen & Skidmore, 1977; Huszar, 1989;)

WATER BODIES AND LAKE SIMCOE

As the main concern with respect to this research is the well-being of Lake Simcoe's ecology, water quality, and residents, it is important to provide background on what sorts of research have been conducted with respect to dust emissions, phosphorus loading in Lake Simcoe, and water bodies in general. As environmental protection continues to gloom over society and more strict environmental laws are being implemented, effectively communicating the extensive research that has been put into understanding water quality degradation is important for lay-persons and specialists alike.

Many research articles suggest that a decrease in water quality can be directly attributed to excessive phosphorus loading. This can result in excessive algae growth, which, at the end of the Summer, depletes dissolved oxygen to levels that are fatal to fish, as seen in Lake Simcoe (Evans, 2007; Ramkellawan et al., 2009). The decrease in dissolved oxygen can be attributed to a process called eutrophication where, after the phosphorus has been used for excessive algae growth, bacteria and other organisms consume the dead algae and use up the dissolved oxygen, eventually suffocating aquatic life (Minnesota Pollution Control Agency, 2007).

Specifically, lake trout have been observed to be impacted by effects of hypoxia, the deficiency of oxygen to muscle tissue, influencing their ability to perform daily activities which are critical to their survival. A study showed that there was a direct correlation between the concentration of dissolved oxygen in the water and the ability of fish to perform life-sustaining activities and that a concentration $> 7 \text{ mg L}^{-1}$ is recommended for the protection of lake trout (Evans, 2007).

Evans et al. also published a research article, in 1996, aiming to establish relationships between phosphorus loading due to human land-use activities, hypolimnetic dissolved oxygen depletion, and loss of fish habitats in Lake Simcoe. As the population in Lake Simcoe's watershed increased from 50 000 residents in 1960 to over 250 000 residents in 1990, an increase in point source loading of phosphorus increased 10-fold over that period of time. It was also noted that, during the late Summers of 1975 to 1993, 10-50% of the cold-water habitat volume in Lake Simcoe dropped below 3 mg L⁻¹, the lethal threshold for lake trout (Evans et al., 1996).

Atmospheric deposition of dust into water bodies can occur from two main mechanisms: gravity and precipitation. Murphy and Doskey (1976) prepared and analyzed precipitation samples from six locations surrounding Lake Michigan to determine the concentrations of phosphorus, in different forms, found in the precipitation. It was concluded that roughly 1.0×10^6 kg, or 18%, of the present phosphorus in Lake Michigan was deposited into the lake, per year, from precipitation. It was also noted that dissolved reactive phosphates made up greater than 40% of the total phosphorus found in the precipitation and that roughly 60% of the annual deposition of phosphorus from precipitation becomes available to organisms in the lake (Murphy & Doskey, 1976).

HEALTH AND VISIBILITY CONCERNS

The USEPA regulates dust, and specifically PM_{10} , at 150 µg m⁻³ of 24-hour average concentration, as per the National Ambient Air Quality Standards "to protect and enhance the quality of the Nation's air resources to promote the public health and welfare and the productive capacity of its population" (USEPA, 2019). As expected, many research projects have been conducted to try and connect health and safety to air-suspended dust particles.

In 1987, Dockery et al. presented results from the Six Cities Study of Air Pollution and Health, showcasing the association of chronic respiratory health of children and a variety of commonly found urban air pollutants including total suspended particles (TSP), PM₁₀, PM_{2.5}, fine fraction aerosol sulphate (FSO₄), SO₂, O₃, and NO₂. The results indicated that there was a strong correlation between chronic cough, bronchitis, and chest illness in children during the 1980-1981 school year and particulate pollution concentrations of TSP, PM₁₅, PM₅, and FSO₄ during that time (Dockery et al., 1989).

Kanatani et al. conducted a study from February to April 2005 to 2009, relating airborne desert dust particle concentration to increased incidences of asthma in children. These children, ages 1 to 15 years, had their visits recorded from eight hospitals in Toyama, Japan, which borders the Japanese sea. Measurements were conducted using a Light Detection And Ranging (LIDAR) instrument to distinguish mineral dust particles from others and showed a significant association

between asthma hospitalization and particle concentration, especially during a heavy dust storm (Kanatani, et al., 2010).

Particles in Our Air, a book written by Spengler and Wilson at Harvard University, suggests that airborne dust not only degrades human health and air quality in general, but is also felt by other animals and vegetation. A study from Pope et al., published in 1991, found that PM_{10} concentrations higher than 150 µg m⁻³ were connected to a 3-6% decrease in overall lung function as well as increased use of asthma medications and higher rates of emerging respiratory disease symptoms. Ultrafine particles, particles with diameters less than 0.1 µm, can also initiate alveolar inflammation and concentrations in ambient air are heavily influenced by soil disturbances (Penttinen et al., 2001).

Hagen and Skidmore (1977) were interested in quantifying the reduction in visibility given suspended dust particles in the air. They found that wind erosion events generally created hazards for vehicles, especially near highways and airports, because of the abundance of particles that are suspended in the air during the events. Though the concentration and size distribution of the particles are a function of the severity of visibility reduction, in typical conditions, they found that visibility is reduced even further (50-75%) when there is overcast and even more so when facing the sun (Hagen & Skidmore, 1977).

ON- AND OFF-SITE COSTS

Erosion from construction activities, and lack of erosion control, contribute to extra costs for contractors and conservation authorities. When best management practices for erosion and sediment control are not appropriately employed, or better yet, at all, extra construction costs, including delays, can often be a consequence of preventable or better-managed erosion (Clyde et al., 1978). Other reasons for dust emission and erosion control include lowered maintenance and housekeeping costs on-site (Herron, 2011).

Dust emissions due to wind erosion also contribute to high off-site costs. As mentioned previously, airborne dust particles have been shown to pose negative impacts on respiratory health in humans and animals, which would increase healthcare costs. Like on-site, dust emissions increase the amount of cleaning and maintenance that must be done while reducing production opportunities (Huszar, 1989).

CHAPTER 4 – REVIEW OF TOOLS USED TO MODEL DUST EMISSIONS, DUST EMISSIONS FROM CONSTRUCTION SITES, AND BEST MANAGEMENT PRACTICES

Since dust emissions have been proven to have negative impacts on the environment, it is essential to be able to effectively model these emissions so that a relative contribution can be understood. Quantifying the contribution of activities can help policymakers make more wellinformed decisions when redefining legislation to improve upon the conservation of natural resources.

DUST EMISSION MODELS AND RELATED WORKS

Wind erosion modelling can be stemmed from the Wind Erosion Equation (WEQ) developed by the United States Department of Agriculture (USDA) and first reported by Woodruff and Siddoway (1965). This equation relates several independent variables to the total suspended particulate (TSP) fraction, E, in ton ac⁻¹ yr⁻¹ from an agricultural field as follows:

$$E = f(I', K', C', L', V)$$

Where:

I'= soil erodibility index K'= soil ridge roughness factor C'= climate factor L'= field length V= vegetative cover The WEQ has had various improvement recommendations by Woodruff and Armbrust (1968), Bondy et al. (1980), Fryrear et al. (1998), and many others.

The Wind Erosion Prediction System (WEPS) was developed as a process-based model to understand wind erosion susceptibility on a daily-time step basis by incorportating management effects from common machinery usage and other soil disturbance effects on agricultural sites (Tatarko et al., 2016). Previous works using WEPS to assess wind erosion on agricultural sites include L.J. Hagen, 1991, Skidmore & Van Donk, 2003, Coen et al., 2004, Weiss et al., 2013, and Chen et al., 2013. In addition, various WEPS validation works are offered by Funk et al., 2004, Feng & Sharratt, 2007, and Buschiazzo & Zobeck, 2008. Jarrah et al., 2020, completed an extensive review of critical wind erosion models, including WEPS.

TRANSPORT AND DEPOSITION MODELS

Transport and deposition of dust is another critical aspect concerning construction site dust emissions. CALMET uses meteorological information, digitized terrain maps, and land use data to develop 3D windfields in a specified modeling domain. Then, using CALMET windfield modeling results as input, CALPUFF, a Lagrangian Gaussian long-range transport model, can be used to determine wet and dry deposition (Weiss et al., 2014). Chapter 15 of the book "*Air Dispersion Modeling: Foundations and Applications*", written by De Visscher, provides a detailed description of CALPUFF and CALMET.

Weiss et al., 2014, used this methodology to develop Location Reduction Factors (LRFs): conversion factors that take point source dust emission estimations from different regions around Lake Simcoe and convert them into deposition estimates. Chong-Bum et al., 2009, conducted an evaluation of the CALPUFF model using measured data. Oleniacz & Rzeszutek, 2014, generated spatial databases for Poland using CALMET and CALPUFF.

AERMOD and AERMET are used in conjunction to develop atmospheric dispersion models. AERMET is used to determine the critical calculation of surface heat, stability, friction velocity, and Obukov length to be used as input into AERMOD, a Gaussian plume model, as per De Visscher's detailed description in Chapter 14 of "*Air Dispersion Modeling: Foundations and Applications*."

Sang-Jin, 2011, estimates odour emissions from industrial sources and their transport to surrounding residents using AERMOD. Chea-Hyun et al., 2015, models dispersion of a hazardous chemical accident using AERMOD, while Boadh et al., 2015, determined the dispersion of NO_x over Visakhapatnam, India using the Weather Research and Forecasting (WRF) model and AERMOD.

CONSTRUCTION SITE DUST EMISSIONS MODELS AND RELATED WORKS

CONSTRUCTION SITE DUST EMISSIONS MODELS AND WORKS

Various studies have focused on estimating or measuring dust emissions from construction sites. Weiss et al., 2014, used the USEPA AP-42 Guide for PM_{10} to developed a rough estimate of PM_{10} emissions around Lake Simcoe from construction. As these estimates were low resolution, this research was designed to gain further insight into construction site emissions.

Muleski et al., 2005, developed a series of emission factors from on-site testing on construction site activities from 1998-2001; their focus was on earthmoving operations given its

high-intensity nature concerning dust emissions. They found that emissions were up to an order of magnitude higher than estimates found in studies predicted by AP-42 emission factors.

Im et al., 2018, developed a methodology for estimating dust emissions from construction sites using digital image information. Using a Digital Single-Lens Reflex (DSLR) camera, dust from a dust generator is measured at specific illuminance values and related to the images to derive a correlation.

Ku & Park, 2013, used an inverse analysis of satellite and ground PM_{10} emission measurements to estimate large scale dust emissions from deserts in East Asia. There was a contrast in results when comparing the Gobi Desert and the Taklamakan Desert. Limitations and suggestions for improvement of their methodology are provided and discussed.

Payus et al., 2017, collected various particulate sizes during two early phases of construction of a five-story building in Kota Kinabalu, Malaysia. It was found that meteorological factors, including temperature, relative humidity, and wind speed were influential on the distribution of particle size and the rate of PM emission.

The work by Liu et al., 2017, has similarities to the proposed research. It used WEPS and AP-42 to evaluate wind-blown dust emissions from construction of a railway project focusing on the beginning, active, and ending phases of construction. It was deemed that various construction BMPs can be modelled after agricultural BMPs found in WEPS. It also noted that soils of sandy nature are most susceptible to erosion.

BEST MANAGEMENT PRACTICES

A review of the effectiveness of standard best management practices that have been tested in the laboratory or in-situ follows. Many of the in-situ best management practice tests were conducted for an agricultural application; however, based on the similarities in best management practices used, bare soil exposure, and soil disturbances patterns, it was deemed appropriate to assume that standard best management practices in agricultural settings will perform similarily in construction sites.

EROSION BLANKETS AND MULCHING

Sutherland (1998) performed a critical review on rolled erosion control systems and found that tacked straw performed at a mean of 40.6% reduction with a maximum and minimum of 72% and 14.4%, respectively, while mulch blankets performed at a mean of 69% with a maximum and minimum of 84.8% and 52.4%, respectively. Laboratory experiments were also conducted which found that straw-mulch covers emitted 2-27% of the sediment obtained from bare soil conditions (Jennings & Jarrett, 1985). When testing the role of geotextile blankets on soil erosion, Rickson (1990) found that erosion was reduced to 10%.

Chang et al. (2007) performed wind tunnel work with woven straw erosion blankets on bare soils to generate a simple model that can estimate the efficiency based on percent coverage, silt content, wind velocity, moisture content, exposure time, and soil surface roughness. They determined that maximum reduction from a woven straw erosion blanket is 42%. Su et al. (2008) investigated the reduction efficiency of woven straw erosion blankets on construction sites and found that PM₁₀ emission can be reduced by 40%.

WATERING

Watering is a common best management practice for reducing dust emissions in construction and roads. Countess Environmental developed the *WRAP Fugitive Dust Handbook* for the Western Regional Air Partnership (WRAP) in 2006 and summarized that watering unpaved roads in construction settings can reduce PM₁₀ emissions by 10-74%, while watering bare soils before high wind events reduce PM₁₀ emission by 90%. Watering has also been found to reduce dust emissions from construction sites by 75-95% (XCG Consultants, 2013).

Watering techniques have also been used in reducing dust emissions from cement cutting processes. A wet scrubbing cleaner was found to reduce particulate emissions during cement and expanded clay cutting by 30% (Koshkarev et al., 2016). Fitz & Bumiller (2000) found that dust emissions can be decreased by 90% using water applications to increase moisture content in the soil.

Other literature that has explored the effectiveness of dust suppressants in constructiontype activities includes: investigating the efficacy of different dust suppressing agents when cutting different kinds of concrete (Boudreaux et al., 1997), creating a dump truck-mounted spray system which can reduce water consumption by 30% while achieving the same amount of dust emission suppression (Gambatese & James, 2001), and testing three different dust suppressants on radioactive waste site for dust emission reduction (Ligotke et al., 1993).

SILT FENCES

Various studies have been conducted on the effectiveness of silt fences and other windbreak efforts at reducing shear velocities downwind and, therefore, decreasing soil erodability. Billman & Arya (1985) conducted a wind tunnel study on wind erosion from different shaped soil piles and how different fence porosities, heights, and distances from the piles reduce dust emissions downwind. At 50% porosity and a distance from the pile equal to the height of the fence, there was a 53% reduction in dust emissions compared to the bare pile. Additionally, with 10 trials varying pile heights and distances from the fence to the pile, a mean of 52.2% in dust emission reduction was measured (Billman & Arya, 1985).

Golder Associates released a *Literature Review of Current Fugitive Dust Control Practices within the Mining Industry* in 2010. They noted that artificial wind barriers could reduce fugitive dust emissions by 4%-88% in general, but they may reduce dust emissions from a storage pile by 75% (Golder Associates, 2010).

In-situ dust emission monitoring was performed to access dust emissions from coal stockpiles and the ability for wind fences to reduce fugitive dust emissions due to high winds. It was concluded that practically, the reduction of dust emissions from wind fences is 40+/-10%, but when optimally placed, could reduce dust emissions up to 75+/-10%, though this is difficult due to impossibilities such as restriction due to vehicular access (King, 1997). Cowherd & Kinsey (1986) found that wind fences with a 50% porosity can reduce total suspended particulates by 64% on average.

Windbreak technology is very common in agricultural settings, so various studies have been performed to access the effectiveness of these windbreaks at reducing dust emissions from agricultural fields, which can be closely related to construction sites due to their bare soil nature. Brandle et al., (2004) tested wind speed reductions from a single row conifer, with porosities of 40-60%, similar to the porosity of a standard silt fence in the GGHA (Toronto and Region Conservation, 2009). Their work concluded that wind speed reductions at five times and 30 times the windbreak height were 70% and 5%, respectively, with an average of 34% reduction over the whole distance.

Computer simulations have also been conducted to assess the effectiveness of trees as windbreaks. After determining the drag coefficient of a Black Pine tree, computational fluid dynamics (CFD) simulations were run and concluded that wind speeds were reduced by 50% at 15 times the tree height (Bitog, et al., 2012). He et al., (2017) developed and validated a simple windbreak model for reducing wind speeds to help mitigate windchill from sheep. They concluded that to achieve a maximum wind speed reduction of 27%, a porosity of 0.5 is ideal, which reinforces the decision by the Toronto Regional Conservation Authroity (TRCA) to have silt fences with a porosity of 0.5.

MULTI BARRIER APPROACH

While investigating visibility issues due to suspended dust particles, Hagen & Skidmore (1977) concluded that though reducing dust emissions at the source or diffusing/trapping particles may reduce particle concentrations in air, a combination would be most appropriate during high wind erosion events or where soils are most susceptible (Hagen & Skidmore, 1977).

Lemly (1982) also noted during his research on stabilization treatments at urban and highway construction sites on red clay soils that a multi-barrier would significantly improve erosion control, yet economical and construction policy seems to deter contractors from taking this initiative.

DUST EMISSIONS AND DUST SUPPRESSANTS ON UNPAVED ROADS

Construction projects are riddled with unpaved roads during the early stages of construction. These unpaved roads act as a source of fugitive dust emission and disturbed dust emission from vehicles travelling over the roads. In section 13.2.2 of the AP-42: Compilation of Air Emissions Factors, developed by the United States Environmental Protection Agency (USEPA), a simple empirical equation is described for estimating dust emissions from unpaved roads on industrial construction sites from vehicle disturbances:

$$E = k \left(\frac{s}{12}\right)^a \left(\frac{W}{3}\right)^b E_p$$

Where:

 $E = \text{size-specific emission factor [kg VMT^{-1}]}$ s = surface material silt content [%] W = mean vehicle weight [tons] $k, a, b = 0.7, 0.9, 0.45 \text{ (respectively; for PM_{10})}$ $E_p = (N-P) N^{-1}$ $N = \# \text{ days month}^{-1}$

P = # days with precipitation >0.25 mm month⁻¹

Kinsey et al., 2005, conducted a variety of in-situ field tests and determined an emission of 3.1 kg PM_{10} VKT⁻¹ (given similar conditions as those estimates from the AP-42 equations mentioned above) while noting that equations used in section 13.2.2 of the AP-42 underpredict their own findings by a factor of three (Muleski & Cowherd, 1999).

Other works that have explored dust emissions from vehicle travel and its respective BMP suppression performance include Goossens et al., 2012, who conducted wind erosion

measurements with off-road vehicles, Edvardsson et al., 2012, looking at dust suppressant performance on gravel roads in Sweden, Amato et al., 2010, a review on dust emission reduction strategies from urban PM emissions, Edvardsson & Magnusson, 2009, developed a methodology for monitoring dust emissions from gravel roads, Vernath et al., 2003, conducted fieldwork and analytic models for fugitive dust transport from vehicles, and Etyemezian et al., 2003, who determined influencing factors for vehicle-based road emissions in Treasure Valley, ID.

SCARIFICATION

Scarification is another common best management practice that can be used on construction sites. This process is a tillage operation that increases the random roughness of a soil structure using tracks of large machinery. In the book *Environmental Benefits: Status and Knowledge* (Baker et al., 2006), the authors concluded that this could achieve a 25 percent reduction in the rate of wind erosion. Appendix C of Alberta's Ministry of Transportation's Design Guidelines for Erosion and Sediment Control advise operators to use this method on exposed slopes, large flat surfaces, and stockpile areas to achieve 30-50% reduction in emissions.

DISCONNECT BETWEEN ENVIRONMENTAL PROTECTION, ECONOMICS AND POLICY

After conducting the literature review, it was noted that many of the researchers expressed a disconnect between expected environmental protection requirements, available economics, and policies regarding wind sediment and erosion control. During the telecommuncations interviews,
many contractors and city workers expressed the lack of consideration or requirement to include wind erosion and atmospheric dust emission BMPs in erosion and sediment control plants on-site. Lemly (1982) concluded that though best management practices can significantly decrease dust erosion, economic and construction policies make it difficult for contractors to take the initiative. The Utah Water Research Laboratory, out of Utah State University, published the "Manual of erosion control principles and practices" in 1978 and included that even though the implementation of best management practices for erosion control has improved significantly, it is still a significant problem. The lack of readily available knowledge to improve erosion control and resistance to implementing these improvements because of lack of familiarity are likely reasons why it has been challenging to continue to improve the solution to the problem (Clyde et al., 1978).

CHAPTER 5 – METHODOLOGY USING THE CONSTRUCTION INDUED DUST EMISSIONS MANAGEMENT (CIDEM) MODEL

Using the Wind Erosion Prediction System (WEPS, Tatarko et al., 2016), bare soil emissions, BMP performance, and construction activity effects were modelled to estimate PM₁₀ emissions of various soil types during the typical construction project timeline. Previous works using WEPS to assess wind erosion on agricultural sites include L.J. Hagen, 1991, Skidmore and van Donk, 2003, Coen et al., 2004, Weiss et al., 2013, and Chen et al., 2013. In addition, various WEPS validation works are offered by Funk et al., 2004, Feng and Sharratt, 2007, and Buschiazzo and Zobeck, 2008. Jarrah et al., 2020, completed an extensive review of critical wind erosion models, including WEPS.

Figure 3 provides a conceptual flow diagram for the CIDEM model used to evaluate construction sites for dust emissions.



Figure 3: Conceptual flow diagram for the CIDEM model

Using a table of agricultural land use developed by Weiss et al., 2013, with a similar methodology using WEPS, pre-development emissions were estimated to compare to middevelopment emissions and BMP performance. Combined, these features create the basis for the new Construction Induced Dust Emissions Model (CIDEM), a regional probabilistic dust emissions management model to estimate PM₁₀ emissions from construction sites and to optimize BMPs. CIDEM is also capable of estimating regional dust emissions for larger-scale applications while including probabilistic construction data to better estimate trends in construction site effects on regional PM₁₀ emissions.

THE WIND EROSION PREDICTION SYSTEM (WEPS)

WEPS, a process-based model using daily time-steps, estimates soil loss from agricultural sites using a combination of weather, hydrology, management, crop, residue decomposition, soil, and erosion sub-models (Tatarko et al., 2016). This field-scale prediction model was used in this study, similar to Hagen (2004) and Weiss (2012), assuming a 1 ha field with non-erodible boundaries to predict bare emissions from the 11 soil types that comprise the topsoil layer surrounding Lake Simcoe. By modifying the management files to represent typical timelines, processes, best management practices used in construction, and using the pre-development conditions, the change in PM_{10} emission from pre-development to mid-development can be predicted.

BARE EMISSIONS AND MANAGEMENT IN WEPS

Modelling scenarios for mid-development emissions were developed using WEPS. Using wind and weather files acquired from Weiss et al., 2013 that represent weather conditions surrounding Lake Simcoe (Rochester weather files found in WEPS were used and validated for Lake Simcoe; standard meteorological parameters were compared by Weiss et al., 2013, as per Figures A.1, A.2, and A.3, found in the Appendix), bare emission estimates were generated for each 11 soil types found in the region. A Lake Simcoe soil map was provided by the Lake Simcoe Conservation Authority as Figure A.4 in the Appendix. Similar calculations were generated for

managed land, or construction induced land, with management files generated and integrated by the National Resource Conservation Services (NRCS) that represent each construction activity or BMP being modelled. Bare emissions were then split into three classes based on soil composition and erosion susceptibility: *Highly susceptible (High)*, Sand, Loamy Sand, Sandy Loam, Fine Sandy Loam; *Moderately susceptible (Medium)*, Silt, Organic Soil, Silt Loam; *Less susceptible (Low)*, Clay Loam, Silty Clay Loam, Loam, Clay.

THE CONSTRUCTION PROCESS IN ONTARIO

Interviews were conducted with construction and city workers in the Lake Simcoe region to develop the following information about construction in the surrounding area and can be found in Appendix A. These telephone interviews with 10 contractors, city workers, or construction company representatives categorize construction activities and achieve a better understanding of the relationship between PM₁₀ emissions and construction activities in Ontario. A generalization and breakdown of the construction schedule with the activities that are most susceptible to PM₁₀ emissions are described below. The first three processes of construction, grubbing (removal of trees and other debris), levelling, and servicing, were deemed the most susceptible to dust emissions due to the soil's constant exposure to the wind, removal of pre-existing vegetation, and disturbances to the soil during these processes. One process must be completed before the next can begin.

When construction sites become larger (greater than 1 ha), contractors may be required to phase their sites to reduce the instantaneous workload, requiring fewer vehicles and reducing equipment and personnel costs (Gharabaghi et al., 2006). The area of the construction phases is unique from site to site.

Building Reports and Statistics from Barrie from January 2014 to December 2017 are summarized in Figure 8, influencing the way the construction activity breakdown was developed as dust emissions are strongly related to weather patterns. Using the average of the surface area of contracts for each month found in the Barrie Building Reports and Statistics, it is understood from Figure 8 that construction in the Lake Simcoe area occurs primarily in two seasons: Spring (April, May, June) and Fall (August, September, October).

A PROBABILISTIC APPROACH TO A DUST EMISSIONS MODEL FOR CONSTRUCTION SITES

As the exact location, size, and timing of future construction activities within a region can be difficult to predict, a probabilistic approach is incorporated into the regional scale in this methodology. This includes incorporating the spatial and temporal variation of construction within the region to the model estimation results. As future construction sites have not been developed, data pertaining to previous construction site can be used to achieve a more educated prediction of future annual construction activity distribution as the impact of PM_{10} emissions is seasonally variable within the region.

THE CONSTRUCTION INDUCED DUST EMISSIONS MANAGEMENT (CIDEM) MODEL

Contractors need to minimize the environmental impact of PM_{10} emissions from active construction sites (mid-development phases) by incorporating best management practices (BMPs) to try and reduce dust emissions down to the pre-development emission levels. All equations found in this study, other than the unpaved road emissions, were generated in the development of the CIDEM as part of this study. The general form of the CIDEM model is then:

 $\Delta PM10 \ Emissions \ From \ Construction \ Activites \ (PM10)[PM10 \ kg \ ha^{-1} \ month^{-1}]$ $= Mid \ Development \ Emissions \ (MDE) \ [PM10 \ kg \ ha^{-1} \ month^{-1}]$ $- Pre \ Development \ Emissions \ (PDE) \ [PM10 \ kg \ ha^{-1} \ month^{-1}]$ (1)

MID DEVELOPMENT EMISSIONS (MDE)

To determine the impact of construction activities on bare soil emissions, model runs with modified management files were run for each phase of construction for each soil class and compared to bare soil emissions to create conversion factors.

MDE = Bare Emissions × (Mid Development Factor (MDF) + Untreated Emissions Factor(UEF)) + Unpaved Roads
(2)

Depending on the division of sections within each phase, a fraction of the phase surface area may have different activities or BMPs in each section.

MDF = Construction Factor (CF)(3) × Best Management Practice Factor (BMPF)

THE CONSTRUCTION FACTOR (CF)

The construction factors, shown in Table 1, were generated by dividing the soil emission from each activity by its respective bare soil emission and are conversion factors (unitless). WEPS provides pre-made operations, developed by the NRCS, which model the effect of using different heavy excavation machinery on site, ultimately increasing PM₁₀ emissions compared to bare soils. The following three activities were modelled to generate their construction factor value with their respective operations in WEPS: Grubbing (Bulldozer, clearing-cutting), Leveling (Bulldozer, filling-leveling), and Servicing (Bulldozer, clearing-cutting light).

	Grubbing	Leveling	Servicing
Operation	C-C	F-L	F-L Light
Class: High	2.31	3.02	2.45
Class: Med	2.19	2.63	1.85
Class: Low	2.02	2.40	1.82
Average	2.17	2.68	2.04

 Table 1: The construction factors

BEST MANAGEMENT PRACTICE FACTOR (BMPF)

Different construction activities call for different BMPs to effectively reduce PM₁₀ emission susceptibility on site. The most common BMPs used around the Lake Simcoe Region for exposed soils include silt fences, erosion blanket application or mulching, watering, road dust suppressants, and revegetation. These processes were modelled in WEPS and used to generate Watering Reduction Factors (WRF), Blanket Mulch Reduction Factors (BMRF), and Revegetation Reduction Factors (RRF), with the same methodology as the CFs.

The "E" prefix (effective) is a modified reduction factor that includes the area of treated soil in a phase. Silt fences were neglected for the CIDEM and discussed in section "*Silt fence*

performance." When the best management practice is not being used, the value of the respective reduction factor is set to 1.

$$BMPF = EWRF \times EBMRF \times ERRF \tag{4}$$

WATERING REDUCTION FACTOR (WRF)

The WRF was modelled in WEPS using a suspended wheel-line irrigation operation to best represent how a watering truck is used as a BMP on construction sites. Note that as WEPS was developed by the USEPA, inputs are in imperial units, though the CIDEM converts these as it was developed in SI-units. It was then determined that the two most influencing factors affecting the performance of watering on PM_{10} emissions were the depth of water being applied and the frequency of application. Using 2.5 mm, 6.4 mm, and 10 mm of water applied, and every day, every other day, and every third day for the frequency of application, a mathematical representation of the relationship between these nine scenarios was generated for the two main seasons of construction.

$$WRF_{Spring} = 1 - (0.1433 * (f^2) - 0.1378 * f + 0.1649)$$

$$* EXP((0.9417 * LN(f) + 4.0969) * 0.04 * D)$$
(5)

$$WRF_{Fall} = 1 - (0.0406 * (f^2) + 0.0675 * f + 0.0745)$$

$$* EXP((0.9417 * LN(f) + 4.0969) * 0.04 * D)$$
(6)

Where:

f = frequency of application $[d^{-1}]$ (everyday = 1; every other day = 0.5, every third day = 0.33) D = Depth of water applied [mm]

These equations were developed by determining the equation of the line for each frequency of application at all three depths of water for the general function with respect to depth (exponential).

$$WRF = C_1 e^{C_2 D}$$

Then, by determining the constants as a function of frequency, an equation for reduction due to the two most influencing factors (frequency and depth of water applied for watering) was determined in excel using the "Solver" add-in. The sum of errors was the objective cell set to minimum, and the changing variable cells were made to be the constants. The "GRG Nonlinear" solving method was used. A similar methodology was used for the BMRF equations.

Watering is only used during the "Leveling", "Servicing", and "Completed" processes of construction.

The area of the site or phase being managed with watering is then incorporated to develop an "effective" reduction factor:

$$EWRF = WRF \times AT\%_{w} + (1 - AT\%_{w}) \tag{7}$$

Where:

 $AT\%_w = area of site or phase being treated by watering [%]$

The non-residential cost of water in Barrie is \$0.0016 mm⁻¹ m⁻². To determine how much the watering will cost, D, the depth of water applied, can be converted to a dollar value:

$$D = \frac{C_w}{P_w f} \tag{8}$$

Where:

 $C_w = Cost \text{ of water incurred by the contractor [$]}$ $P_w = Price \text{ of water [$ mm⁻¹ m⁻²]}$

BLANKET MULCH REDUCTION FACTOR (BMRF)

The BMRF was modeled in WEPS using an erosion blanket application operation to best represent the use of erosion blankets or mulches on bare soils. As WEPS does not include the performance of erosion blankets in their model, erosion blankets were modeled using crop residue. It was then determined that the two most influencing factors affecting the performance of erosion blankets or mulches are the weight of crop residue applied and the material used. Using 100, 250, and 500 kg ha⁻¹, and corn stock, straw, and wood chips as different materials, a mathematical representation of the relationship between these nine scenarios were generated for the two main seasons of construction:

$$BMRF_{spring} = 1 - (-624361 * CM^{2} + 463.38 * CM + 0.1046) * LN(1.12 * W)$$
(9)
+ 1388 * CM - 0.9518

$$BMRF_{Fall} = 1 - (-384793 * CM^2 + 308 * CM + 0.114) * LN(1.12 * W)$$
(10)
+ 972.9 * CM - 0.7152

Where:

CM = Cover-to-Mass Ratio (Wood chips = 2.03×10^{-4} ; Corn Stock = 3.79×10^{-4} ; Straw = 5.86×10^{-4}) [ha kg⁻¹] W = Weight per unit area [kg ha⁻¹]

Erosion blankets and mulches are only used after a particular phase area of the site is mostly idle of earthworks, so this is applied during the "Servicing" and "Completed" processes, as earthworks are minimal or finished.

The area of the site or phase being managed with blankets or mulches is then incorporated to develop an "effective" reduction factor:

$$EBMRF = BMRF \times AT\%_{BM} + (1 - AT\%_{BM})$$
(11)

Where:

 $AT\%_{BM}$ = area of site or phase being treated by watering [%]

To determine the cost of mulch, the weight can be converted to a dollar value:

$$W = \frac{C_{BM}}{P_{BM}} \tag{12}$$

Where:

 $C_{BM} = \text{Cost of Blanket Mulch incurred by the contractor [$ ha^{-1}]}$ $P_{BM} = \text{Price of Blanket Mulch [$ kg^{-1} ha^{-1}]}$ $(P_{BMCorn} = \$0.1 kg^{-1} ha^{-1};$ $P_{BMStraw} = \$0.1 kg^{-1} ha^{-1};$ $P_{BMWoodchips} = \$0.05 kg^{-1} ha^{-1})$

REVEGETATION REDUCTION FACTOR (RRF)

Revegetation is another important BMP used in construction practices. Revegetation was modelled in WEPS using a broadcast seeder operation with grass seed to determine how effective revegetation was at mitigating PM_{10} emissions over time. Model runs considered grown grass starting in the different months of the construction seasons, as well as the different soil type classes, to determine their efficacy at reducing PM_{10} emissions over time depending on when they began. Similar to erosion blankets and mulches, revegetation can only occur after a particular phase, where and when an area of the site is mostly idle of earthworks, so this is applied during the "Servicing" and "Completed" processes, as earthworks are minimal or finished. Hydroseeding, a mixture of mulch, water, binding agents, and grass seed, is a common best management practice used on construction sites and can be modelled as a combination of all blankets/mulching, watering, and revegetation.

The area of the site or phase being managed with revegetation is then incorporated to develop an "effective" reduction factor:

$$ERRF = RRF \times AT\%_R + (1 - AT\%_R)$$
(13)

Where:

 $AT\%_R$ = area of site or phase being treated by watering [%]

UNPAVED ROADS

Construction projects are riddled with unpaved roads during the early stages of construction. These unpaved roads act as a source of fugitive dust emission and disturbed dust emission from vehicles travelling over the roads. In section 13.2.2 of the AP-42: Compilation of Air Emissions Factors, developed by the United States Environmental Protection Agency (USEPA), a simple empirical equation is described for estimating dust emissions from unpaved roads per vehicle kilometre traveled (VKT) on industrial construction sites from vehicle disturbances:

$$E = k \left(\frac{s}{12}\right)^a \left(\frac{W}{3}\right)^b E_p \tag{14}$$

Where:

E = size-specific emission factor [kg VKT⁻¹] s = surface material silt content [%] W = mean vehicle weight [tons] k, a, b = 0.7, 0.9, 0.45 (respectively; empirical constants for PM₁₀) E_p = (N-P) N⁻¹ N = # days month⁻¹ P = # days with precipitation >0.25 mm month⁻¹

Using sized trucks that are representative of the equipment for each process, emissions are at 0.8 kg PM10 VKT⁻¹ and 0.5 kg PM10 VKT⁻¹ for unpaved roads from equations found under section 13.2.2 of the AP-42. Kinsey et al., 2005, conducted a variety of in-situ field tests and determined an emission of 3.1 kg PM10 VKT⁻¹ (given similar conditions as those estimates from the AP-42 equations mentioned above) while noting that equations used in section 13.2.2 of the AP-42 underpredict their own findings by a factor of three (Muleski & Cowherd, 1999). As such, unpaved road emissions (URE), are reported from Kinsey et al., 2005, as 3.1 kg PM10 VKT⁻¹.

 $Unpaved Roads = Unpaved Road Emission (URE) [kg VKT^{-1}] x$ (15)

Average Vehicle Distance Travelled [km travelled vehicle⁻¹ month⁻¹] x Number of Vehicles

The average vehicle distance travelled and # of vehicles can be modified by the user, but an average of 0.2 km ha⁻¹ of unpaved roads on construction sites was determined using Google Earth. A common BMP for reducing dust emissions from unpaved roads on construction sites is the application of a calcium chloride solution, which costs \$2800 km⁻¹ with a 60% suppression factor (Weiss et al., 2018).

PRE-DEVELOPMENT EMISSIONS

Understanding the relative difference between mid-development PM_{10} emissions and predevelopment PM_{10} emissions, while performing construction, is important for the conservation of the surrounding environment. First, the Lake Simcoe region was split up into 4 sub-regions based on soil type groupings and land use around the Lake, as seen in Figure 4. A table generated by Weiss et al. (2013) indicates the amount of PM_{10} that is released from each soil type and land use combination compared to bare emissions. Using an area-weighted average of soil type and predevelopment land-use factors found on GIS and the table developed by Weiss et al., 2013, as well as the bare emissions generated in WEPS, pre-development emissions were estimated.



Figure 4. Sub-regions for pre-development PM₁₀ emissions

CHAPTER 6 - CONSTRUCTION INDUCED DUST EMISSION MANAGEMENT (CIDEM) MODEL RESULTS

BARE EMISSIONS RESULTS

Results from bare soil PM₁₀ emission runs using WEPS were found to be similar to those found by Weiss et al. 2013, whose results were also consistent with a variety of wind tunnel studies (Weiss et al., 2013). Like Weiss et al., 2013, PM₁₀ emissions from sand and loamy sand were found to be significantly higher than all other soil types. Averaged over 8 years, major soil erosion events mainly occur between April and November, which are all concerning months for wind erosion due to lack of snow cover and frozen soils. This reinforces the importance of a proper soil erosion management plan for wind erosion and fugitive dust emissions on construction sites because, as seen in the Barrie Building Reports, construction activities generally occur between April and November. Similarly, soil classes are usually grouped by their soil composition and can be seen to have a similar magnitude as their other class members. Literature values for comparison to CIDEM estimates are found in Table 2.

Construction Factor	Max PM10 Concentration [µg m ⁻³]	Source
1.2	16.42	Yan et al. (2019)
1.18 - 2.2	25.5	Azarmi, F. et al. (2016)
1.68	162	Jutze, G. & Axetell, K. (1974)
1.27 - 2.13	287	Jutze, G. & Axetell, K. (1974)

Table 2: Construction and bare soil emission - literature values

BMP PERFORMANCE RESULTS

Mathematical representations of the relationship between the two main influencing factors of a BMP's performance (watering and erosion blankets/mulches) and the performance of the mentioned BMPs under the same values for influencing factors, using WEPS, were compared ($R^2 = 0.96$). The purpose of these mathematical representations was to offer the user of Evolver the flexibility of using values for BMP performance between the maximum and minimum used to generate their performances in WEPS.

WATERING PERFORMANCE

Using watering depths of 10 mm, 6 mm, and 3 mm, and using watering every day, every other day, and every third day, minimum and maximum reduction values of 16% and 79% were determined. Figure 5 demonstrates the change in performance when the two most influencing factors, the depth of water applied and the frequency at which that water is applied are used together in different combinations.



Figure 5: 3D plot of watering performance based on depth of water and frequency

For both frequency and depth, there is a steady increase in reduction with an increase in one variable while keeping the other constant. There is a significant increase in reduction when watering frequency is set to every day, and higher depths of watering (10 mm and 6 mm) are applied. When watering is applied less than once a day, there is a larger potential for major drying periods with strong winds, indicating that the soil dryness and wind power are important factors in watering performance. It is also important, then, for the on-site personnel responsible for the performance of BMPs to be vigilant of these factors and administer watering accordingly to reduce the cost of BMPs while reducing dust.

BLANKET/MULCH PERFORMANCE

Similar to watering, the two most influencing factors that affect the performance of blankets/mulches were used in different combinations to determine the minimum and maximum reduction values of 87% and 20%, for blankets/mulches. These combinations included selecting between potential materials (Corn, Straw, and Woodchips) and potential weights (500 kg ha⁻¹, 250 kg ha⁻¹, and 100 kg ha⁻¹). Figure 6 demonstrates the change in performance when these factors



Figure 6: 3D plot of blanket/mulch performance based on material and weight

Blanket performance, compared to watering performance, shows a similar trend of steady increase between variable. When the weight of crop residue is set to 100 kg ha⁻¹, straw outperforms wood chips and corn. As the weight per ha increases to 250 and 500 kg ha⁻¹, the difference between performance shrinks. This can be explained by the increase in surface area of the residue when a larger amount is applied: a larger percentage of the surface area will be covered with more residue, regardless of the material, so if sufficient and even spread of cover is achieved, material type is not as important as the percent of surface area covered by the blanket or residue. Straw outperforms corn and wood chips, reinforcing that straw erosion blankets are the most effective crop for blanket manufacturing (GGHA, 2006)

REVEGETATION PERFORMANCE

Revegetation performance provides insight into when revegetation should be considered on specific construction sites to optimize the cost and performance of BMPs. Vegetation reduces wind speeds by providing surface soils with coverage, both in thickness and in height, to ultimately minimize dust emissions. Reduction values increase as time persists because of the increase in crop cover area and height as the vegetation matures. Spring revegetation establishes earlier than their Fall counterparts, concurrent with the increased soil fertility and vegetation growth rates in the Spring. Similarly, the performance of revegetation is higher at the end of Spring compared to Fall as improved growth conditions allow for vegetation to grow thicker upon maturation. Lower soil classes perform better than higher classes as sandier soils, which are most susceptible to wind erosion, do not retain water as well as more silt- or clay-heavy soils (Sommers, 1984).

SILT FENCE PERFORMANCE

Silt fences are a common best management practice used on construction sites in Ontario as a perimeter safety fence for trespassers and stormwater management. Though silt fences do provide some shelter from wind erosion around the perimeter of the site, the reduction in the sheltered area is insignificant compared to the total surface area of most construction sites (especially large construction sites) unless optimally placed throughout the inside of a construction site, which would create undesirable vehicular mobility and construction activity issues (Billman & Arya, 1985; King, 1997).

WEPS management files were developed to investigate this hypothesis and, given the standard height of 0.6 m and porosity of 50% for silt fences (GGHA, 2006), 0.5, 2, and 5-ha sites

reduced PM_{10} emissions by 32%, 25%, and 16% on a mass-basis, respectively. However, the installation of additional silt fences for site-specific instances (e.g., stockpiles, highly erodible soil patches that cannot be worked on or covered) may be effective, as well as higher silt fences for larger area coverage.

UNPAVED ROADS RESULTS

Estimates used for PM_{10} emissions from unpaved roads were consistent with the published values in the literature and the standard government equations like those found in section 13.2.2 of the USEPA AP-42, as portrayed in Table 3.

Unpaved Roads Emission Literature

Average Value	Weight	Source	Comments
0.83 [kg-PM10 VKT ⁻¹]	76 t	Grubbing & Leveling Avg.	AP-42: Industrial Construction Unpaved Roads
0.5 [kg-PM10 VKT ⁻¹]	25 t	Servicing Avg.	AP-42: Industrial Construction Unpaved Roads
2.2 [kg-PM10 VKT-1]	19.5 t	Gillies, J. et al. (2005)	Measured
3.1 [kg-PM10 VKT-1]	42 t	Muleski, G. et al. (2005)	Measured
0.2 [kg-PM10 VKT ⁻¹]	2 t	Weiss, L. et al. (2014)	AP-42: Public Unpaved Roads

Table 3: Dust emissions from unpaved roads - literature values

CHAPTER 7 – METHODOLOGY FOR USING THE CIDEM TO ESTIMATE EMISSIONS, TRANSPORT, AND DEPOSITION RELATED TO IMPACTS ON THE SURROUNDING ENVIRONMENT

Given the nature of construction, it can be difficult to accurately estimate dust emissions as certain major variables may be unknown: how long patches of bare soil will remain bare, problems which extend soil disturbance intensive activities, permitting issues, and others. Therefore, to develop an understanding of how to more accurately estimate emissions, physical characteristics of historic construction sites were used to relate other essential aspects of the construction process to better predict the nature of a particular site for emission estimation.

The timing of construction site activities plays a significant role in its susceptibility to dust emissions. This includes the total amount of time the site is active, the time of year construction began, how long bare surfaces are left untreated, the spacing and type of activities, and others. To estimate the total lifespan of a site, Google Time Lapse images were analyzed to determine a relationship between its footprint and its lifespan, as seen in Figure 7.



Figure 7: Construction site size versus lifespan in the Lake Simcoe region

The time of year, especially when construction activities are well underway, is another major contributor to dust emissions susceptibility. The changing climate from month to month can change emissions based on snow cover, rain, wind patterns, solar radiation, and others (Weiss et al., 2011). City of Barrie building reports (Jan. 2014 to Dec. 2017) were analyzed to determine the seasonal distribution of construction activities; generally, maximums occurred the Spring and Fall, as Figure 8.



Figure 8: City of Barrie seasonal construction distribution

It is essential to determine how long certain activities and bare soil surfaces will stay bare or active as duration influences emission rates. Various construction sites found around Lake Simcoe were analyzed in greater depth. First, a large scale construction site was identified in East Gwillimbury, ON., at Mt. Albert and Leslie, as per Figure 9. Then, multiple smaller sites, adjacent to residents, were identified in a rapidly growing community West of the lake in Alcona, ON, as seen in Figure 10.



Figure 9: Lake Simcoe and the Mt. Albert and Leslie construction site with annual development growth from Google Time Lapse



Figure 10: Alcona construction site examples

THE LAKE SIMCOE AIRSHED URBAN GROWTH MAP

The urban growth map was developed using QGIS, an open-source Geographical Information System (GIS) program, to determine the historic annual urbanization rate around Lake Simcoe as this is directly related to the amount of construction activity taking place and a good indication of future growth trends. Google Time Lapse images, a time-series of satellite images developed by Google, were overlaid on a street base map in QGIS at various time intervals (1990, 2000, 2010, 2018).

Then, after creating shapefiles for each Dust Response Unit (DRU: 56 sub-regions of Lake Simcoe developed by Weiss et al., 2013), all urbanized lands were traced using another shapefile for each respective year within each DRU. Finally, the areas of the shapefiles were calculated using integrated algorithms in QGIS and compared to the DRU area to determine the rate of growth in each DRU, as seen in Figure 11.



Figure 11: The Lake Simcoe airshed urban growth map

CALPUFF/CALMET AND THE LOCATION REDUCTION FACTORS (LRFS)

The Location Reduction Factors (LRFs) were developed to evaluate dust transport and deposition in the region with help from *Lakes Environmental* by generating a wind field using CALMET, then using those modelling results as input to the CALPUFF modelling system (Weiss et al., 2014).

LRFs are percentages that represent the fraction of PM_{10} that transports and deposits into Lake Simcoe compared to their emissions per DRU. A DRU is a sub-area of the modelling space; in this case, the 100km by 100km modelling space surrounding Lake Simcoe is comprised of 56 DRUs. The LRFs are unique for each DRU and depend on the location relative to the lake, typical meteorological data in the area, soil type, and land-use (Weiss et al., 2014). LRFs range from 0.1% up to 13.5%.

Wind fields can be generated using many validated models, including CALMET, RAMS, MM5, WRF, and others (Exponent Inc., 2020). CALMET, a three-dimensional meteorological model, was used in conjunction with datasets from the MM5 model (including meteorological surface and upper-air data including precipitation) and inputs from 10 local meteorological stations to generate a Windfield for Lake Simcoe.

Modelling runs were validated by matching bulk dust collector results with modelling results to ultimately achieve spatial hourly friction velocities. Statisitical verification was also performed on the temperature and wind speed/direction results generated for the Windfield, indicating a reasonable relationship between measured and modelled results (Weiss et al., 2014).

CALPUFF, a Lagrangian Gaussian transport model, uses Windfield results from its preprocessor, CALMET, to determine wet/dry deposition. Results from CALPUFF are then passed onto CALPOST for post-processing. Receptors were employed over a 1km by 1km grid across Lake Simcoe to determine the direct contribution of dust from DRUs to the lake (Weiss et al., 2014).

LOCATION REDUCTION FACTORS (LRFs)

Location Reduction Factors (LRFs) were developed as a result of CALPUFF/CALMET runs to determine the percent contributions of dust emissions from Dust Response Units (DRUs) that deposit into Lake Simcoe. As construction within close proximity to water bodies and urban centres is a major concern due to deposition into the lake and the abundance of residents/urban growth surrounding the lake, and wind direction is a large contributor to transport and deposition results, West (sites found on the west side of Lake Simcoe) and East (sites found on the east side of Lake Simcoe) equations for determining percent contribution to transport and deposition for any site location were generated by fitting equations to the distance of a DRU to the closest Lake Simcoe shore and its respective LRF value, as seen in Figure 12. The measurement of distance was performed using a built-in measurement tool in QGIS.



Figure 12: LRF values for sites West/East of the Lake Simcoe

RESIDENT EXPOSURE AND PM10 EMISSION THRESHOLDS

As urban growth generally occurs as the expansion of pre-existing developments, as seen in Figure 11, dust emissions generated from construction activities are susceptible to exposure to humans, so emission estimates were compared to MOECC/USEPA standards. The maximum rate of allowable 24-h PM₁₀ emissions from the case study construction sites to nearby residents was determined to be roughly 83 kg d⁻¹ (BOEM, 2016) to meet the Ontario Interim Air Quality Guidelines for PM₁₀ (i.e. 50 μ g m⁻³, MOE AAQC, 2009). This was determined by calculating the threshold equation assuming a 1-mile distance, then converting the units from s.tons/year to kg/day.

EVOLVER OPTIMIZATION METHODOLOGY

Evolver was used to test variable input parameters for CIDEM estimates to determine the best configuration of BMPs at different cost intervals that provide a minimum emission (or maximizing the reduction of BMPs). Table 4 and the following paragraph describe the constraints and criteria used for optimization of the CIDEM estimates.

Parameter	Range or Formula	Step Value	Description
D	0.1 <= D <= 0.4	0.05	Depth of watering
W	100 <= W <= 500	25	Weight of mulch

AT%i	$0 \le AT\%_i \le 1$	$0 \le AT\%_i \le 1$ 0.05 Percent area treated by i (i: respective BMP)		
PM ₁₀ E	-	Optimize: Minimum	Total PM ₁₀ emission after BMP application	
Total Cost	Total Cost <= (cost interval of interest)	-	Optimization of minimizing total PM ₁₀ emission using a specific limit of resources (cost interval of interest)	

Table 4: Constraints and criteria used for Evolver optimizations

Respective values for frequency of watering application and cover-to-mass ratio of the mulch materials were not included in the table as the input values are not equally spaced and had to be optimized by different means than a simple adjustable step value range. To let Evolver attempt to optimize these two parameters, the input value for each parameter used was determined by creating an integer-weighted average of the parameters of interest to be used in the BMP equations, where the weighted "areas" are binary (1 or 0). Then, the adjustable cell range is set to each parameter "area" and the values are set to *Integer* in Evolver, forcing the "area" to be either chosen as a 1 or 0. Then, to ensure that only 1 of the three parameters are chosen (ie, an area distribution of 0, 0, 1; ultimately choosing the third parameter), a *Hard Constraint* in Evolver was developed, indicating that the sum of all parameter "area" must be equal to one. This way, Evolver tries different parameter inputs for frequency and material type without having to use discrete steps as Evolver was intended by assigning "area" values of 1 to the parameter value being tested and a 0 to the other two possibilities.

CHAPTER 8 – CONSTRUCTION SITE CASE STUDY RESULTS

EAST GWILLIMBURY RESULTS

To demonstrate CIDEM's performance, a residential construction site was used (44° 5' 34.9044" N, 79° 27' 2.8548" W), located south of Lake Simcoe on a sandy loam deposit. The surface area of the site is 157 ha. Table 5 presents the change in land-use overtime on the site and emission estimates given a no-BMP scenario using the CIDEM and Google Time Lapse images.

	2012	2013	2014	2015	2016	2017	2018	2019	*2020
Pre-development	100%	59%	27%	0%	0%	0%	0%	0%	0%
Exposed Soils (dormant)	0%	41%	63%	100%	75%	60%	45%	30%	15%
Active Construction	0%	0%	0%	0%	25%	15%	15%	15%	15%
Construction Completed	0%	0%	0%	0%	0%	25%	40%	55%	70%
PM-10 Emission [kg/yr]	26,612	56,621	70,062	99,805	149,707	104,795	89,824	74,854	59,883

 Table 5: Change in land-use on the case study site from start to present (2012-2020)

 *Note: Forecast values

Estimations of construction induced PM_{10} emissions, pre-development PM_{10} emissions, unpaved roads, and BMP performance were identified using WEPS, the AP-42: Unpaved Roads emissions inventory (USEPA, 2006), and Weiss et al., 2013, to develop the CIDEM model.

BACKGROUND PRE-DEVELOPMENT AND ACTIVE EMISSIONS

To understand the possible change in background fugitive dust emissions for a specific site, it is important to incorporate the probabilistic approach to construction to better predict these changes. Background emissions for region 2 sites assume no construction occurs that year. Given that construction activities are not evenly distributed across a given year, incorporating the monthly variation in construction activities for a particular year, as per Figure 13, provides a better indication of the changes in PM_{10} emissions. 2016 was chosen as a "worst-case-scenario" example given the high amount of activity and bare surface exposure on-site.



Figure 13: Comparison of the monthly pre-development background PM_{10} emissions with the 100% bare soil (dormant site) and during active construction given no BMP scenario in 2016

CASE STUDY OPTIMIZATION RESULTS AND DISCUSSION

Results generated by the research methodology, implemented in the CIDEM for the year 2016 was validated using the East Gwillimbury case study site characteristics and the optimization, using Evolver, of these characteristics with BMP performance and cost provide insight into effectively reducing PM_{10} emissions from construction sites using BMPs.

First, there is an exponential trend with the total cost and emission reduction, as seen in Figure 14. As more total resources are allocated to the reduction of dust emissions, the optimization tool has less opportunity to take advantage of those high-value reduction strategies. Figure 14 demonstrates the Evolvers optimization of the CIDEM at different costs to achieve the most significant reduction in PM_{10} emissions. Variables that affect BMP performance were modified by Evolver to reduce emissions as much as possible, given a targeted maximum investment.



Figure 14: Total BMP cost vs. PM₁₀ emission reduction efficiency scenarios for the case study construction site

Results show that calcium chloride solutions on unpaved roads are the most valuable strategy for reducing dust on construction sites as it allocated all of its resources into the unpaved road BMP. The stacked bar graphs demonstrate this for the first three optimization runs at 10%, 20%, and 27% reduction. As total cost increased, resources were then allocated to erosion blankets, revegetation, and watering. However, as unpaved roads are constantly being used and exposed during most of the construction schedule, the opportunity to reduce their emissions is greater compared to erosion blankets and revegetation, which can only be established once most of the

earth-work heavy phases have been completed. Though watering can be used to reduce emissions during high-risk activities such as leveling and servicing, its cost is far greater than that of using other dust suppressants.

The low cost associated with revegetation and erosion blankets provides cost-effective emission reductions compared to watering. As revegetation and erosion blanket/mulch supplies are only applied once to reduce dust indefinitely, similar to calcium chloride solutions, watering costs much more due to its daily reapplication condition to keep soils moist, especially in drier periods. The increase in resource allocation for watering is consistent with the increase in available funds as the frequency and depth of watering increased. Watering is also necessary when redeveloping vegetation after the seeds have been planted.

Based on the monthly emissions throughout the project, the early stages of construction are more susceptible to higher emissions even though low-value resource allocation is more prominent in the later stages. This is due to more intensive earthwork in the early stages, which makes it more difficult to effectively apply BMPs. Therefore, it is critical to investigate new ways to apply more effective BMPs in these early stages. Higher winds in the Spring can also produce more PM_{10} emissions than in the later months.

ALCONA CASE STUDY RESULTS AND DISCUSSION

To validate the methodology and to gain more insight on the major effects of dust emissions generated from construction sites, multiple case studies in a similar area were analyzed. Seven construction sites found on Google Time Lapse in Alcona, ON, from 2003 to 2018, were evaluated using the CIDEM, as presented in Table 6.

Site	1	2	3	4	5	6	7
Soil Type	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Loamy Sand
Size [ha]	7.91	22.62	0.94	0.56	2.88	1.36	37.58
Max Daily PM10 [kg]	49	321	5.8	3.5	17.9	54	144
Construction Period	2014- present	2011- present	2013- 2014	2015- 2016	2005- 2014	2014- present	2004- present
Fully Exposed Years	3+	2	1	1	1	1	6
Partially Exposed Years	4+	7+	1	0	9	4	14+

 Table 6: Alcona construction site characteristics

This table summarizes important characteristics of how construction projects are developed and provides insight into practical solutions for reducing dust emissions from construction activities. Figure 15 shows the annual change in emissions overtime based on untreated construction activities evaluated using the CIDEM and Google Time Lapse images.


Figure 15: Untreated annual emissions from Alcona construction sites

Based on Figure 15, emissions from construction sites are associated mainly with the amount of area clearing near the beginning of construction, as seen by the peaks in their first few years of each site. Contractors clear out all, or a large portion, of the proposed project early to save costs on equipment, leaving exposed soils for multiple years while housing demand is gradually met by building on smaller pieces of the total exposed soil over multiple years. Though active construction generates more emissions than bare soils, exposing the site will leave bare soils for extended periods of time. If construction companies phased out their projects and left predevelopment conditions until right before the building phase begins, these high emissions will be reduced and spread across their timeline, ultimately reducing emissions and reducing maximum concentrations to surrounding residents. In Table 6, this would reduce the maximum daily bare emission for each site as the total area of exposed and active construction would be partitioned. Table 6 also summarizes the amount of time that the site is wholly or partially left exposed for consecutive years. All the largest sites (sites 1, 2, and 7) have extended periods of exposed soils which could conveniently be avoided if phased properly. These are the sites that exhibit the highest maximum daily emission, and so more significant sites should be the focus for reducing emissions.

To evaluate the risk associated with untreated emissions from construction sites, a frequency duration curve was developed based on these more significant sites with smaller sites to compare, per Figure 16.



Figure 16: Frequency duration curves for untreated emission occurrence and likelihood to emit

These frequency duration curves demonstrate possible untreated max daily emissions and their likelihood of occurrence. The vertical black line represents the 83 kg/day threshold for resident exposure (BOEM, 2016) to meet the Ontario Interim Air Quality Guidelines for PM₁₀ (i.e. $50 \ \mu g \ m^{-3}$, MOE AAQC, 2009). It is important to note that these curves are generated based on days where emissions are higher than 0 kg, as per the "likelihood to emit" table. Only about 1/3 of all days throughout the year emit dust emissions as there are no emissions during the winter months and on rainy days. Figure 16 was generated to see the impact of size on untreated emissions and how they can potentially exceed regulations. As the size is a major contributor to emissions, Table 7 was generated to evaluate the average of the 90th percentile of the highest untreated emitting days for each soil type with a respective size.

	Size [ha]					
Soil Type	1	2	5	10	15	20
Clay loam	1.25	2.5	6.25	12.5	18.75	25
Silty clay loam	1.18	2.36	5.9	11.8	17.7	23.6
Loam	1.75	3.5	8.75	17.5	26.25	35
Sandy loam	23	46	115	230	345	460
Silt loam	3.21	6.42	16.05	32.1	48.15	64.2
Clay	0.005	0.01	0.025	0.05	0.075	0.1
Fine sandy loam	11.9	23.8	59.5	119	178.5	238
Silt	33.7	67.4	168.5	337	505.5	674
Sand	81.4	162.8	407	814	1221	1628
Loamy sand	65.4	130.8	327	654	981	1308
Organic soil	10.2	20.4	51	102	153	204

Table 7: Max daily emissions based on size and soil type in Alcona

This table highlights the two most important factors when considering dust emissions BMPs in an erosion and sediment control plan: size and soil type. Any grey and bolded cells are indicative of untreated emissions from potential construction sites that may exceed regulations.

Based on Table 7, to try and effectively reduce emissions from construction sites, any site greater than 5 ha, or whose topsoil is of sandy nature, should consider best management practices or other practical prevention techniques such as phasing and avoiding mass excavation without a clear building plan there-after.

CHAPTER 9 – LAKE SIMCOE REGIONAL EMISSION ESTIMATE RESULTS AND DISCUSSION

URBAN GROWTH IN THE LAKE SIMCOE REGION

Urban growth typically occurs around pre-existing urban centres, as seen by most urban growth trends in 2000, 2010, and 2018 happening around the largest communities in 1990, based on the Lake Simcoe Airshed Urban Growth Map. These pre-existing urban centres also represent the biggest municipalities found in the airshed, including the Newmarket Area (south), the Barrie/Innisfil area (west shore of the lake), Orillia (north shore of the lake), and the Collingwood area (east). Another significant observation is that most pre-existing urban areas are developed around water bodies, including both large and small municipalities. Limitations and assumptions of the growth map include: resolution of Google Time Lapse images (especially in earlier years) made digitization difficult resulting in less accurate estimates, the entire area of a growth shapefile is being modified for construction even though most construction projects have small patches of undisturbed land, and sites that go under reconstruction (soil disturbances on pre-urbanized land) were not considered.

As Lake Simcoe is known for its cottage communities, residents want to build on the waterfront, as seen by the vast amount of urbanization that surrounds the lake and other water bodies in the map (ILEC, 2019). This is a concern with respect to dust emissions from construction sites since new developments will likely occur around pre-existing urban centres, which are generally closer to the lake, ultimately increasing the likelihood that those emissions will transport and deposit into Lake Simcoe.

A REGIONAL PROBABILISTIC APPROACH TO ESTIMATING PM₁₀ TRANSPORT AND DEPOSITION INTO LAKE SIMCOE

A probabilistic approach was used in conjunction with CIDEM emission estimates to determine Dust Response Unit (DRU) emissions. First, the CIDEM was run using no BMPs to determine emission estimates for different start times (Spring and Fall), size (smaller than 1ha and larger than 1ha), and soil erosion susceptibility (High, Medium, and Low). Then, based on the probability of each of these scenarios occurring for each DRU, 10000 example scenarios were generated and averaged on a per area basis to generate a probabilistic estimate of emissions from each DRU to develop an understanding of the regional distribution of dust emissions from construction sites in the Lake Simcoe region. As excessive nutrient loading is a concern with respect to the water quality in Lake Simcoe, determining regional PM₁₀ emissions from construction sites provides insight into areas of concern.



Figure 17: Untreated annual PM₁₀ emissions per DRU in the Lake Simcoe airshed

Table 8 highlights DRUs with both significant growth rates and high LRFs, indicating high-risk DRUs that may deposit the most amount of PM₁₀ into the lake. It was determined that emissions within a specific range of the lake are the primary concern, but the LRFs do not properly represent the transport and deposition from construction for DRUs directly adjacent to water bodies. LRFs were developed using point source emissions from the centroid of each DRU into Lake Simcoe receptors. Based on the Lake Simcoe Airshed Urban Growth Map, however, the average point location of growth in high-risk DRUs is closer to the lake than the centroid of the DRU. To account for this, an effective LRF (eLRF) value was incorporated using the West and East LRF equations. Table 8 demonstrates the eLRFs used for high-risk DRU deposition estimates.

DRU	LRF	eLRF	Growth Rate [ha yr ⁻¹]	Description
22	8.4%	23.1%	24.3	Orillia Area
29, 30	5.7%, 7.9%	15.7%, 15.9%	23	Barrie Area
37, 38	2.4%, 13.5%	8.4%, 31.1%	13.9	Innisfil/North Region of York Area

Table 8: High-risk DRU's in the Lake Simcoe airshed

The untreated annual deposition of PM_{10} into Lake Simcoe was estimated and displayed in Figure 18. Proximity to water bodies and urban expansion rates, which are closely related, are the dominant factors in the deposition of PM_{10} from construction sites into Lake Simcoe.



Figure 18: Untreated deposition of PM₁₀ per DRU in the Lake Simcoe airshed

OPTIMIZATION OF BMPS USING EVOLVER FOR LAKE SIMCOE

Using CIDEM estimates, the West and East LRFs equations, and BMP cost and performance, Evolver was used to optimize resource allocation at different costs to determine the best use of investment in BMPs on construction sites for all DRUs in the Lake Simcoe airshed.



Figure 19: Total BMP cost vs. reduction in phosphorus deposition to Lake Simcoe

There is an exponential relationship between the return on investment through the reduction of phosphorus loading to Lake Simcoe and the investments themselves. When Evolver is provided minimal resources, it seeks out high-value BMPs at high-risk DRUs to reduce phosphorus emissions as much as possible. As such, resources for lower total investment were allocated to calcium chloride solutions for unpaved roads on construction sites found in high-growth areas with high LRFs, indicating that the calcium chloride solution were the most cost-effective BMP for reducing phosphorus emission, transportation, and deposition into Lake Simcoe from construction sites. As resources become more abundant, Evolver begins to run out of these high-value/high-risk scenarios, and so the return on investment begins to diminish exponentially. The application of erosion blankets and revegetation became more prominent in high-risk DRUs as the total investments increased and were prioritized over using calcium chloride solutions on unpaved roads in lower-risk DRUs (LRF <1%). After roughly CDN\$200000, the return on

investment becomes exponentially diminished as evolver has run out of its high-value targets and begins allocating extra resources to watering, blankets, and revegetation in low-risk DRUs.

Table 9 provides a summary of the total investments used for the optimization, as well as its respective cost per kg of phosphorus removed from the lake.

Tota	l Investment	\$ kg ⁻¹ P-removed ⁻¹	
\$	25,000	1248	
\$	50,000	1549	
\$	100,000	2032	
\$	200,000	3587	
\$	500,000	7631	
\$	1,000,000	14098	
\$	2,000,000	26739	

Table 9: Total investments and cost per kg-phosphorus removed, as per Evolver optimization

Costs per kg-P (phosphorus) removed from water bodies found in this study, a normalized parameter for comparing these sorts of technologies, are comparable to other nutrient removal strategies. Weiss et al., 2018, found that \$740 kg-P⁻¹ was optimal for a reduction on agricultural sites, while Zukovs et al., 2010, found that stormwater control technologies can achieve \$1800 kg-P⁻¹, agricultural BMPs can achieve \$170-\$1700 kg-P⁻¹, and phosphorus removal technologies retrofitted to sewage treatment plants can cost as much as \$13100 kg-P⁻¹.

CHAPTER 10 – SUMMARY AND CONCLUSIONS

CONCLUSIONS

From a regional air quality management perspective, fugitive dust emission from construction sites in the high-growth-rate urbanizing areas is a challenging task as these sites appear in random locations, sizes, and exhibit different start dates for construction within a year. Therefore, this research was developed and validated to provide insight into how differences in construction activities on-site affect PM_{10} emissions, transport, and deposition. This method was employed to identify to what degree these different factors influence emissions and their impacts to the surrounding residents and the environment. This novel methodology, along with the new CIDEM model, can be applied to construction sites for significant air quality improvements with reductions in control costs for this complex problem.

In this study, a dust emission prediction model for construction sites (CIDEM) is presented as a new air quality management tool for municipalities and conservation authorities in charge of permitting and monitoring construction sites. Every construction project is unique with respect to dust emission concerns and must be treated as such when developing a wind erosion and dust emission control plan for optimal resource allocation. The main factors in the development of the PM_{10} dust emission control plan include the distance to the nearby residential areas, the type of earthworks, the extent of the exposed surfaces, the size, and soil type.

This study highlights that sand and loamy-sand soils produce 5-10 times higher emissions than other soil types, indicating that soil type and size should be the primary risk factors when assessing a site for reducing PM_{10} emissions. To try and effectively reduce emissions from

construction sites, any site greater than 5 ha, or whose topsoil is of sandy nature, should consider best management practices or other practical prevention techniques like phasing and avoiding mass excavation without a clear building plan there-after.

Watering, mulching, road dust suppressants, and revegetation are all effective best management practices (BMPs) for PM_{10} emission reduction on construction sites (maximum reductions of 78%, 87%, 60%, and 90% respectively, on a mass-basis). Focusing resources on calcium chloride solutions for unpaved roads is the most valuable way to reduce dust emissions. Though watering is the most expensive BMP, it is the most versatile as it can be used as a reduction agent for more construction processes than blankets/mulches and revegetation. To achieve higher cost-efficiency of the BMP resource allocation, personnel should target highly dust-emissionsusceptible areas of the site, including unpaved roads and areas with little-to-no boundary obstructions and flat bare-soil surfaces that will remain exposed for an extended period. Silt fences provide an insignificant reduction for wind erosion, especially on more significant sites, unless placed within the boundaries of the site, which can cause issues with transportation and others. Maintaining as much pre-existing vegetation as possible, re-vegetation of exposed soils, and increasing the number of phases to create smaller areas of exposed soil are all practical solutions to help reduce the potential adverse health effects of construction sites to nearby residents without spending money on BMPs.

Urban growth rates in the Lake Simcoe region are highest close to pre-existing developments, which are close to water bodies, increasing their susceptibility to transport and deposit phosphorus into the lake. Optimization performed by Evolver on the CIDEM estimates for Lake Simcoe DRUs and BMP performance and cost indicated there is an exponential relationship

between total investment and phosphorus loading reduction and that the most valuable allocation of resources would be using calcium chloride solutions on unpaved roads in high-risk DRUs. The costs per kg of phosphorus removed, a normalized parameter when comparing these types of technologies, is comparable to other studies investigating nutrient removal strategies. Evolver was an effective tool to optimize CIDEM estimates for individual construction site emissions and regional emissions by providing insight into resource allocation for reducing cost and PM₁₀ emissions.

LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORKS

Below is a list of limitations concerning concerning the CIDEM and the overall evaluation methodology for emissions from construction sites:

- Erosion blankets were modelled using crop residues which may not be representative of the cost and performance of commercially available erosion control blankets;
- The emission factors with respective soil dropping were not considered as this is not a part of WEPS sub-models;
- WEPS assumes a homogenous surface when calculating wind erosion, which is never the case on a construction site due to slopes, piles of soil, and other topological differences;
- WEPS assumes no obstructions at the boundaries, where most construction sites have unique surroundings that alter wind patterns, including off-site buildings and vegetation, adding conservatism to the CIDEM estimates;

- The stochastic weather generator, though representative, does not take into account the individual weather patterns for a specific construction site location and the weather changes due to construction impact are not considered;
- Using LRFs as a point source does not very accurately represent emissions from an area source like construction sites;
- Other sources of PM₁₀ and dust from construction sites are not considered, including:
 Heavy Goods Vehicle (HGV) exhaust emissions, non-exhaust emissions (tire and brake dust), and others.

Recommendations for future works on this research include:

- Address various limitations set above;
- 3D modelling using AERMOD or others to assess transport and deposition using topologically accurate construction site examples;
- In-situ testing of various BMPs on construction sites to further validate their performance and respective cost;
- Develop a program to standardize construction site activity reporting for a more comprehensive data-set with respect to processes, timelines, phasing, and other influencing factors on dust emissions from construction sites.

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APPENDIX A

Appendix Figures



Figure A.1: Total precipitation comparison (Barrie versus Rochester) by Weiss et al., 2013



Figure A.2: Minimum average temperature comparison (Barrie versus Rochester) by Weiss et al., 2013



Figure A.3: Minimum average temperature comparison (Barrie versus Rochester) by Weiss et al., 2013



Figure A.4: Lake Simcoe soil type map (as provideded by the Lake Simcoe Region Conservation Authority)

Interviews with Construction and Contract workers

Steve Sperling: Aerarium Group

Phone: (705) 726-7130 May 22nd, 12:35 pm, 2018

- Most projects are 1-5 acres
- Recent project: 4 acres, multiple industrial building lot, 3 story office and single story units

Preparation of the site: (1 month)

- Scraping, 1 week max, using silt fences
- Excavating for 2 weeks
- Rarely soil hauling, maybe 10% of projects
- Servicing for 1 week: sewer, water, bare soils

Starts mid April to mid May

Lasted 3-4 months For Projects bigger than 5 acres, watering Park place was 100 acres; experienced lots of wind erosion

Brian Materazo: Arnot Construction Limited

Phone: (705) 735-9121 May 22nd, 2:39 pm, 2018

Dust suppression: watering, calcium chloride, silt fences Generally 1-3 years, up to 5 years Soil hauling 50% of the time Current project: 1 year – subdivision Mid April to late November During the winter uses seed and mulch, erosion blanket and fencing

Derek Watson: Watson Group Homes

Phone: (705) 721-2590 May 23rd, 1:27 pm, 2018

3-4 projects -> mostly houses or apartments 1-4 rating for technical challenges Subdivision home: complete sand -> 1 Tough soil -> 2 Custom home: Sand -> 2 Bad soil -> 3

Subdivision home, infield: 3, busy streets make it harder Projects this year: 1s: 6 months (8) 2s: 7-8 months (0) 3s: 9-11 months (5) 4s: 1-1 and ½ years (1) 2 months added if the projects not finished by the end of August

Generally don't start new projects until July because of overflow from the previous year

Current project: 3 rating Starts with grubbing: 1 week • Pinned off, longtime before project starts Cut and fill -> 1-2 weeks Basements/servicing -> 2-4 weeks

Erosion Control: Silt fences, dust suppressants (he doesn't use them), tarping

Grant Dermott: UFC Contracting Inc

Phone: (705) 333-8532 June 8th, 2:23 pm, 2018 Current Job: 4 months Grubbing: 2 weeks, uses silt fences Excavation: 4-6 weeks Servicing: 2 weeks

Longer projects: 1 and $\frac{1}{2}$ - 2 years

Jacob Lane: Tacoma Engineering Inc

Phone: (705) 735-4801 June 8th, 2:52 pm, 2018 BMPs: Silt fences the whole time Watering/calcium chloride: mostly in civil/new subdivisions Most construction starts april or September when the ground is softer, but can start in January

Lloyd Exton: Cherokee Contracting Inc.

Phone: (705) 435 – 2393 June 11th, 2:00 pm, 2018

Most projects (>50%) last less than 6 months
Grubbing: 1 week Cut and fill: 1 week Servicing: 1-4 weeks Only uses silt fences when there is risk of flooding and runoff but not usually May use snow fences for wind erosion Never uses tarpping or watering May is when projects ramp up, works all year around

Rick King: Cambria Design Build LTD

Phone: (416) 881-1232 June 20th, 12:57 pm, 2018

Commercial Construction Duration: 3000 sq ft building – 18 weeks 20000 sq ft building – 36-48 weeks

Grubbing: 2-3 days for smaller projects 1-2 weeks for medium sized Up to 1 month for large projects

Cut and fill and Servicing are similar; dependant on the size of the project

Best and most frequent (~60%) when frost leaves: end of march early april Most projects start then and want to be done before Christmas Can and do start any time of the year

Servicing -> mostly heavy/medium burrowing for commercial

BMP's: silt fences – always Never uses watering Tarping – always

Laura McGinnis: Lake Simcoe Region Conservation Authority Phone: (905) 895-1281 EXT 324 E-mail: lmcginnis@lsrca.on.ca

June 20th, 1:40 pm, 2018

3 types of residential permits:

- Minor: fence, pool, deck, shed
- Intermediate: garage, shed, shoreline
- Major: single family dwellings

LSRCA Permits look at: flooding, erosion control, flood plans, wetlands 3 types of permits: residential, commercial, subdivision

Commercial Permit Steps:

- 1. Planning approval
- 2. Building Permit

Timeline for Residential:

Minor (septic): 6 months, up to 2 years extension

Single Dwelling Homes: 1 year, extended up to 2 years

Subdivision: Call that municipality (Barrie or Innisfil would be good starts)

Industrial and Commercial are the same: 1 year, extended up to 2 years

Chris Glanville: Manager of Building Services for the City of Barrie

Phone: (705) 739-4220 x 4501

June 24th, 2:52 pm, 2018

Using the start time from building reports as the start of construction activities is correct Engineer: Frank Paulka EXT: 4445

- "Site Alteration": Contact to talk about subdivisions
- May have data to confirm the relationship of duration and area

Single Dwelling: Average single parcel = 500 m.sq

More useful information may be found by searching "growth management" on barrie.ca Agrees that the relationship between area and duration of activities is exponential

• IE: It's not a linear relationship like 1day/acre, rather as the projects get bigger, the increase in duration decreases

Another good contact would be Adam Hawboldt EXT: 4889

• Adam is the field inspector/manager while Chris is the office manager

Commercial vs. Industrial vs. Institutional

Commercial: more refined area, generally higher cost/m.sq, smaller lots Industrial and Institutional: Bigger than commercial. Agrees with combining the two for simplicity of modeling wind erosion; Agrees with characterization for start times

Frank Palka: Manager of Development Services at City of Barrie

Phone: (705) 739-4220 x 4445 June 20th, 11:19 pm, 2018

Deals with Subdivision construction through "Site Alteration" permits

Subdivisions start with a farm or woodlot. Once the draft is approved, tree removal begins through "Site Alteration" permits

Anything greater than 5 ha in size requires the permit (50000 m.sq)

Area vs. Duration Relationship: Depends on the earthwork load, duration depends on size. Working 7-8 hours a day, 2-3 months until all foundations and servicing is finished. Bigger lots take less time per area because of more machines and phasing.

Examples: Small -> 6 lots, 2.2 acres. 1-2 months

Big -> 600 lots, phase is into 24 hectares. Usually takes 2-3 months. Open farm fields create more wind erosion than surrounding tree cover

More info with TVC, LSRCA, MOECC: Wind Erosion Criteria Management

Site Alteration Bi-Law: sediment control

• Sodding, seeding, mulching, tarping, mulch spray, watering

Look at the erosion and sediment control guidelines for urban construction -> golden horseshoe

Each phase of construction is generally the same amount of time; ideally. Phases lengthen at the same rate depending on size.

Major development:

• 1 residential, 40 ha. Could see it all from the 400. All Earthworks would be done in 1 go.

Start times: depends largely on site.

The Migratory Bird act requires contractors to hire biologists to assess the potential impact of construction on birds between march – September. Best case scenario is to start in late spring and be done before frost in December.

Small projects like to be started in September to avoid migratory bird act.

Charles Burgess: Manager of Planning for the LSRCA

Phone: (905) 895-1281 -> Ask for Charles Burgess June 28th, 12:07 pm, 2018

Agrees with the assumption of the relationship of Area vs Duration No idea who would keep data to justify this

Tom Hogenbirk: Manager of Engineering for the LSRCA -> contact?

GIS Maps: Look for official planning maps on municipal websites

- Bulk of construction in settlement areas (Barrie, Aurora, Innisfil, etc)
- Look for Green Belt Plan, Revised 2017 Growth Plan

BMP's: Not quite sure what the most popular are, all should be used based on Dust Control agreement

• Can ask barrie for the Dust Control Plan to see what BMP's should be used

Site Visits: Annexed land in Barrie has lots of development People to contact for potential site visits and other contacts:

- Barrie: Michelle Banfield
- Bradford: Ryan Windell
- Cheswick: Harold Lenters
- Innisfil: Kim Cane (****)

Mark Bradshaw: Mark Bradshaw Construction

From "Why builders spray water on construction sites" URL: <u>https://www.desertsun.com/story/money/real-estate/2015/09/01/builders-spray-water-construction-sites/71519806/</u>

Uses 4000 gallons / acre, which is about 0.25 inches of water. Water must moisten through several inches of water so that when it is dug up the underbelly of soil is also moist. Soil moisture must be checked before servicing.

Mickie Riley: La Quinta-based Rilington Group

Certain moisture level required before building to ensure ground won't shift. Lasts 2 to 3 weeks before moving dirt and grading (leveling). Grading and servicing, 2-3 months on a 40-acre lot.

https://www.ontario.ca/page/technical-bulletin-management-approaches-industrial-fugitive-dust-sources