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Uncertainty Analysis of the Performance of a System of Best Management Practices for Achieving Phosphorus Load Reduction to Surface Waters

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Abstract and Keywords

The repeated occurrence of Lake Erie's harmful algal blooms suggests an inadequate phosphorus management system that results in excessive loads to the lake. In response, Canadian and United States' governments have issued a new management objective, a 40% reduction in total and dissolved reactive phosphorus loads relative to 2008. To provide scientific evidence to guide managers toward achieving their management objective, we used the International Standard of Organization (ISO) 31010 Bowtie Risk Analysis Tool to analyze the performance of the phosphorus management system. The effectiveness of agricultural best management practices (BMPs) and their adoption were combined into a Bayesian belief network model to predict watershed performance of each BMP. Then, the BMPs were analyzed for their probability of high risk phosphorus load reduction and achieving the management objective. Trade-offs were observed among the BMPs that will require decision makers to decide whether the management priority is to achieve the 40% load reduction objectives, or prevent further increase in the proportion of dissolved reactive phosphorus in the load, the identified culprit causing the repeated algal blooms.

Co-Authorship Statement

This thesis will be reformatted for submission to an academic journal. Jason D.M. Igras will be first author as he was responsible for writing the thesis and contributed to conceptualizing the management approach, building the modeling structure, acquiring and assimilating data to parameterize the model, and operating the model for simulations. Irena F. Creed will be the second author as she was the primary editor of the thesis and contributed to conceptualizing the management approach, building the model structure, and validating its functional relevance to filling the management gap it was designed for. Irena F. Creed also provided the financial resources to support the research.

Dedication

I dedicate this thesis to my Grandmother, Pauline, who, confined to a wheelchair for over 40 years, taught me that family is all you need to smile.

My Grandfather, Bill, for showing me what true and dedicated love looks like, in sickness and health.

Thank you mother Averil, father Dave, Sister Mel and Brother Josh for always encouraging me to pursue my passions, loving me for the weirdo I am, and pushing me to always stay positive.

Finally, my teammate, world traveling partner and girlfriend Sara Martinali, who was always available to support and push me; your encouragement contributed much to this thesis.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

Pollutants:

DRP   Dissolved reactive phosphorus

PP   Particulate phosphorus

TP   Total phosphorus

Best management practices:

BMP   Best management practice

CR   Crop rotation

CSC   Contour strip cropping

FFS   Forest filter strips (tree species)

NAM   Nutrient application management

PF   Precision feeding

RT   Reduced tillage

VFS   Vegetative filter strips (non-tree species)

WR   Wetland restoration

Units:

km   Kilometer

MT   Metric tonnes

MTA   Metric tonnes per annum

Other:

BBN   Bayesian belief network

GLWQA   Great Lakes Water Quality Agreement

GRCA   Grand River Conservation Authority

ISO   International Organization for Standardization

Chapter 1: Introduction

1.1 Problem Statement

The Laurentian Great Lakes basin is home to a bi-national population of 48.5 million inhabitants (Methot et al. 2015). The basin supports 25% of the combined Canada and United States' economy, where $344 billion in Canadian exports were directly dependent on the basin's natural resources in 2011 (Campbell et al. 2015). Increasing population and land use alterations with associated nutrient loads (particularly phosphorus) to the lakes, caused localized eutrophication and nuisance algae hazards to nearshore areas throughout the Great Lakes, with the problem most prevalent in Lake Erie. Total phosphorus (TP; combining particulate and dissolved forms of phosphorus) management in the 1970s and 1980s had successfully reduced TP loads below the policy objective in most years since the 1990s (Dolan and Chapra, 2012; Maccoux et al. 2016). However, eutrophication has remerged as a crucial problem in large areas of Lake Erie, with nuisance algae again threatening coastal dependent tourism, fish harvesting, property value, drinking water supplies and other ecosystem services (Michalak et al. 2013; Scavia et al. 2014).

The re-eutrophication of Lake Erie, suggests ecosystem functions are changing such that long-standing policy objectives are no longer reliable to prevent eutrophication and related impacts. Evidence suggests the Great Lakes are vulnerable to climate change (Bartolai et al. 2015), future populations will impose greater demand on the basin's resources (Methot et al. 2015) while a deficient management system is unable to prevent threats to valued ecosystem services (Jetoo et al. 2015). In response, a 40% reduction in TP and dissolved reactive phosphorus (DRP) loads relative to 2008 was recommended by the Great Lakes Water Quality Agreement's Annex 4 Nutrient Objectives and Targets Task Team (2015). It appears urgent to re-visit Great Lakes management (Creed and Laurent, 2015; Creed et al. 2016). There is a need to develop innovative and adaptive tools to guide decision making to achieve the new phosphorus load reduction policy objective (Kalcic et al. 2016).

1.2 Scientific Justification

1.2.1 Lake Erie Eutrophication and Re-eutrophication

The International Joint Commission (IJC, 2014) defines eutrophication as the "excessive enrichment of freshwater with nutrients". In an email survey distributed to limnology experts worldwide by Downing et al. (2014), eutrophication was the most frequently cited environmental problem in 2013 and the greatest problem predicted for 2023, having socio-economic and environmental implications; a "wicked problem" that cannot be solved, but can be *managed* (Thornton et al. 2013). Loading of nutrients prior to 1970, especially phosphorus, from point sources like wastewater treatment plants and industry and non-point sources from agriculture, led to the eutrophication of localized areas around the Great Lakes. The phosphorus loads contributed to the proliferation of nuisance algal blooms in Lake Erie that threatened the quality and quantity of ecosystem services (Dolan and Chapra, 2012; Gidding et al. 2012; Michalak et al. 2013; Scavia et al. 2014).

The decline in Great Lakes' ecosystem health triggered a bi-national movement to manage environmental risks that led to the 1972 Great Lakes Water Quality Agreement (the Agreement). The Agreement states in Article 3, General Objective *vii* that the waters of the Great Lakes should "*be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health and human use of the ecosystem*". The Agreement also implemented an 11,000 MTA TP load objective that was achieved in the 1980s by regulations placed on phosphorus detergents, industry and wastewater treatment facility upgrades, as well as the implementation of agricultural soil conservation practices, such as nutrient application management that spatially and temporally targets fertilizer application (Richards and Baker, 2002; Sharpley et al. 2012). Following TP load management in the 1980s, Lake Erie's "*rapid and profound ecological response*" (Michalak et al. 2013) was considered *"one of humankind's greatest environmental success stories"* (Matisoff and Ciborowski, 2005).

In a study that calculated trends in TP loads to Lake Erie, Dolan and Chapra (2012) reported the TP load objective was exceeded just four times between 1994 and 2008, re-affirmed in a recent study by Maccoux et al. (2016). Despite the successful environmental management of TP load in past decades, scientific literature suggests Lake Erie is experiencing a re-eutrophication (Baker et al. 2014, Scavia et al. 2014). In 2008, Lake Erie experienced the second largest algal bloom in history, only to be succeeded three years later by an algal bloom three times the size with an areal extent greater than 5,000 km^2 (IJC, 2014; Michalak et al. 2013). These algal events both occurred in years when the TP load to the lake was below the policy objective (Figure 1.1) (Dolan and Chapra, 2012). Repeated eutrophication events, occurring within the limitations of the TP load objective, suggests the objective is no longer effective at meeting the Agreement's General Objectives, and those specifically of the Annex 4 for nutrients.

Gakstatter et al. (1978) showed if point sources were eradicated, 72−82% of United States' eutrophic lakes would still require management of non-point phosphorus sources to meet water quality objectives. Scavia et al. (2014) similarly showed that even with eradication of point sources in the Lake Erie basin, non-point sources would still require additional management to reduce central basin hypoxia to acceptable levels in compliance with relevant policy objectives. Baker et al. (2014) showed significant annual variability in TP load from non-point sources compared to point sources that suggest ineffective management and/or the influence of external environmental factors like climate change (Figure 1.2). With 63% of Lake Erie's catchment contributing non-point P from agricultural human activities, the IJC (2014) has identified farming not only as a driver of eutrophication but also a potential solution.

1.2.2 Phosphorus management

The most significant proportion of TP discharged from agricultural tributaries has traditionally been the fraction sorbed to sediments (particulate phosphorus, PP) (Richards et al. 2008; Panuska and Karthikeyan, 2010; Coelho et al. 2012). Management of non-point agricultural sources has therefore focused on PP reduction to achieve the TP policy objectives (Coelho et al. 2012; Sharpley et al. 2012).
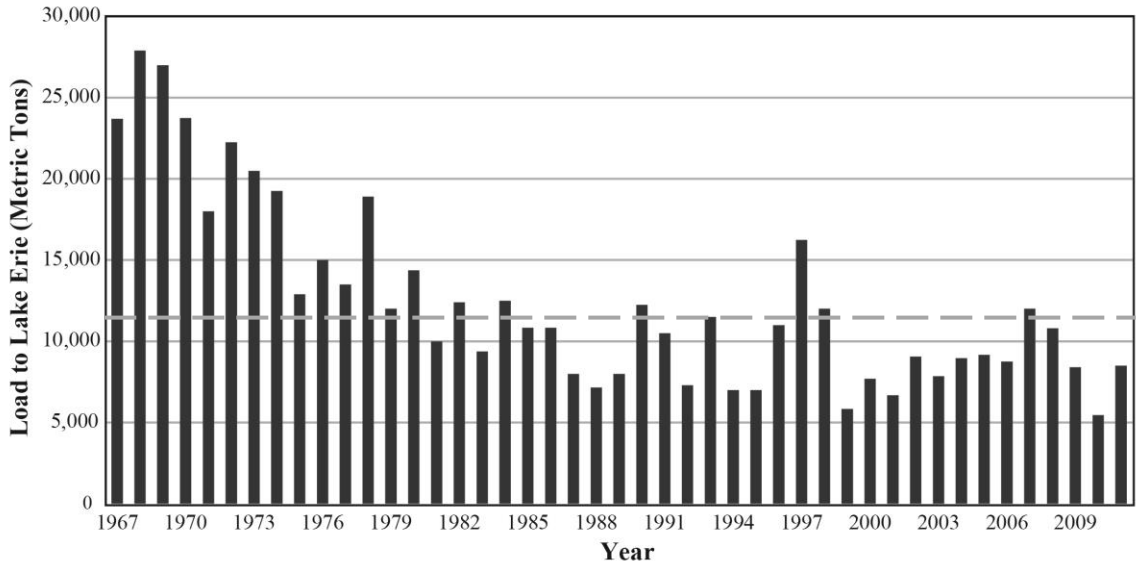
Figure 1.1: TP loads to Lake Erie from 1967−2011. The Great Lakes Water Quality Agreement implemented the 11,000 MTA TP loading objective (grey dashed line) in 1972 that lead to decreases in TP load that levelled off below the loading objective in the late 1980s. The largest algal bloom in 2011 and the second largest in 2008 occurred below the loading objective (Adapted from Scavia et al. 2014, who used data from Dolan and Chapra, 2012).
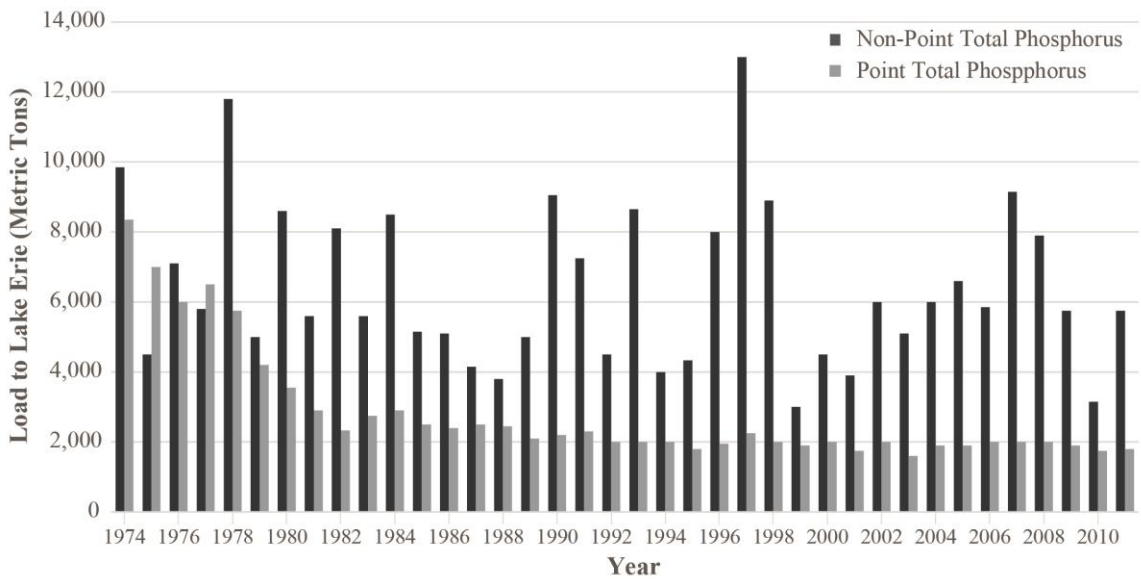
Figure 1.2: Point and non-point TP loads to Lake Erie from 1974−2011 (Baker et al. 2014).

Sharpley et al. (2012) showed a substantial 75% decline in TP load (1975−1995) from Lake Erie's largest agricultural tributaries, the Maumee and Sandusky Rivers. The

4

reduction was achieved by voluntary implementation of best management practices (BMPs), specifically nutrient application management to meet crop requirements and soil conservation practices to prevent soil erosion and PP transport from farms. These declines are also described by Dolan and Chapra (2012) and Maccoux et al. (2016) for the Lake Erie basin. At the same time, Sharpley et al. (2012) described a 50% reduction in DRP load, the fraction of TP that is in dissolved form and almost 100% biologically available, and therefore, easily accessible for algae proliferation (Baker et al. 2014). This undoubtedly contributed to the "*rapid and profound ecological response*" of Lake Erie in the 1980s described by Michalak et al. (2013). However, despite the reductions, a substantial upward trend in DRP load followed in the mid−1990s (Figure 1.3), simultaneous with the peak adoption of reduced tillage (Richards and Baker, 2002; Sharpley et al. 2012) and tile drainage (King et al. 2015; Kleinman et al. 2015; Lamba et al. 2009; Molder et al. 2015; Statistics Canada, 2006). Many criticize traditional TP management for contributing increased DRP load, causing unintended consequences (Dodd and Sharpley, 2016) including the re-eutrophication of Lake Erie (Scavia et al. 2014). However, this criticism has been met with mixed support from the agricultural community, watershed managers and scientist's alike (Kleinman et al. 2015). Although traditional soil conservation management has been successful at achieving TP load objectives (Dolan and Chapra, 2012; Sharpley et al. 2012), the management of DRP load from non-point agricultural landscapes has proven a more complex challenge with reductions highly variable and the potential for load increases a priority concern (Sharpley, 2016).

1.2.3 A new policy objective for phosphorus load reduction

With Lake Erie returning to a eutrophic state and threatening to compromise valued ecosystem services, governments from Canada and the United States have once again mobilized to tackle the issue from a perspective that considers both TP and DRP management. The Annex 4 Nutrient Objectives and Targets Task Team (2015) (Task Team) was assembled to recommend policy objectives for reducing the probability of Lake Erie cyanobacteria algal blooms. Based on tributary loading and in-lake eutrophication modeling, the Task Team recommended a 40% reduction in TP and DRP
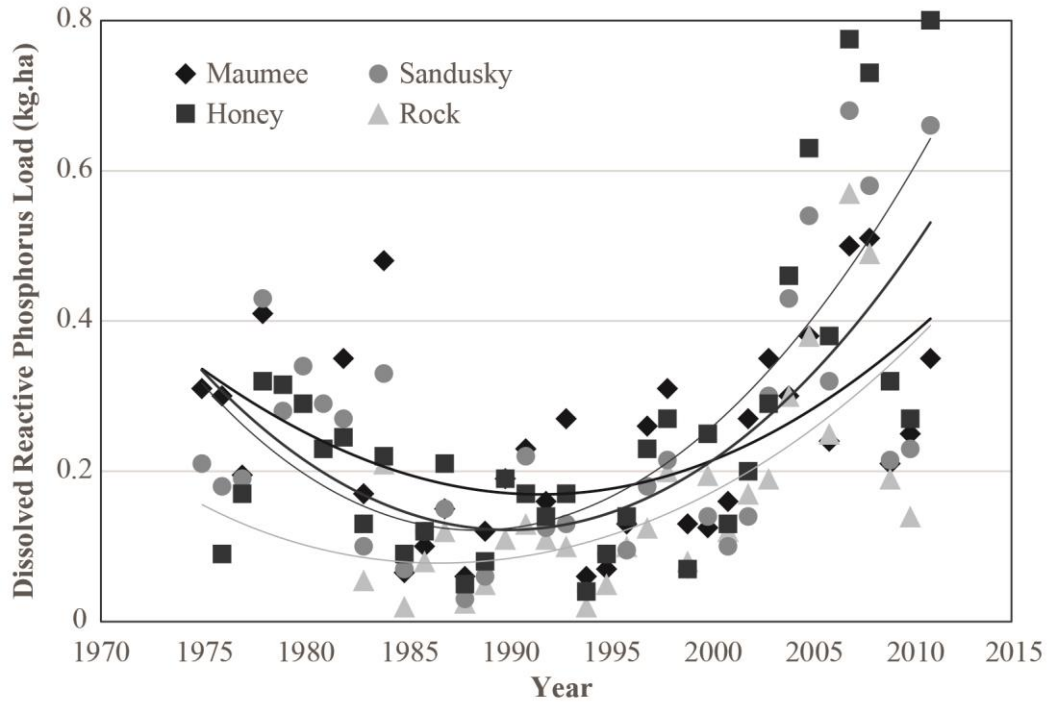
Figure 1.3: Trends in DRP loads from the Sandusky, Maumee and Raisin tributaries; DRP loads decrease in the 1970s and 1980s, but increase in the mid−90s coincident with the peak of reduced tillage adoption (Kleinman et al. 2015, with data from the International Joint Commission, 2014).

load relative to 2008 from all western basin tributaries and the Thames River. This reduction was recommended to achieve a 90% annual probability of causing western basin cyanobacteria bloom no greater than those observed in 2004 and 2012. To achieve the policy objective, the performance of the system of phosphorus management measures for reducing loads needs to be analyzed and then improved (Creed et al. 2016).

1.2.4 High risk uncertainty of phosphorus management

Agriculture and its contribution to non-point phosphorus loads to aquatic ecosystems can be managed by regulatory measures (i.e., the 2006 Nutrient Management Act) or voluntary measures. In Ontario, agricultural Best Management Practices (BMPs) are farming methods that are voluntarily implemented by the farm operation and farm operators. This thesis focused on BMPs for environmental conservation, specifically BMPs designed to directly reduce pollutant loads (i.e., vegetative filter strips), and BMPs for other purposes that can indirectly reduce pollutant loads (i.e., tile drainage). Farming

methods only qualify as "best" management practices when approved by a team of researchers, farmers, extension staff and agribusiness professionals (Ontario Ministry Agriculture Food and Rural Affairs, 2014). Europe relies predominantly on regulatory strategies, whereas North America and the Great Lakes region relies more on voluntary strategies such as BMPs (Kleinman et al. 2015). Both suffer from a lack of research and relevant data, and therefore anticipating management outcomes is uncertain (Kleinman et al. 2015).

One way to measure effectiveness of a management measure is to examine the percent of pollutant or contaminant load that is reduced by the management measure. In the Great Lakes, Chesapeake Bay and other agricultural basins in North America, the effectiveness of BMPs has been a considerable focus of science and management initiatives (Kleinman et al. 2009; McElmurry et al. 2013), but clear trends in BMP effectiveness remain uncertain (Dodd and Sharpley, 2016; Sharpley et al. 2009), as there is considerable variation in TP and DRP load reductions by individual BMPs (Dodd and Sharpley, 2016; Gitau et al. 2005; McElmurry et al. 2013).

Dillaha et al. (1989) examined the effectiveness of vegetative filter strips (VFSs) for reducing nutrient pollution from cropland; their effectiveness ranged from 35 to 95% reduction for TP and from −258 to 79% reduction for DRP, indicating an overall reduction in TP load but a possible increase in DRP. Similar variation in VFS effectiveness for TP and DRP load reduction was reported in other studies (Blanco-Canqui et al. 2004; Chaubey et al. 1994; Daniels and Gilliam, 1996; Lee et al. 2000; Lee et al. 2003; Schmit et al. 1999). Uncertainty exists with other BMPs, Gitau et al. (2005) reported phosphorus load reductions for contour strip cropping (CSC) to range between 8−93% for TP and 20−93% for DRP. Schreiber and Cullen (1998) reported that reduced tillage (RT) reduced TP loads by 59%, however a 390% increase in DRP loads was also observed. Koskiaho et al. (2003) reported wetland restoration (WR) and construction or, gully plug installation, resulted in −6−67% reduction in TP load and −33−33% reduction in DRP load. A review of wetlands worldwide by Fisher and Acreman (2004) showed effectiveness to range from 50 to 90% for TP load and 25 to 95% for DRP load. This variation in management outcomes by BMPs causes considerable uncertainty when

anticipating their effect prior to implementation and therefore creates risk of failing to achieve policy objectives.

Current management approaches favour the adoption of BMPs that effectively manage TP, but are variable in their effectiveness to manage DRP with potential for antagonistic effects. For example, in the Lake Erie basin, RT (combining conservation tillage and no-tillage) has gained considerable adoption by the Great Lakes States (Kleinman et al. 2015) and Ontario farm operations (Statistics Canada 2006; Lamba et al. 2009; Molder et al. 2015). RT is designed for sediment conservation and, although effective for TP reduction for its retention of the PP fraction, some studies have reported increased DRP loads partly responsible for the recent re-eutrophication (McElmurry et al. 2013; Scavia et al. 2014; Smith et al. 2015). In addition, tile drainage, a BMP to increase crop biomass and economic return (not an environmental conservation BMP) through water table management, has also been advocated for additional benefits as an indirect BMP for phosphorus load reduction by preventing surface runoff causing erosion and the transport of PP. Tile drainage has also gained considerable adoption in Lake Erie tributaries and have received similar criticisms for increased DRP load (King et al. 2015). The literature seems to indicate trade-offs for targeting soil conservation methods that further enhance the uncertainty of the management system for DRP management and preventing eutrophication in Lake Erie.

Consideration of site-specific attributes like slope, soil type, weather and climate is often suggested to better predict effectiveness of BMPs prior to their implementation (Baker and Johnson, 1983; Dodd and Sharpley 2016; Geng et al. 2015). Gitau et al. (2005) developed a simple tool for estimating BMP effectiveness based on a synthesis of data found in scientific literature focused on the United States. Slope, soil type and study location attributes gathered from reviewed studies were populated into lookup tables and used to query TP, PP and DRP reduction predictions for BMPs. Geng et al. (2015) developed the same tool for application in China. The simplicity of these prediction tools is a major benefit, however, if the tool operator attempts to predict effectiveness for a BMP where data are lacking for location, soil and/or slope variables, the tool does not interpolate or extrapolate predictions. Rather, it returns a null value for effectiveness

estimations (Gitau et al. 2005), limiting its general application. These tools draw attention to the lack of region-specific BMP effectiveness data, an observation also reported in a review of BMPs for application in the Great Lakes basin by McElmurry et al. (2013) and is consistent with observations for the United States, United Kingdom and Sweden (Kleinman et al. 2015).

The broad ranges in BMP effectiveness for reducing phosphorus loads produces considerable risk for achieving policy objectives. This risk is greater because of the potential for some BMPs to reduce TP but increase DRP, thereby increasing the likelihood of eutrophication events. Dodd and Sharpley (2016) emphasize these "unintended consequences" of BMP implementation despite best intentions. Without better predictions of anticipated BMP effectiveness *prior* to implementation, achieving water quality objectives in agricultural tributaries of the Great Lakes may be a "shot in the dark", with the potential to exasperate eutrophication risk and its impacts (Dodd and Sharpley 2015; Sharpley et al. 2009; Smith et al. 2015). For Lake Erie tributaries to achieve their TP and DRP load reduction objectives while reducing the uncertainty of alternative high risk load scenarios, simple tools are needed that can identify strengths and weaknesses as well as gaps and redundancies in the management system, and that can communicate the uncertainty of alternative management outcomes to decision makers.

1.3 Thesis objectives and hypotheses

The goal of this thesis was to contribute further knowledge into phosphorus management methods and the performance of the system of voluntary management measures in place for reduction of phosphorus loads to the Great Lakes. The first objective was to develop a novel approach that quantifies the probability of TP and DRP load reduction and accommodates management uncertainty with different agricultural BMPs individually and as an integrated management system. The second objective was to implement the approach to optimize BMP management strategies for reducing the uncertainty of achieving the 40% load reduction objectives in the Grand River watershed of southern Ontario. Considering current BMPs are designed for soil conservation (Dodd and Sharpley, 2015; Kleinman et al. 2015), we hypothesized: (1) adoption of TP effective

BMPs is the most suitable strategy for achieving the TP objective but increases the risk of elevated DRP loads; and (2) adoption of DRP effective BMPs is the optimal strategy to simultaneously achieve both TP and DRP reduction objectives.

To achieve the thesis objectives and test the hypotheses, we developed a Bayesian belief network model to simulate the probability of TP and DRP load reductions by agricultural BMPs, individually and collectively as a management system. This relied on data compiled from BMP effectiveness studies and databases, which were used to determine the optimal BMP management strategy to increase probability of achieving the 40% TP and DRP load reduction policy objective while managing the uncertainty of alternative high risk loading scenarios. We applied our Bayesian belief network model to the Grand River watershed in southern Ontario, Canada.

1.4 Thesis organization

This thesis is written as a monograph. Chapter 1 presents the problem statement, a scientific justification for researching the problem, and thesis objectives and hypotheses. Chapter 2 details the study area where the model is applied, including the sources of phosphorus and the governing authorities with influence on phosphorus management for load reduction to Lake Erie. Chapter 3 describes the Bayesian belief network model and its application to quantify the probability of TP and DRP loads from agricultural activities in the Grand River to Lake Erie, and the simulation of different BMP management strategies for achieving the 40% TP and DRP load reduction policy objective. Chapter 4 presents the scientific findings related to the quantification of TP and DRP loads from agriculture, the effectiveness of individual and combined BMPs, and the probability of achieving the policy objective of a 40% reduction in TP and DRP loads under different management scenarios and hypothesis outcomes. Chapter 5 discusses the scientific findings within the context of current and past literature studies and implications for phosphorus management. Chapter 6 provides a conclusion to the thesis with implications for Great Lakes phosphorus management and identifies opportunities of future research to fill the gaps not addressed in the current project.

Chapter 2: Test Area: The Grand River Watershed

2.1 Rationale for selecting the Grand River Watershed Test Area

The IJC identified agriculture not only as the source of re-eutrophication in Lake Erie but also a solution (IJC, 2014). Specifically, the Annex 4 Nutrient Objectives and Targets Task Team (2015) identifies the Grand River as a priority watershed for continued and enhanced management and monitoring of phosphorus loads to avoid proliferation of nuisance algae, primarily *Cladophora* sp. in the eastern basin's nearshore areas. In addition, the Grand River Conservation Authority (GRCA) is considered an agency with an abundance of relevant data available to support this thesis, relative to comparable Lake Erie watersheds. Applying the recommended 40% reduction in phosphorus load intended for western basin tributaries to the lower risk but data rich eastern basin is suitable to demonstrate the implementation of our approach to manage TP and DRP loads for achieving policy objectives. For these reasons, the Grand River watershed in southern Ontario, Canada was selected as a suitable test area for the thesis.

2.2 Characterization of the Grand River Watershed, Ontario

The Grand River watershed covers an area of 6,800 km^2 of southern Ontario (Figure 2.1) and flows from its northern headwaters in a cool temperate climate region, 535 m.a.s.l. near Orangeville, Ontario, to its southern outlet south of Brantford discharging into Lake Erie's eastern basin in a moderate temperature climate region at 173 m.a.s.l.

Seasonality in the Grand River watershed is characteristic of southern Ontario, with high precipitation and increasing temperature in the spring causing accumulated snow melt to runoff over thawing, impermeable soils that produce large flows with dispersed flooding. Temperatures peak in the summer months when precipitation is low and evapotranspiration is high, resulting in drought-like conditions and hydrologic flows confined to the low flow channel. With reduced water quantity flowing through the system, the water is vulnerable to increased nutrient concentrations. Autumn months also

have low precipitation but increased flows attributed to declining evapotranspiration and lower water withdrawal demands.
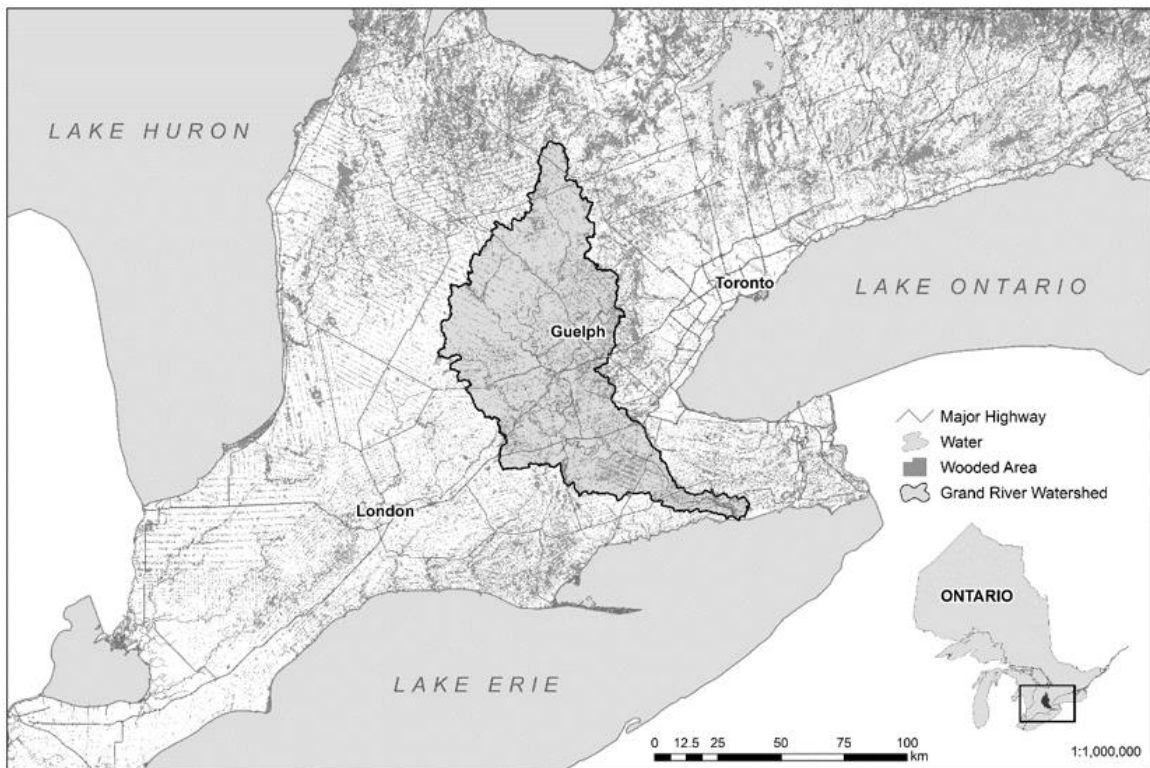
Figure 2.1: Grand River Watershed in Southern Ontario.

In the winter months, temperatures reach annual lows and precipitation falls as snow. The cold temperatures have many implications on Grand River watershed hydrology with lower flows and frozen soils. The frozen soils decrease soil porosity and infiltration capacity causing increased runoff and transport of nutrients from uplands to receiving surface water during winter rains expected to become more frequent with climate change (LSPRTT, 2008). Average monthly temperatures ranges from -9°C in January to 21°C in July. Temperature extremes have been reported as low as -35°C and as high as 40°C.

The Grand River watershed physiography is heavily influenced by the glacial retreat nearly 13,000 years ago. The quaternary geology is distributed into three regions that pose different implications for the transport of nutrients to receiving surface waters. The northern region is characterized by low relief, low permeability till plains. The middle

region hosts higher relief and permeability in its courser grained, sand and gravel moraines. The southern region experiences lower relief and permeability like the northern region with surface lacustrine clays. Two major tributaries, the Nith and Conestogo, drain much of the north-western contributing area and the Speed tributary drains much of the eastern contributing area with smaller tributaries draining what remains to the main stem of the Grand River (LSPRTT, 2008).

According to the Watershed Characterization Report (LSPRTT, 2008), a minimum of 30% vegetation cover is required to maintain the ecological functioning of a watershed. The Grand River watershed has 19% vegetation cover from natural forests, leaving it vulnerable to increased flows and nutrient export (GRCA, 2013). The vegetation cover and specifically forest cover continues to be threatened by urbanization, agriculture, invasive species and now climate change (LSPRTT, 2008). There are 38 upper and lower tier municipalities within the watershed where a total population of 821,000 reside. Of the total population, 73.5% are centralized in the urban municipalities of Brantford, Cambridge, Kitchener, Waterloo and Guelph, an area representing just 7% of the watershed. The remaining 26.5% of the population lives in smaller towns and rural areas. Projections into 2031 show significant population growth in major urban centers as well as rural areas like Wellington and Brant Counties. This trend is an expectation of the rising costs of living in Toronto and the lateral urban growth restrictions posed by the Green Belt Act (2005) that surrounds the metropolis of the Greater Toronto Area (Hemson Consulting Limited, 2005).

The most extensive land-use in the Grand River watershed is agriculture at 75% of the watershed area. Agricultural areas of the Grand River watershed are a significant source of phosphorus to Lake Erie's eastern basin and nearshore (Annex 4 Objectives and Targets Task Team, 2015; Maccoux et al. 2015). Agricultural activities include approximately 6,400 farms divided between livestock, crop, or combined operations. Most crop agriculture produces crops necessary to support livestock operations with feed. According to the Lake Erie Source Protection Region Technical Team (2008) (LSPRTT), crop agriculture is divided into 29.1% corn, 24.9% hay for forage and fodder, 20.7% soybeans, 19.8% grains and the remaining 5.5% to vegetables and specialty crops. The

2006 Census of Agriculture (Statistics Canada, 2006) reports that livestock is divided into approximately 290,000 head of cattle, 500,000 head of swine and 8,800,000 head of poultry. The 2006 Census of Agriculture is relatively dated, however in the context of the policy objective for a 40% reduction relative to 2008, 2006 is a reasonable source year.

Livestock is a significant source of nutrients from: (1) the manure that is either lost in runoff or applied to crop as a fertilizer; and (2) the application of mineral fertilizers to crops to support livestock feeding as well. In addition, the higher clay content and thus lower permeability in the agriculturally dominant northern and southern regions result in enhanced overland flow, that rapidly transports water and phosphorus to nearby surface water systems (LSPRTT, 2008).

2.3 Governance of phosphorus management in the Grand River Watershed

The management of phosphorus is a collective, yet disorganized, effort by different governing agencies whose jurisdictions extend beyond the topographic confinements of the watershed (Friedman et al. 2015). For phosphorus management in the Grand River watershed, the governing authorities range from local counties and municipalities, to provincial, federal and even bi-national agencies. The IJC is considered the over-arching bi-national governance authority for the Great Lakes basin responsible for the Great Lakes Water Quality Agreement and delegating responsibility to other authorities for its implementation. At the federal level, the most relevant governance agencies are, Agriculture and Agri-Food Canada (2015) who work with farmers and food producers to grow the industry and help farmers achieve their social and economic objectives. Environment and Climate Change Canada (2013a, 2013b) is responsible for research on environmental quality with initiatives directed toward agriculture, their land use and ecosystems to understand their impact on water quality and develop programs to manage these pressures with Acts like the Environment Protection Act 1999 to guide land management.

At the provincial level, relevant agencies include the Ontario Ministry of Agriculture, Food and Rural Affairs (2016) who are responsible for developing programs to advertise and educate farmers on the use of nutrient management practices as well as implementing Acts like the Nutrient Management Act 2002 to prevent nutrient effects and resulting impacts in surface waters. The Ontario Ministry of the Environment and Climate Change (2016) is responsible for developing policies, acts, and regulations through research and ensure compliance to protect the environment and its waters. They implement Acts like the Great Lakes Protection Act 2015 and the Clean Water Act 2006.

However, the Grand River Conservation Authority (GRCA) is the primary authority for watershed management of water quantity and quality under the Conservation Authorities Act (1990). Within the Grand River watershed, the 38 upper and lower tier municipalities have varying degrees of responsibility that influence agricultural practices and water quality in their jurisdictions (LSPRTT, 2008). Each of these authorities impose different policies with regulatory measures, offer incentives to encourage adoption of voluntary measures, as well as provide channels to communicate and educate farmers on the implications of their operation for water quality.

In addition to governing authorities, other organizations influence agricultural activities and farmer decisions including organizations like the Ontario Federation of Agriculture (2016) which is a farmer run, volunteer organization (among others) that acts as the voice for farmers and their families and provides an information resource on relevant nutrient regulations and management practices.

Chapter 3: Methods

3.1 Best management practices (BMPs)

The BMPs considered in this thesis were selected based on available data and their suitability for application in the Grand River watershed. Due to limited data availability, some BMPs were combined into one based on their similar design and function.

Precision feeding (PF) customizes livestock diets to the individual animal's nutritional requirements (OMAFRA, 2011). Conventional feeding diets are implemented to maximize livestock quality for market sale and is often the same diet for the entire herd as opposed to the individual animal, however, this conventional method often provides more phosphorus than required which is then excreted as excess in manure (Pomar et al. 2011). By tailoring diets to individual livestock needs, the amount of phosphorus excreted in manure can be reduced on livestock operations and crop operations where it is applied.

Nutrient application management (NAM) implements one or all the following: applying phosphorus in the right form, at the right rate to meet crop requirements, at the right timing to avoid runoff from precipitation events, and with the right method of application to reduce phosphorus availability for runoff (OMAFRA, 2011). Implementing these practices in combination is called the 4Rs of nutrient stewardship; right source, right rate, right time and right method (Mikkelsen, 2011).

The BMP of reduced tillage (RT) combined both no tillage and conservation or "mulch" tillage. In no-till operations, the soil remains undisturbed prior to seeding, allowing the soil structure to develop and maintain crop residue on the surface to increase surface roughness and decrease overland flow. Conservation tillage or "mulch" tillage only partially tills the surface, incorporating crop residue into the soil leaving approximately 30% on the surface. Alternatively, conservation tillage is conventionally tilled once every three years (OMAFRA, 2011). RT allows soils to develop structure reducing their vulnerability to erosion and transportation of phosphorus that is sorbed to sediments. By comparison, conventional tillage systems disturb soil structure prior to seeding and incorporate all crop residue in situ leaving the soils vulnerable to erosion and export of PP

in runoff (Doran, 1980). The context and implications for grouping similar functioning BMPs is discussed in section 3.3.2 and in Table C.1.

Crop rotation (CR) involves seeding the soil with a different crop family in alternating years to increase nutrient uptake, and reduce soil degradation and vulnerability to erosion and transport of PP (OMAFRA, 2011). No relevant data was found for TP and therefore we defaulted to PP data based on it being traditionally the largest fraction of TP (Baker et al. 2014).

Contour strip cropping (CSC) involves alternating bands of crop species (row crops and forage or cereals) planted parallel to field contours to reduce vulnerability of soil erosion and transport of phosphorus in runoff (Ontario Ministry of Agriculture, Food and Rural Affairs, 2011).

Vegetative filter strips (VFS) require land that is taken out of production to allow permanent vegetative cover to develop along hydrological flow paths or surround surface water conduits (OMAFRA, 2011). VFSs increase surface roughness and decrease overland flow of runoff passing through, allowing runoff and nutrients in runoff to infiltrate the soil and be retained (Zhang et al. 2010).

Forest filter strips (FFS) are functionally identical to VFS, but with trees rather than grasses or shrubs. The root systems of trees further increase soil infiltration relative to VFSs and their far-reaching roots have a greater ability to uptake nutrients from the soil thereby reducing their accumulation in the soil (Kleinman et al. 2009).

Wetland restoration and construction (WR) were combined into one BMP. Wetlands can be restored or constructed in topographic depressions on farm operations to purify runoff waters through phosphorus sorption in wetland sediments or through biological uptake in plants or microorganisms (OMAFRA, 2011).

Tile drainage is implemented considerably in agricultural areas of the Grand River watershed, exceeding 30% by area in a few sub-watersheds (Grand River Watershed Management Plan, 2013) even though it is controversial in terms of its benefits to reduce phosphorus runoff (King et al. 2015; Kleinman et al. 2015). Tile drainage, is an economic

and crop production BMP advocated for additional soil and phosphorus reduction benefits, however it has been criticized for facilitating DRP transport from farm operations and may be one of the factors contributing to the recent re-eutrophication of Lake Erie (King et al. 2015; Scavia et al. 2014). Unfortunately, despite relatively considerable research, a lack of 'relevant' BMP effectiveness coefficient data as well as relevant experts being uncomfortable providing an opinion due to considerable uncertainty, tile drainage had to be eliminated from the analyses.

3.2 Bayesian Belief Networks (BBNs)

Bayesian belief networks (BBN) are conditional probability, cause-and-effect models with output distributions that communicate model and scenario uncertainty to decision makers. They consist of an interacting network of variables called nodes and each node represents a different ecosystem predictor and response variable connected by arrows that characterize their relationship to other nodes in the network like an influence diagram. Input nodes to the BBN network (nodes with no parents) have states whose probability of being observed are quantified using empirical data or expert opinion where data are lacking. Intermediate nodes have conditional probability distributions, where the probability of observing each state is conditional on the probability of each state of their parent nodes (Landuyt et al. 2013). Empirical equations are used to quantify the probabilistic relationship of each state in these child nodes based on the probability of each state in their parent nodes. If empirical equations do not exist to characterize the relationship, expert opinion can be consulted. Finally, output nodes are joint probability distributions representing the different possible outcomes based on the intermediate and input nodes. The probability of each state in each node is communicated as a percent and a bar graph (belief bar), with all states in the node and their belief bars combining to form a probability distribution (Marcot et al. 2006).

The benefits of BBNs include their ability to incorporate expert opinion when empirical data are lacking (Landuyt et al. 2013; Nash and Hannah, 2011). BBNs can be easily updated as science develops or environmental conditions change, enhancing its suitability for adaptive management (Landuyt et al. 2013; Nash and Hannah, 2011; Quinn et al.

2013). Furthermore, BBNs enable transparency that leads to better communication between scientists and ecosystem managers (Allen et al. 2012; McCann et al. 2006; McDowell et al. 2009; Quinn et al. 2013). Often decision makers rely on a single deterministic value and do not consider the uncertainty with other possible outcomes, in BBNs, uncertainty is communicated to decision makers by providing a probability distribution of possible outcomes (Barton et al. 2008; McDowell et al. 2009; Rigosi et al. 2015). Marcot et al. (2006) advised against BBN models that are too large with too many intermediate nodes that separate input nodes from the model output node. The influence of nodes higher up in the network becomes considerably supressed relative to nodes closer to the model output.

BBNs have been previously applied in ecosystem management (Landuyt et al. 2013; McCann et al. 2007). Of particular interest for this thesis is the demonstrated ability of BBNs to predict the probable influence of different agricultural BMPs on phosphorus loads (Barton et al. 2008; Lucci et al. 2014; McVittie et al. 2015; Nash and Hannah 2011), as well as predicting the risk of failure to achieve policy objectives (Gudimov et al. 2012; Stow et al. 2014). To our knowledge, BBNs have not integrated both analysis objectives; predicting the probability of phosphorus load reduction by BMPs *and* their probable influence as a management system on achieving policy objectives, such as the 40% reduction in 2008 TP and DRP loads to Lake Erie. We used BBNs to quantify the probability of achieving the load reduction policy objective from Grand River *agricultural areas only*, given the initial 2008 TP and DRP load from agricultural activities, the probability distributions of BMP effectiveness, and different BMP management strategies and rates of increased adoption relative to 2008.

3.2.1 Bayesian probability in Bayesian belief networks

The classical, or frequentist approach to statistics interprets probabilities as the relative frequency of outcomes from a long series of *identical* experiments or trials (VanderPlas, 2014). When estimating the probability of phosphorus load reduction by a BMP or a management system of BMPs in the Grand River watershed, it is impossible to conduct a long series of *identical* management system experiments and therefore the classical approach to statistics is not suitable to satisfy the objectives of this thesis. Instead

Bayesian statistics interprets probabilities as our own, subjective, beliefs about a parameter of interest with the uncertainty of our belief communicated with a probability distribution (VanderPlas, 2014). We can update our beliefs, called 'belief updating' using Bayes theorem, the mathematical theory underlying the operation of BBNs (Parent and Rivot, 2012) in equation (1):

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

Equation 1

In Bayes theorem, the parameter of interest to be estimated is the posterior distribution, denoted P(A|B). The posterior distribution is a conditional probability statement that estimates the true probability distribution of A, given or *conditional on* some new data we observed; B (VanderPlas, 2014). This could be the estimated true probability distribution for watershed phosphorus load reduction by a BMP, given some new observed data. The initial, subjective belief about the posterior distribution, before *new* collected data is observed, is represented by P(A), known as the prior distribution in Bayes theorem and could be based on previous data (VanderPlas, 2014). Bayes theorem is used for belief updating of the prior distribution to incorporate new data represented by P(B|A). In this way, Bayes theorem is subjective, the cause for so much criticism by classical frequentists who suggest statistics should be unbiased (VanderPlas, 2014). Therefore, the prior distribution could represent the current belief about watershed phosphorus load reduction by a BMP, and the posterior distribution is the updated belief that incorporates the new data. The variable P(B) in Bayes theorem is a normalization constant that ensures the posterior distribution is estimated between 0-1 (VanderPlas, 2014).

In BBN models, the probability distributions for input nodes are estimated from empirical data or expert opinion and represent prior distributions. The probability distribution in intermediate nodes are conditional on the distribution of their parent, input nodes that can be updated by changing the distribution of one or multiple parent nodes with new *findings* or data. In this way, the posterior distribution, P(A|B), in the intermediate child node is an updated belief, conditional on the prior distribution, P(A), in the unchanged parent node(s), and the new data distribution, P(B|A) in the updated parent node(s). Belief

updating in BBNs is why scientists have advocated its use adaptive management (Marcot et al. 2006).

3.3 Building the BBN model structure for phosphorus management

Building and quantifying the BBN model required making assumptions (Table C.1) that differ from true environmental and human behaviour, and should be considered when interpreting the results of this thesis. The structure of the BBN model was inspired by the International Organization for Standardization (ISO) 31010:2009 Bowtie Risk Analysis Tool (BRAT) (Figure 3.1), which diagrammatically analyzes the causal pathway of a risk event (the effect), from its pressures leading to the risk event, and the impacts that could result from the risk event, while incorporating the influence of intervening preventative and mitigation management measures (Creed et al. 2016). Drivers are the social, cultural,
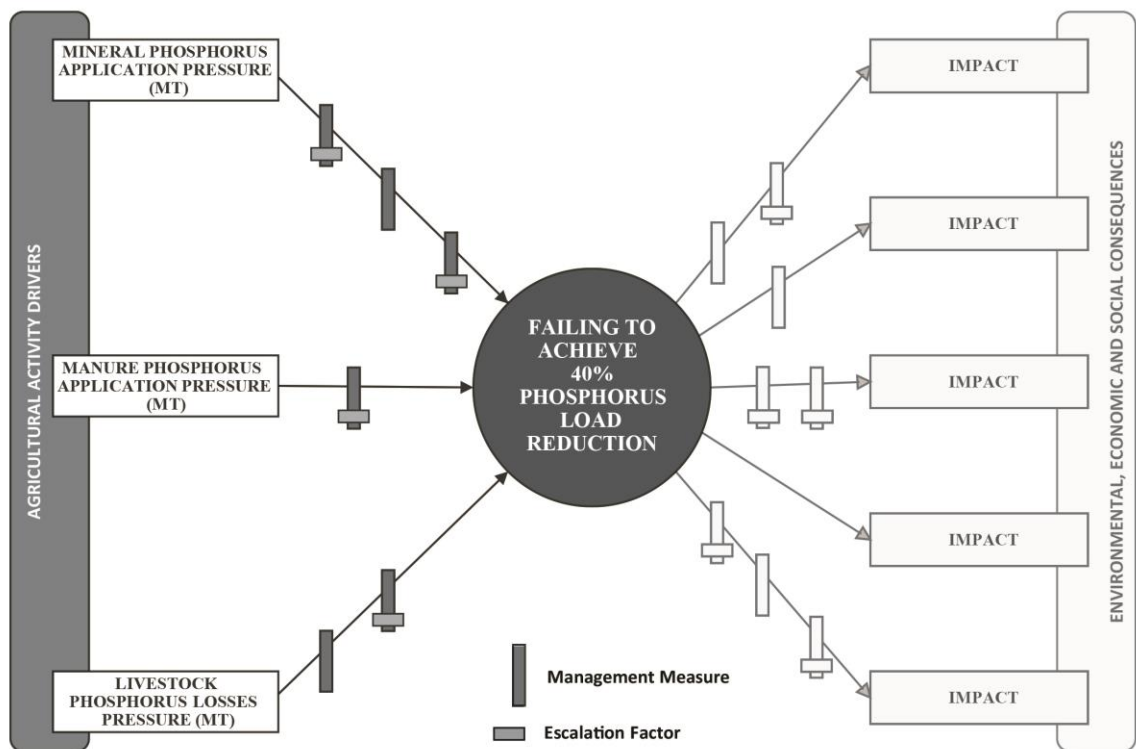
Figure 3.1: ISO 31010:2009 Bowtie Risk Analysis Tool evaluates the performance of a management system.

economic, and political influences that drive human activities like agricultural operations. Pressures result from human activities that introduce physical, chemical (like phosphorus), or biological agents into the ecosystem that could cause undesirable effects. Effects are the risk event that result from the residual pressures after the implemented preventive management measures. Impacts describe a reduction in the quality and/or quantity of ecosystem services that might occur if the effect is not mitigated. Consequences are the economic, environmental and social implications that result from the impacts. The management system includes prevention measures that act to reduce the likelihood of pressures causing the effect, and mitigation measures that reduce the severity of impacts (Creed et al. 2016). Escalation factors are outside influences that undermine the effectiveness of prevention or mitigation measures, but their consideration was beyond the scope of this thesis.

For this thesis, the BBN model structure was based on the preventative, left side of the BRAT only, with the risk event being the failure to achieve the 40% reduction in 2008 TP and DRP loads to Lake Erie objective (Figure 3.1). Norsys Netica 5.24 (Norsys Software Corp. 2016) for Bayes Nets software was used to build and operate the model. The BBN model structure incorporated four main components (Figure 3.2). First, (1) input nodes for 2008 TP and DRP load from agricultural activity pressures, (2) output risk event (effect) nodes that represented the final residual TP and DRP load discharged from the Grand River watershed, (3) the BMP sub-models aligned in sequence to collectively reduce the 2008 agricultural activity TP and DRP input loads and, (4) residual TP and DRP load nodes that tracked the amount of TP and DRP load as it was influenced by each BMP sub-model (Figure 3.2). Loads were indicated as constants in MT, adoption as probability distribution in proportions from 0−1 (0−100% adoption) and effectiveness and performance as probability distributions in proportions (representing percent reduction).

Three agricultural activities that contribute TP and DRP loads were identified for input pressure nodes: (1) cropland mineral phosphorus application; (2) cropland manure phosphorus application; and (3) livestock manure phosphorus losses, each agricultural activity pressure had a separate input node for TP and DRP.

In the BMP sub-models, BMP *effectiveness* referred to the 'local' TP and DRP load reductions by a BMP on a single farm operation and assumed 100% of the operation's hydrological flow path is treated by the BMP (Table C.1). BMP *adoption* referred to the percent of the hydrological flow path in agricultural areas of the watershed that is treated by the BMP. BMP *performance* referred to the TP and DRP load reduction from all
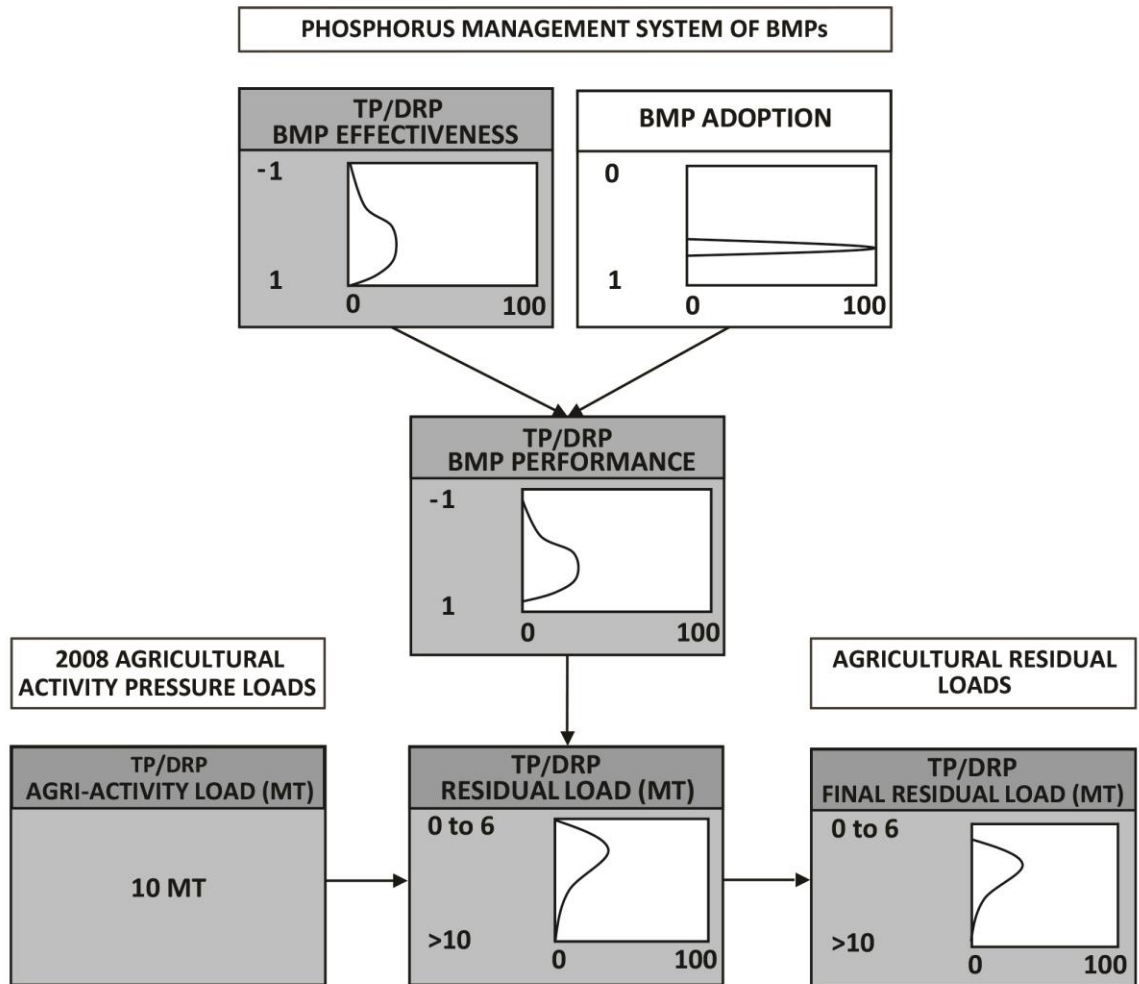
Figure 3.2: BBN model structure for phosphorus management based on the left side of the Bowtie Risk Analysis Tool.

agricultural areas in the watershed attributed to a BMP and was conditional on the BMP's effectiveness, and adoption (Figure 3.2).

BMP sub-models were aligned in sequence for each agricultural activity based on their suitability to manage their phosphorus load, which resulted in seven BMPs as a management system for cropland mineral phosphorus application, eight for cropland manure phosphorus application, and four for livestock manure phosphorus losses. The

order of BMPs in the agricultural activity pressure sequences was an important consideration as BBNs represent the causal pathways of influence (Marcot et al. 2006). The order of BMP sub-models was sequenced in relation to their position along the hydrological flow path between phosphorus application and the receiving surface water. BMPs that influenced the amount and availability of phosphorus were positioned first, their residual loads were then influenced by soil and crop management BMPs positioned next, and finally phosphorus trapping and retention BMPs at the end of the sequence before the final residual load is exported from farm operations/agricultural areas (Dodd and Sharpley, 2015). *Residual* load nodes referred to the resulting watershed TP or DRP load following the implementation of a BMP and were accumulated at each step along the sequence of BMP sub-models. The *final* TP and DRP load (effect node) was the summation of residual loads from the three agricultural activities following the implementation of their specific system of BMP management sequence (Figure 3.2).

3.3.1 Estimating phosphorus loads from agricultural activities

The 2008 TP load to the Grand River watershed was 447 MT (Maccoux et al. 2016), with 40.01 MT contributed by municipal areas and industry, leaving 406.99 MT remaining assumed to have been contributed by agricultural activities (LSPRTT, 2008). The 406.99 MT TP load from agricultural activity was divided into contributions from cropland mineral phosphorus application, cropland manure phosphorus application and livestock manure phosphorus losses. The BBN model assumed the area of agricultural land receiving phosphorus application was representative of the load of phosphorus in discharge from Grand River agricultural areas (Table C.1). The 2006 Census of Agriculture for the Grand River watershed reported that 4,353.14 km^2 received mineral fertilizer application and 1,509.84 km^2 received manure application (Statistics Canada, 2006). The resulting total area of phosphorus application was greater than the area of agricultural land use reported in the Census, which we attributed to repeated application of phosphorus to the same farm operations in a year.

A proportion of the manure phosphorus produced on a livestock operation can be collected (i.e., manure recoverability) and used for application elsewhere (Kellogg et al.

2000). Therefore, the BBN model assumed the proportion of manure phosphorus that was *not collected* (1-recoverability) was the proportion that was exported from operations as livestock phosphorus losses (Table C.1). The average proportion of manure phosphorus in the Grand River watershed that is recoverable and available for application is 0.58, as determined by a weighted average calculated from livestock species-specific recoverability coefficients for Ontario (International Crop Nutrient Institute, 2013) that we applied to livestock counts in the 2006 Census of Agriculture for the Grand River watershed. Therefore, if the 0.58 fraction represented 1,509.84 km^2, then the 0.42 fraction represented 1,093.33 km^2. A total representative area of 6,956.13 km^2 included the cropland mineral phosphorus application (4,353.14 km^2), the cropland manure phosphorus application (1,509.84 km^2), and the livestock manure phosphorus losses (1,093.33 km^2). The total representative area summed greater than the area of the watershed, this reflected the census reporting fertilizer and manure application multiple times a year to the same area by farmers. Each representative area was converted to their proportion of the total area and used to divide the total 406.99MT TP load among the three agricultural activities.

The Maccoux et al. (2015) study reported dissolved reactive phosphorus (DRP) loads for 2009−2013. The BBN model assumed the annual average proportion of TP load was the DRP load, was representative of the proportion of DRP load for 2008 (Table C.1) The average proportion of TP that was DRP over this period was 0.27 with a standard deviation of 0.04. The 2008 DRP loads in MT was therefore assumed to be 0.27 of the calculated 2008 TP loads for each of the three agricultural activity pressures.

3.3.2 Estimating probability distributions for BMP Effectiveness

BMP effectiveness coefficients for TP and DRP were compiled into a database from a review of the scientific literature. The lack of BMP effectiveness data for the Grand River watershed and even the Great Lakes basin meant data had to be compiled from all available studies including those from the United States, Canada (Ontario and Quebec only), and internationally. This assumed that the compiled BMP effectiveness coefficients represented load reductions by BMPs in the Grand River watershed (Table C.1).

Effectiveness data for mineral and manure phosphorus reduction by BMPs was too limited to generate their separate distributions, thus their effectiveness data was combined and assumed that BMPs treated manure and mineral phosphorus the same (Table C.1). Some BMPs still had limited effectiveness data (n < 5). It was assumed these BMPs could be grouped and analyzed together if, and only if, they performed similar functions to reduce phosphorus load (Table C.1). This resulted in two grouped BMPs described previously in section 3.1 for NAM and RT. Also, TP effectiveness data was not found for CR, and therefore we defaulted to PP data as it represented the dominant fraction of TP from crop operations (Table C.1) (Coelho et al. 2012; Panuska and Karthikeyan, 2010; Richards et al. 2002). Finally, the number of effectiveness coefficients for most BMPs was < 30 and therefore the entire range of potential effectiveness may not be represented in the compiled data and should be considered when interpreting results. The maximum and minimum effectiveness coefficient for percent load reduction, established the range of BMP effectiveness. BMP effectiveness nodes were discretized into five equal bins for reductions ≥ 0 and five equal bins for reductions < 0 for a total of five bins for BMPs with no probability of increased loads, and ten bins otherwise. As seen in Figure 3.2 (or Figures A.1−8), percent reductions were populated into effectiveness nodes as proportions for computational purposes, therefore 0−100% was 0−1; however, we used percent reduction when describing effectiveness in this thesis for better communication and knowledge transfer.

The distribution for effectiveness of most BMPs was not evident through visual inspection of the data and therefore it was assumed to follow a normal distribution (Table C.1). The distribution of effectiveness coefficients for all BMPs were tested for normality using the Shapiro-Wilk test (Figures A.1-8) and verified using a quantile-quantile plot in Sigma Plot (Systat Software Inc., 2016). For BMPs that passed the normality test (generally those with n < 30), the probability distributions were generated with the following equation:

$$P\ (Effectiveness) = NormalDist\ (Effectiveness, Mean, Standard\ Deviation)$$

Equation 2

which describes the probability of observing any BMP effectiveness state in the node is equal to the normal distribution of reported BMP effectiveness. For BMPs that failed the normality test (generally those with n ≥ 30), the probability distributions were generated using the "Learn from Cases" function in the Netica software, with the resulting probability distribution that reflected the true distribution of the data.

3.3.3 Estimating probability distributions for BMP adoption

It was assumed that a 100% adoption indicated that 100% of the hydrological flow path (surface and subsurface conduits that transport water) in agricultural areas was treated by farm operations that implemented a specific BMP and hence 100% of the phosphorus load was also treated (Table C.1). The adoption nodes in the model ranged from 0 to 100% adoption, discretized into five equal bins. As seen in Figure 3.2, percent adoption was populated as proportions for computational purposes, therefore 0−100% is 0−1. The 2008 TP and DRP loads from the watershed outlet which were used as input into the model, already reflected BMP adoption in that year. Therefore, the 0−100% adoption to BMPs in the adoption node referred only to the remaining area of hydrological flow paths not treated by the BMPs in 2008. For this reason, a non-informative, flat distribution for adoption nodes was generated initially, however, when belief updating was implemented to simulate further adoption of BMPs relative to 2008 (described later in section 3.5), distributions were configured to reflect the simulation scenario.

Adoption nodes that ranged from 0−100% assumed that BMPs have the potential to treat 0−100% of the hydrological flow path transporting phosphorus load. While this assumption is true for many BMPs, the assumption does not hold true for WR. The adoption of WR as a BMP is constrained by site-specific attributes that are suitable for wetlands to be restored or constructed. Therefore, the total possible proportion of hydrological flow paths in agricultural areas in the Grand River watershed that could be treated by WR was calculated. It was assumed that tile drainage was the main mechanism of wetland loss. A map of historical wetlands (from 1800) with current wetlands removed, was intersected with a map of farm operations that implemented tile drainage to generate a map of restorable wetlands. A map of sub-watersheds draining into each of the

restorable wetlands was generated to calculate the proportion of agricultural land that could be treated by WR. The proportion of agricultural land in the Grand River watershed was 0.48 which constituted the upper limit of its adoption in the watershed's hydrological flow path in agricultural areas (note that WR effectiveness distributions included data for wetland construction, however this thesis only considered areas were wetlands could be *restored*).

3.3.4 Calculating performance distributions for BMPs

Performance nodes had load reduction ranges and intervals that matched their effectiveness nodes in the BMP sub-model. The probability distribution for performance was generated within Netica using the equation:

$$Performance\ (Effectiveness,\ Adoption) = Effectiveness * Adoption$$

Equation 3

If 100% adoption was observed in the watershed, the BBN model assumed the performance distribution equaled the effectiveness distribution (Table C.1). Otherwise, the performance distribution was configured by the adoption in this function to reflect a 0% probability of reductions to the fraction of TP and DRP load contributed by the un-treated hydrological flow path. This function neglected the potential for BMP implementation to treat source areas of phosphorus loads that contributed phosphorus load disproportionately compared to other agricultural areas (Doody et al. 2012; Strauss et al. 2007). In Figures A.1−8, the scenario simulated indicated a 100% probability of further BMP adoption in the watershed between 40 and 59% relative to 2008, and the resulting distribution for performance was considerably concentrated below 60% load reduction with significantly smaller probabilities attributed to the remaining intervals. The smaller probabilities assumed the small *chance* for a BMP to treat ≥ 60% of the phosphorus load with randomly distributed BMP adoption treating only 40−59% of the hydrological flow path (Table C.1). However, the probability of reductions ≥ 60% could increase if BMP implementation was spatially targeted to phosphorus source areas.

3.3.5 Calculating residuals of phosphorus load after BMP implementation

The performance nodes for all BMP sub-models flowed into residual load nodes that indicated the resulting TP and DRP loads following the reductions of its parent BMP and the BMPs that preceded it. The probability distribution for the residual load following treatment by the first BMP was generated within Netica using the equation:

$$ResidualLoad1\ (InitialLoad,\ Performance) = (1-Performance) * InitialLoad$$

Equation 4

The probability distributions for the residual load following treatment by the remaining BMPs were generated in Netica with the equation:

$$ResidualLoadN\ (ResidualLoadN-1,\ Performance) = (1-Performance) *$$
$$ResidualLoadN-1$$

Equation 5

3.3.6 Calculating probability distributions for discharged phosphorus loads

After the BMP management sequence for each agricultural activity pressure was implemented, their final residual loads were summed to generate the total residual load for TP and for DRP from all three agricultural activities within Netica using the equation:

$$AgriculturalPhosphorusResidualLoad =$$
$$MineralPhosphorusApplicationResidualLoad +$$
$$ManurePhosphorusApplicationResidualLoad +$$
$$LivestockManurePhosphorusLossesResidualLoad$$

Equation 6

These final probability distributions for total discharged residual loads were discretized into four states including 40−100% reduced from the total 2008 TP and DRP agricultural load (policy objective), 20−39%, 0−19%, and finally < 0% reduction, or increased loads relative to the 2008 TP and DRP agriculture load.

3.4 Sensitivity analysis of the phosphorus management system

Sensitivity analysis in Netica uses variance reduction (VR), a measure that characterizes how sensitive the results of a *target node* are to all other nodes in the network. A VR

value of zero indicates the node has no influence on the target node or it is not connected to the target node. Increasing values away from 0 indicate a greater influence of a node on the results observed at the target node (Marcot et al. 2006). The objective of the sensitivity analysis was to characterize the relative influence of each BMP in the BBN on TP and DRP residual load and confirm the model's behaviour was reasonable with scientific evidence found in the literature. The sensitivity analysis was confined to the manure phosphorus application sequence, as this sequence had all eight BMPs in its management system. The influence of each BMP on the sequence's final residual TP and DRP loads was quantified and compared to observations found in other modeling and field studies.

3.5 Optimization of the phosphorus management system

Four BMP management strategies were simulated and analyzed for their ability to achieve the policy objective, including: (1) increased adoption of all BMPs simultaneously; (2) increased adoption of the most commonly adopted or promoted BMPs simultaneously (based on the 2006 Census of Agriculture and scientific literature); (3) increased adoption of BMPs effective for TP reduction; and (4) increased adoption of BMPs effective for DRP reduction. It was hypothesized that the only scenario suitable for meeting the objective with the highest probability for both TP and DRP was prioritizing DRP effective BMPs. A corollary to this hypothesis was that targeting the adoption of TP effective BMPs is the most suitable strategy for achieving the TP objective but increases the risk of elevated DRP loads.

To simulate the further adoption of all BMPs, the flat distributions in the BMP adoption nodes were updated to reflect a 100% probability of 0−19% further adoption relative to 2008, then 20−39% and so on. It is unrealistic to assume that all BMPs in a management system will be implemented at the same rate relative to 2008, however more complicated adoption scenarios were beyond the scope of this thesis, instead demonstrating the use of BBNs for management system analysis was a primary objective. Figures A.1−8 show BMP simulations for 40−59% adoption with the resulting posterior distribution calculated in the performance nodes conditional on the new adoption data and the prior

distribution for BMP effectiveness. To simulate the increased adoption of the most common BMPs, the BBN model was configured to remove BMP sub-models so that only NAM, RT, CR and VFS remained in the network. To simulate the increased adoption of TP effective BMPs, the BBN model was configured to remove all BMP sub-models with potential to increase TP loads, including RT and WR. Finally, to simulate the increased adoption of DRP effective BMPs, the BBN model was configured to remove all BMP sub-models with the potential to increase DRP loads, including PF, NAM, RT, VFS and WR.

Chapter 4: Results

4.1 Performance of the phosphorus management system

4.1.1 Phosphorus loads

The 2008 TP load for the Grand River was 447 MT, of which 406.99 MT (91%) was contributed by agricultural areas (Table 4.1). 254.69 MT of TP and 67.94 MT of DRP was contributed by cropland mineral phosphorus application, 88.34 MT of TP load and 23.56 MT for DRP load contributed by cropland manure phosphorus application, and 63.97 MT for TP and 17.06 MT for DRP load contributed by livestock phosphorus losses.

4.1.2 BMP effectiveness

The effectiveness of a specific BMP, that represented the probability of load reductions on a single farm operation, varied between TP and DRP (Table 4.2). Most BMPs had a 100% probability of reducing TP, except for RT with a 95.6% probability of reducing TP loads and WR that had a 76.5% probability of reducing TP loads. Few BMPs had a 100% probability of reducing DRP loads. CSC, CR and FFS had a 100% probability of reducing DRP loads. The remaining five BMPs identified the potential to reduce or increase DRP loads (Table 4.2). The probability distributions for effectiveness of each BMP for TP and DRP are presented in Appendix A (Figures A.1−8) and their summary statistics are presented in Appendix B (Tables B.18).

TP loads: Probability distributions for effectiveness were used to determine the probability of load reductions ≥80%, ≥40%, and increased loads. The most effective BMPs for TP reduction were CR (for PP, see Section 3.3.3), VFS and RT with a 100%, 82.8% and 66.1% probability of achieving ≥ 40% reduction in TP loads, respectively. VFS and RT had the highest probability of achieving ≥ 80% reduction in TP loads with a probability of 18.1% and 17.1%. In comparison, CR had a 0% probability of achieving ≥ 80% reduction in TP loads. Moderately effective BMPs for TP reduction were PF and WR with a 29.4% and 26.5% probability of achieving ≥ 40% load reduction respectively.

FF and WR, together with CR, had a 0% probability of achieving ≥ 80% TP load reduction. Some BMPs showed potential to increase TP loads; WR had a 23.5% probability and RT had a 4.3% probability of increasing loads. WR and RT had the potential to increase TP loads by as much as 130% and 20% respectively (Table 4.3).

Table 4.1: Estimated phosphorus loads for mineral phosphorus application, manure phosphorus application and livestock phosphorus losses. [Based on data reported in Maccoux et al. (2015), which was modified using data from the Census of Agriculture (2006) together with manure P recoverability coefficients from International Plant Nutrient Institute (2013)].

Pressures (2008)	TP (MT)	DRP (MT)
Grand River Agriculture	406.99	109.56
Mineral Phosphorus Application	254.69	67.94
Manure Phosphorus Application	88.34	23.56
Livestock Phosphorus Losses	63.97	17.06

DRP loads: The most effective BMPs for DRP reduction were FFS, CR and CSC with an 83.7%, 73.8% and 69.1% probability of achieving ≥ 40% reduction in TP loads, respectively. This was similar to the three most effective BMPs for TP load reduction. FFS and CSC also had the highest probability of achieving ≥ 80% reduction in DRP loads, with a probability of 19.8% and 10.3%, respectively. In comparison, CR had a 0% probability of achieving ≥ 80% reduction in DRP loads. Moderately effective BMPs for DRP reduction were RT, PF and WR BMPs with a 4.2%, 23.5% and 31.4% probability of achieving ≥40% reduction, respectively. RT and PF both had a 0% probability of achieving ≥ 80% DRP load reduction, whereas the remaining BMPs varied between 5.9 and 19.8%. BMPs whose treatment increased the risk of DRP load were RT, WR, NAM, VFS and PF, with a probability of increasing DRP loads of 89.4%, 31.3%, 26.2%, 18.3% and 5.6%, respectively. RT, VFSs and WR showed potential to increase DRP loads by as much as 500%, 250% and 160% (Table 4.3).

TP and DRP Trade-offs: BMPs that were most consistent when comparing TP to DRP effectiveness were PF, CSC, FFS and WR. The only BMP that showed a "significant" trade-off when comparing TP to DRP effectiveness was RT, with the probability distributions for TP load reduction being the inverse for DRP load reduction, indicating as

Table 4.2: The probability that TP and DRP load is reduced by each BMP and the distribution of percent TP and DRP load reductions in 25% increment percentiles compiled from the scientific literature. Note that these results for effectiveness assumed 100% adoption of the BMP and comprises the information used to populate the effectiveness nodes of the BBN model.

	Best Management Practices	Probability of Load Reduction	Effectiveness Distribution (Percentiles)				
			100	75	50	25	0
TP	Precision Feeding	100	70	41	22	14	9
	Nutrient App. Mgmt.	100	91	49	39	35	14
	Reduced Tillage	95.6	95	82	67	50	-22
	Crop Rotation*	100	70	69	68	64	60
	Contour Strip Cropping	100	93	59	39	31	8
	Vegetative Filter Strips	100	99	87	70	47	10
	Forest Filter Strips	100	93	72	46	7	2
	Wetland Restoration	76.5	98	42	23	6	-127
DRP	Precision Feeding	92.6	68	29	18	13	-6
	Nutrient App. Mgmt.	73.7	94	53	22	1	-66
	Reduced Tillage	10.5	69	-17	-37	-410	-500
	Crop Rotation*	100	75	54	53	35	30
	Contour Strip Cropping	100	93	45	38	30	20
	Vegetative Filter Strips	81.7	97	71	55	28	-258
	Forest Filter Strips	100	99	85	64	42	28
	Wetland Restoration	68.7	90	42	28	-2	-156

TP loads decreased, the DRP loads increased (Figure A.3). Other BMPs, including VFS, WR and NAM, showed a trade-off comparing TP and DRP effectiveness but the trend was less pronounced with lower probabilities of increased DRP load compared to RT (Figure A2, A6 and A8).

Management Uncertainty: The magnitude of uncertainty in BMP effectiveness was reflected in the range and shape of the effectiveness distributions. With respect to the range of effectiveness, CR and FFS had the smallest range of TP and DRP effectiveness and therefore the greatest consistency in their effects on phosphorus loads; however, the number of data entries that generated their probability distributions was small ($4 > n < 22$) introducing uncertainty due to the lack of data. In contrast, RT, VFS, WR and NAM had a larger range of DRP effectiveness introducing uncertainty from the variability of possible

management outcomes. With respect to the shape of the TP effectiveness distributions, PF, NAM, CR, VFS and WR had peaked distributions thereby reducing uncertainty, but RT, CSC and FFS had flatter distributions, with WR having two peaks indicating greater uncertainty with management outcomes (Figures A.1−8).

Table 4.3: Summary of BMP *effectiveness at the scale of a farm operation* with the probability of achieving $< 0\%$, $> 40\%$, and $> 80\%$ phosphorus load reductions by BMPs.

Best Management Practice	≥ 80% Reduction		≥ 40% Reduction		Increased Load	
	TP	DRP	TP	DRP	TP	DRP
Precision Feeding	0.0	0.0	29.0	23.5	0.0	5.6
Nutrient App. Mgmt.	7.6	6.3	63.0	35.0	0.0	26.2
Reduced Tillage	17.1	0.0	66.1	4.2	4.3	89.4
Crop Rotation*	0*	0.0	100*	73.8	0*	0.0
Contour Strip Cropping	6.6	10.3	57.7	69.1	0.0	0.0
Vegetative Filter Strips	18.1	7.7	82.8	63.4	0.0	18.3
Forest Filter Strips	11.4	19.8	57.3	83.7	0.0	0.0
Wetland Restoration	11.8	5.9	26.5	31.4	23.5	31.3

4.1.3 BMP adoption

For the Grand River watershed, BMP adoption data were not consistently available. Farmer adoption rates for BMPs were: 49% for RT, 77% for CR, 12% for CSC and 26% for VFS. Farmer adoption rates for PF, NAM, FFS and WL were not available. These adoption rates were not used in the model as the effect of BMP adoption in 2008 was already accounted for in the 2008 TP and DRP loads discharged from the Grand River watershed and used as input to the model. However, this adoption data was used to inform the relative adoption of BMPs in the Grand River watershed to generate the most common BMPs strategy and could be used to guide adoption of BMPs post 2008.

4.1.4 Sensitivity analysis and most influential BMPs

The sensitivity analysis indicated that WR (VR=11.15−13.00) had the greatest influence on TP load reduction (Table 4.4). After WR, the next most influential BMPs were VFS (VR=3.02−3.45) and FFS (VR=2.11−3.02). The sensitivity analysis showed a general trend of higher VR values lower down the BMP sequence, indicating a greater influence

of BMPs closer to the residual load target node. One exception is RT (VR=1.11) that had a greater influence on TP residual load than CSC (VR=0.76−1.11) despite RT being positioned higher in the network than CSC (Table 4.4).

The sensitivity analysis indicated that RT (VR=635.10−815.00) had the greatest influence on DRP load reduction. The VR values for RT were much higher than the next most influential BMPs, which were VFS (VR=327.20−433.50) and NAM (VR=145.00−215.00).

Table 4.4: Sensitivity analysis of BMPs for reducing TP or DRP load. The larger the number the greater the relative influence of that node on residual TP and DRP load at the pressure sequence output.

TP Node	Variance Reduction	DRP Node	Variance Reduction
WR - Performance	13	RT - Performance	815.2
WR - Effectiveness	11.15	RT - Effectiveness	635.1
VFS - Performance	3.452	VFS - Effectiveness	433.5
FFS - Performance	3.019	VFS - Performance	327.2
VFS - Effectiveness	2.301	NAM - Performance	215.4
FFS - Effectiveness	2.106	NAM - Effectiveness	145
RT - Performance	1.112	WR - Performance	116.5
CSC - Performance	1.107	CSC - Performance	116
CSC - Effectiveness	0.7587	WR - Effectiveness	96.56
RT - Effectiveness	0.7569	PF - Performance	65.13
NAM - Performance	0.6238	CR - Performance	61.74
NAM - Effectiveness	0.4363	FFS - Performance	53.47
PF - Performance	0.3072	CSC - Effectiveness	52.35
PF - Effectiveness	0.2093	PF - Effectiveness	31.6
CR - Performance	0.1764	CR - Effectiveness	27.24
CR - Effectiveness	0.0086	FFS - Effectiveness	22.05

For DRP management, WR was the fourth most influential BMP, despite being closest to the final residual DRP load target node (Table 4.4).

4.2 Achieving phosphorus objectives with optimized management strategies

Four scenarios for management strategies were considered: (1) all BMPs; (2) most common BMPs; (3) BMPs without potential of increasing TP loads (TP effective BMPs); and (4) BMPs without potential of increasing DRP loads (DRP effective BMPs). The all BMPs strategy included PF, NAM, RT, CR, CSC, VFS, FFS and WR. The most common BMPs strategy included NAM, RT, CR and VFS. The TP effective BMPs strategy included PF, NAM, CR, CSC, VFS and FFS. Finally, the DRP effective BMPs strategy included CR, CSC and FFS. The simulation results are presented in Table 4.5a−d.

All four management strategies followed the same trend − increased probability of achieving both TP and DRP load reduction policy objective with simultaneous increased adoption, while the probability of increased loads was reduced. BMP management strategies were all effective at achieving the TP load reduction objective with probabilities ≥ 88.4% assuming ≥ 40% adoption scenario simulated. Despite all BMPs following the same general trends, they varied considerably in their probabilities for achieving the TP and DRP objectives and increasing loads especially for adoption < 40%.

Low Further BMP Adoption (< 20%): Assuming low (0−19%) BMP adoption, the most effective strategy for achieving the TP objective was the adoption of all BMPs (Table 4.5a), with 61.9% probability of achieving ≥ 40% reduction in TP load. However, with a 3.3% probability of increasing the TP load, this strategy was also the highest risk for increased TP loads. For DRP, this strategy only had 8.6% probability of achieving ≥ 40% reduction in DRP load and an 81.5% probability of increasing the DRP load. The BMP strategy least effective for achieving the TP objective with low adoption was the DRP effective strategy with a 14% probability of achieving ≥ 40% reduction in TP load. Interestingly, this strategy yielded a 13.2% probability of achieving >40% reduction in DRP load, but 0% probability of increased DRP loads, indicating an 86.8% probability of 0−39% reduction in DRP load.

Table 4.5: Probability of achieving the TP and DRP load reduction objective (>40%), reductions shy of the objective (0−39%) and increased loads (<0%) with different adoption scenarios for the BMP optimization strategies: (a) increased adoption for all BMPs; (b) increased adoption of the most common BMPs; (c) increased adoption of BMPs effective for TP reduction; and (d) increased adoption of BMPs effective for DRP reduction.

Agriculture Load Reduction (%)		All BMPs Adoption Scenarios (%)					Agriculture Load Reduction (%)		Most Common BMPs Adoption Scenarios (%)				
		0-19	20-39	40-59	60-79	80-100			0-19	20-39	40-59	60-79	80-100
TP	≥40	61.9	86.3	92.3	93.7	94.2	TP	≥40	21.6	74.3	94.4	96.0	96.4
	0-39	34.8	11.3	5.5	4.3	3.9		0-39	77.3	25.2	5.2	3.6	3.2
	<0	3.3	2.4	2.1	2.0	2.0		<0	1.1	0.5	0.4	0.4	0.4
DRP	≥40	8.6	15.3	30.3	45.7	64.0	DRP	≥40	2.7	4.7	10.9	20.7	34.5
	0-39	9.9	9.7	12.2	6.9	5.3		0-39	10.6	12.9	15.1	16.6	15.9
	<0	81.5	75.0	61.5	47.5	30.7		<0	86.8	82.4	74.0	62.6	49.6
Agriculture Load Reduction (%)		TP Effective BMPs Adoption Scenarios (%)					Agriculture Load Reduction (%)		DRP Effective BMPs Adoption Scenarios (%)				
		0-19	20-39	40-59	60-79	80-100			0-19	20-39	40-59	60-79	80-100
TP	≥40	52.8	93.0	98.6	98.8	98.9	TP	≥40	14.0	45.8	88.5	97.9	98.6
	0-39	47.2	7.0	1.4	1.2	1.1		0-39	86.0	54.4	11.6	2.1	1.4
	<0	0.0	0.0	0.0	0.0	0.0		<0	0.0	0.0	0.0	0.0	0.0
DRP	≥40	30.7	60.4	82.9	89.0	91.6	DRP	≥40	13.2	47.6	92.1	98.3	98.8
	0-39	53.9	27.8	10.0	5.7	4.0		0-39	86.8	52.4	7.9	1.8	1.2
	<0	17.3	11.7	7.2	5.3	4.3		<0	0.0	0.0	0.0	0.0	0.0

The most effective strategy for achieving the DRP objective at low adoption was the adoption of TP effective BMPs (Table 4.5c), with a 30.7% probability of achieving ≥40% reduction in DRP load. However, this strategy had a 17.3% probability of increasing DRP load as compared to 0% probability for the DRP effective strategy. This strategy was also effective for TP with a 52.8% probability of achieving ≥ 40% in TP load reduction and a 0% probability of increasing the TP load. The least effective strategy for DRP was the adoption of the most common BMPs with an 86.8% probability of increased DRP load and a 2.7% probability of achieving the DRP objective (Table 4.5b).

The TP effective strategy was the best approach for optimizing the probability of achieving the ≥ 40% reduction of TP and DRP policy objectives; however, there was a 17.3% probability of increased DRP load (Table 4.5c). Though the DRP effective strategy

was not the most suitable to achieve TP and DRP policy objectives, it was the most suitable approach to eliminate the risk of increased TP and DRP loads (Table 4.5d).

Moderate Further BMP Adoption (20−39%): Assuming moderate (20−39%) BMP adoption, the most effective strategy for achieving the TP load objective became the adoption of TP effective BMPs (Table 4.5c), with a 93.0% probability of achieving ≥ 40% reduction in TP load and 0% probability of increased TP load. This strategy remains the most effective for achieving the DRP objective with a 60.4% probability of achieving ≥ 40% DRP load; however, an 11.7% probability of increased DRP load was recorded. The BMP strategy least effective for achieving the TP objective under moderate adoption was still the DRP effective strategy with a 45.8% probability of achieving ≥ 40% reduction in TP load (Table 4.5d). This strategy, however was the second most effective strategy for achieving the DRP objective with a 47.6% probability of ≥ 40% reduction in DRP load.

The least effective strategy for achieving the DRP objective with moderate adoption was still the most common BMPs with a 4.7% probability of achieving the DRP load objective while a substantial 82.4% probability of increased DRP load (Table 4.5b). This strategy resulted in a 74.3% probability of achieving the TP load objective, however was still less effective than other strategies.

The TP effective strategy remained the best approach for optimizing the probability of achieving the TP and DRP load reduction policy objectives with moderate adoption; however, there still remained an 11.7% probability of increased DRP load (Table 4.5c). Though the DRP effective strategy was, again, not the most suitable to achieve TP and DRP policy objectives with moderate adoption, it was the best approach for eliminating the risk of increased TP and DRP loads (Table 4.5d).

Higher BMP Adoption (≥ 40%): For higher adoption (≥ 40%), in general, each of the four strategies was effective for achieving the TP objective. The probability of achieving ≥ 40% reduction in TP load ranged from 88.5% with the DRP effective strategy at 40−59% adoption (Table 4.5d) to 98.9% with the TP effective strategy (Table 4.5c) assuming 80−100% adoption. The probability for increased TP loads ranged from 2.1%

with the all BMPs strategy (Table 4.5b) for 40−59% adoption, to 0.0% probability of increased loads with the TP and DRP effective strategies (Tables 4.5c and 4.5d) with adoption ≥ 40%.

The probability of achieving DRP load policy objective ranged from 10.9% with the most common BMPs strategy (Table 4.5b) assuming 40−59% adoption, to 92.1% probability with the DRP effective strategy (Table 4.5c) assuming 80−100% adoption. The probability for increased DRP loads ranged from 74.0% with the most common BMPs strategy (Table 4.5b) for 40−59% adoption, to 0.0% probability of increased loads with the DRP effective strategy (Tables 4.5d) assuming adoption ≥ 40%.

Assuming higher adoption rates, the probability of achieving the TP objective is >88.5% for the four strategies, while the probability for achieving the DRP objective is more uncertain with higher risk of increased load. Therefore, the most effective strategy at higher adoption to optimize the probability of achieving the TP and DRP policy objective is the DRP effective strategy with 88.5−98.6% probability of achieving ≥ 40% reduction in TP load and 92.1−98.8% probability of achieving ≥ 40% reduction in DRP load while a 0% probability of increasing either loads was reported.

Hypotheses: We hypothesized that targeting adoption of TP effective BMPs (removal of BMPs with potential of increased TP loads) would be the most suitable strategy for achieving the TP objective but would increase the risk of elevated DRP loads. The BBN analysis provided evidence to support this hypothesis for adoption ≥ 20%. However, it was not the most suitable for adoption < 20%, in which the all BMPs strategy had a higher probability of achieving the objective. The BBN analysis also observed increased DRP loads across all adoption scenarios for the TP effective strategy, providing further evidence in support of the hypothesis.

We also hypothesized that targeting adoption of DRP effective BMPs (removal of BMPs with potential of increased DRP loads) was the optimal strategy for achieving both TP and DRP reduction objectives. With adoption < 20%, the DRP effective strategy was less suitable for achieving the DRP objective, the TP effective strategy was the most suitable approach providing evidence that does not support the hypothesis. However, the strategy

yielded the greatest probability for achieving the DRP objective for adoption $\geq 20\%$ in support of the hypothesis but not for the TP objective in contrast to the hypothesis. The DRP effective strategy was not the most suitable approach for achieving the TP objective across all adoption scenarios however there was 0% probability of increased TP and DRP loads providing some support for the hypothesis.

Chapter 5: Discussion

Lake Erie's management system is insufficient to prevent high risk phosphorus loads, a major contributing factor in the recent re-eutrophication (Kleinman et al. 2015; Scavia et al. 2014). In 2015, a policy objective advising a 40% reduction of TP and DRP loads relative to 2008 was recommended for western basin tributaries and the Thames River (Annex 4 Nutrient Objectives and Targets Task Team, 2015). To achieve the objective, credible tools are needed to analyze the performance of the system of management measures and to analyze its probability of TP and DRP load reductions in compliance with the objective (Creed et al. 2016). A BBN model based on the ISO 31010:2009 BRAT, was designed to analyze the performance of eight agricultural BMPs, individually and as a potential management system in the Grand River watershed that discharges to Lake Erie's *eastern* basin. The BBN showed greater TP load reduction by BMPs compared to DRP. Most BMPs showed a 100% probability of TP load reduction, while most showed an alarming probability of and magnitude of increased DRP loads, providing evidence suggesting traditional phosphorus management is effective for TP load reduction but has antagonistic effects for DRP. Based on the BMP effectiveness data compiled and BBN analysis, limiting the further adoption of RT and WR, while increasing the adoption of the remaining six BMPs will result in the greatest probability of achieving the 40% DRP load reduction objective, however, the probability for increased DRP load remains a concern.

5.1 Performance of phosphorus management system

5.1.1 BMP effectiveness and influence on phosphorus load reduction

The position of BMPs in the watershed in relation to the hydrologic transport of phosphorus was reflected in their position within the BBN model. BMPs that targeted phosphorus sources were located near the beginning of BMP sub-model sequences, and BMPs that trapped phosphorus transported in runoff were located near the end. Arabi et al. (2006) suggested BMPs located closer to discharge areas will have a more immediate effect influencing the residual load, confirmed by the BBN model with the results of the

sensitivity analysis for TP generally showing greater influence of BMPs closer to the residual load. In contrast, RT had a greater influence than CSC, despite being positioned farther from the end of the BMP sequence for TP load management. The higher probability of greater TP load reductions by RT resulted in a stronger influence on the final residual load than its position preceding CSC suggested. Arabi et al. (2006) also explained the implementation of individual BMPs, like CSC, may have reduced effect as their influence is supressed by more effective BMPs like RT despite being positioned upslope in the hydrological flow path.

In contrast to TP management, the sensitivity analysis showed the most influential BMPs (RT and VFS) affecting the residual DRP load were positioned relatively further from the end of the BMP sequence which suggested their effect had considerable, overwhelming influence that suppressed the effect of subsequent BMPs (Arabi et al. 2006). In a modeling study by Rao et al. (2009), avoiding application of manure to hydrologically sensitive areas (NAM) did not yield significant load reductions from the watershed as considerable phosphorus had already accumulated in watershed soils and continued to be leached. Likewise, RT and VFS in the BBN model also indicated the potential to increase DRP load, which might be explained by their accumulation of phosphorus in the soil (Kleinman et al. 2011; Dillaha et al. 1989). Additionally, the sensitivity analysis suggested they too supressed the effect of preceding and subsequent BMPs. Studies by Baker et al. (2014), Kleinman et al. (2015) and Scavia et al. (2014) attribute the recent upward trend in DRP load to Lake Erie's *western basin* to the effect of RT practices, despite the adoption of other BMPs present in the watersheds. BMPs like WR has also been criticized for the same phosphorus accumulation, saturation and leaching of DRP load (Fisher and Acreman 2004; Hoffman et al. 2010). The BBN analysis appears to support this criticism, however the probability and magnitude of increased DRP load by WR was lower than RT, and the probability of greater load reductions was lower relative to other BMPs, which suppressed its influence despite being positioned closest to the end of the BMP management sequence.

With BMP effectiveness and performance distributions quantified and the sensitivity analysis with support from the literature confirming the models behaviour and ability to

uncover management system strengths and vulnerabilities, the first thesis objective was satisfied.

5.2 Performance of the different phosphorus management strategies

5.2.1 TP reduction with traditional strategies

The traditional approach for managing phosphorus loads from agricultural landscapes in the Great Lakes basin has been guided by policy objectives that have focused on TP. From 1975 to 1995 in Lake Erie *western basin* watersheds with significant crop agriculture, the greatest proportion of TP loads were contributed by the PP fraction (Coelho et al. 2012; Dolan and Chapra, 2012; Panuska and Karthikeyan, 2010; Richards et al. 2002; Richards et al. 2008). Therefore, BMPs focused on soil conservation were promoted and implemented to reduce soil erosion and PP loads and thereby TP loads (Coelho et al. 2012; Kleinman et al. 2015; Richards et al. 2002). It was assumed that soil is an effective sink for phosphorus (Kleinman et al. 2010) and retaining sediment bound phosphorus within the soil matrix will reduce TP loads. The BBN analysis of BMP *effectiveness* provided support for this assumption with a 100% probability of TP load reduction between 1 and 100%, by most BMPs, apart from RT and WR.

A vulnerable management system is one with an implemented management measure with potential antagonistic effects. These management system vulnerabilities compromise the reductions of other effective measures (Arabi et al. 2006; Dodd and Sharpley, 2016), and increases the uncertainty with achieving policy objectives (Creed et al; 2016). These antagonistic management measures can be discussed in the context of achieving water quality objectives.

Achieving the TP objective: As further adoption in the BBN simulations increased, the probability for achieving the 40% TP load reduction objective also increased for all four BMP management strategies, simultaneous with decreased probability of increased TP load. In addition, the BBN analysis showed all strategies were considerably effective (≥88.5% probability) for achieving the objective at higher adoption levels (≥40%).

Likewise, in a modeling study by Scavia et al. (2016), all BMP strategies reduced greater amounts of TP (and DRP) load with increased implementation in the Maumee watershed. This study suggested the TP objective was achievable with some strategies, but not all, when implemented on 50% of *cropland*. Compared to the Maumee, in the Grand River watershed, a greater proportion of the agricultural land is consumed by livestock operations; an important consideration when comparing these results. Nevertheless, both studies suggested considerable implementation of BMPs in agricultural watersheds to achieve a ≥ 40% TP load reduction. The higher probability of achieving the TP objective (compared to the DRP objective) was expected as most BMPs in the analyzed management system were designed for soil conservation that effectively reduce the PP fraction in TP loads (Smith et al. 2015). However, there was considerable variation in the probability of achieving the TP reduction objective at low (< 20%) and moderate (20−39%) further adoption.

The BBN analysis revealed interesting results for the exclusive adoption of the most commonly implemented and promoted BMPs including RT (combining conservation and no tillage), NAM, CR and VFS (combining all non-tree species buffers at edge of fields or surrounding surface water conduits) (Census of Agriculture, 2006; Wilson et al. 2013, Bukhari at el. 2015). Previous studies showed their implementation resulted in remarkable TP load reductions between 59−81% for RT (Andraski et al. 1985; Sharpley and Smith, 1994), > 90% by VFSs in multiple studies (Chaubey et al. 1994, Dillaha et al. 1989, Hamlett and Epp 1994 and Lee et al. 2003), and between 35 and 75% for CR (Clark et al. 1985; Haith and Loehr, 1979; Rao et al. 2009). Despite the evidence presented in the scientific literature, the BBN analysis showed their exclusive further adoption did not result in the greatest probability for achieving the policy objective of the four BMP strategies simulated. At low, further adoption, the probability of achieving the TP objective was 40.3% lower than the all BMPs strategy. Arabi et al. (2006) explained the synergistic effect of combined BMPs lead to greater reductions than a subset of the management system.

A concern with these BMP strategies was their probability of causing increased TP load that caused antagonistic effects by management system vulnerabilities and increased the

uncertainty for achieving the policy objective. WR and RT indicated the potential to increase TP load and were both implemented as part of the all BMPs and most common BMPs strategies. The 4.3% probability of increased TP load by $0-20\%$ could be explained by findings reported by Hansen et al. (2000), where leached DRP from soils treated with RT comprised 75% of the TP load during snowmelt runoff which resulted in an overall increase in the DRP load, an important climatic consideration relevant to the Grand River watershed and the Great Lakes basin. The BBN analysis suggested greater management system vulnerability by WR with greater probability and magnitude (1.3 fold) of increased TP load. Hoffman et al. (2012) attributed increased TP load from WR to the internal loading that results when phosphorus rich, wetlands soils are inundated with agricultural runoff, producing anoxic conditions causing phosphorus to be leached for export from the wetland.

Individually, these BMPs introduce management system uncertainty for achieving the TP load reduction objective; however, their probability for TP load reduction was far greater than their probability for increased loads, consistent with studies that reported overall effective load reduction by RT (Andraski et al. 1985; Sharpley et al. 1994) and WR (Braskerud et al. 2005; Raisin et al. 2012).

5.2.2 TP reduction with an alternative strategy

The all BMPs strategy and most common BMPs strategy both implemented management system vulnerability measures as part of their management systems that resulted in antagonistic effects with increased TP load and increased uncertainty for achieving the objective. Removing these antagonistic measures has been suggested as a potential solution to strengthen management systems and reduce the uncertainty with achieving policy objectives (Creed et al. 2016). The BBN model was therefore implemented to simulate an alternative TP load management strategy.

Achieving the TP Objective: When the TP effective BMP strategy was simulated for low further adoption, (which avoided further adoption of RT and WR in the management system), not only was there a 0% probability of increased TP load, but the objective was achieved with a 52.8% probability, more than double the probability for the most

common BMPs strategy, but less than the 61.9% probability for the all BMPs strategy. However, with moderate further adoption of the TP effective strategy, a 93% probability of achieving the TP objective was achieved which represented a 6.7% and 18.7% probability increase over the all BMPs strategy and most common BMPs strategy respectively. Thus, while the first hypothesis does not stand for low further adoption, it does when further adoption exceeds 19%. In addition, a 0% probability of increased TP load for all adoption scenarios was also achieved with the TP effective strategy and not the all BMPs and most common BMPs strategy. The removal of TP management system vulnerabilities improved the probability of achieving the TP load reduction objective for moderate adoption and decreased the uncertainty with higher risk loading scenarios. The management of TP incompliance with the policy objective appears plausible with different management strategies however, however, it was hypothesized that the strategies effective for TP management would have antagonistic effects for the management of DRP loads (Dodd and Sharpley, 2015; Smith et al. 2015).

The BBN analysis for these three strategies provided evidence that supported Arabi et al. (2006), as the synergistic effects of combined BMPs was more effective then a subset of the management system for achieving the policy objective. While RT and WR indicated the potential for antagonistic effects, their probability of TP load reduction was greater than their probability for increased loads. When they were included in the all BMPs strategy, the greatest probability for achieving the TP objective was observed. Likewise, in the study by Scavia et al. (2016), BMP strategies that include no-tillage (RT) were among the most effective for reducing TP load in the Maumee watershed. These results from the BBN analysis, with support from the scientific literature, suggest that RT implanted as part of a management system, may be an important strategy to achieve the TP load reduction objective with less adoption relative to other strategies. However, this strategy is not without its demons; the implementation of less common, more effective BMPs that represented management system strengths, appeared to be necessary strategy to manage potential antagonistic effects by RT and WR.

5.2.3 DRP reduction with traditional strategies

Dolan and Chapra (2012) discussed Lake Erie's regular occurrence of harmful algal blooms despite TP loads remaining below the initial 11,00 MTA objective in most years since 1994. They questioned that perhaps a focus on TP loads is inadequate, and that consideration to forms of phosphorus including DRP, might provide insight as to why management systems are failing to prevent eutrophication events. Baker et al. (2014) discussed the increased DRP fraction of discharged phosphorus loads from the Maumee, Sandusky and Cuyahoga river watersheds as a considerable contributor to the recurrence of algal blooms in Lake Erie's western basin, as well as the hypoxia events in the central basin (Scavia et al. 2014).

Increased DRP load to Lake Erie was first observed in the mid−1990s, and was simultaneous with the peak adoption of RT in western basin agricultural watersheds which called into question the implications of soil conservation BMPs on DRP loads. Likewise, the BBN analysis identified RT, and VFS as soil conservation BMPs with a considerable probability (89.4% and 18.3%) of increased DRP load. Their probability for antagonistic effects within the DRP management system (Kleinman et al. 2015), potential magnitude of increased loads (5.00 fold and 2.56−fold respectively) (Baker and Laflen, 1983; Dillaha et al. 1989), while being effective for soil, PP and TP reduction (Gitau et al. 2005; Lee et al. 2003; Sharpley and Smith; 1994), provided evidence in support of a shifting dominance of phosphorus form toward the DRP fraction proposed by Baker et al. (2014). Considering these recent studies, the BBN model was implemented to simulate the further adoption of traditional BMP strategies to provide further insight on their potential for achieving the 40% DRP load reduction policy objective.

Achieving the DRP objective: BBN simulations identified the further adoption of the most common BMPs as the highest risk management strategy which resulted in the lowest probability for achieving the DRP objective and the highest probability for increased DRP loads. Comparatively, when the adoption of all BMPs was simulated, the probability for achieving the DRP objective increased by 2−4−fold across all adoption ranges simulated, however, the probability of increased DRP load remained comparable

for both strategies. This provided evidence to speculate phosphorus *retention* and *trapping* (Kleinman et al. 2000), as well as *application management* (Hanrahan et al. 2009) have the potential to be management system vulnerabilities that result in management trade-offs for TP and DRP load reduction (Figure A.1−8). TP and DRP management trade-offs have been discussed in a literature review by Dodd and Sharpley (2016), and in modeling and monitoring studies by Scavia et al. (2014) and Smith et al. (2012). Antagonistic BMPs increased the uncertainty for achieving the DRP load reduction objective in the BBN analysis, and may be responsible for the recent increased load of high risk DRP to Lake Erie (Baker et al. 2014; Kleinman et al. 2015).

Phosphorus retention with reduced tillage: According to Kleinman et al. (2015), management trade-offs are well reported for RT (Figure A.3), as well as other BMPs like VFS and WR (Dodd and Sharpley, 2016). The implementation of RT in Lake Erie agricultural tributaries has been widespread and driven by economic and time saving benefits for farmers as well as its promotion by scientists and the agri-industry (Gaynor and Findlay, 1995; Kleinman et al. 2015). While the BBN analysis indicated a 95.6% probability for TP load reduction, the probability for increased DRP load was 89.5%, In addition, the greatest potential magnitude of increased DRP load (5.00—fold) was also observed by RT. Similar management trade-offs with RT was also observed in studies by Sharpley and Smith (1994), and Teissen et al. (2009), and discussed in a literature review by Dodd and Sharpley (2016).

Management trade-offs with RT result from minimized disturbance to the soil structure, thereby reducing vulnerability to erosion and allowing macropores develop (Sharpley and Smith; 1994). The phosphorus that is accumulated on the surface of RT system from broadcast applications is highly accessible for export as DRP from farm operations via surface runoff or macropore flow (Coelho et al. 2012; Gaynor and Findlay, 1995). Injecting phosphorus below the surface of farms implementing RT is a potential solution, however a modeling study by Scavia et al. (2016), this strategy was not sufficient for achieving both the TP and DRP objectives. The BBN analysis and scientific literature suggested that further adoption of RT in any management strategy is not a solution.

Accordingly, the results of the BBN analysis recommend watershed managers consider alternative strategies on operations in hydrologically sensitive areas.

Phosphorus trapping with vegetative filter strips and wetland restoration: Traditionally, effective TP management has relied on the ability of soil to trap the greater PP fraction and sorb the infiltrating DRP fraction (Kleinman et al. 2010); the primary mechanism for phosphorus reduction by VFSs (Dillaha et al. 1989; Stutter et al. 2009). This was well represented in the BBN analysis for VFS effectiveness with a 63.4% probability of DRP load reductions greater than 40%. However, an 18% probability of increased load by 0−2.56−fold was also reported. For BMPs that rely on the soil for its phosphorus retention mechanisms, Kleinman et al. (2010) warn that "*yesterday's sinks of phosphorus are today's sources".* Kleinman et al. (2000) explain that soils accumulate phosphorus until sorption sites are saturated preventing further accumulation, with subsequent desorption and export of DRP during precipitation events when inundated with agricultural runoff (Baker and Laflen, 1983; Hoffman et al. 2012; Kleinman et al. 2011; Stutter et al. 2009). The probability distribution for DRP effectiveness by VFSs appears to accommodate this *lifespan* (Dodd and Sharpley, 2016) of the BMP, with the probability of higher reductions in the distribution perhaps representing VFSs prior to soil phosphorus saturation and the probability of lower reductions or increased load, representing VFSs with phosphorus saturated soils.

Dodd and Sharpley (2016) also observed a DRP management lifespan by WR, perhaps represented in its BBN effectiveness distribution with a 31.3% probability of increased DRP load by 0−1.54−fold. Increased DRP load from WR primarily occurs from internal loading from inundated soils that have similarly accumulated phosphorus to the point of saturation (Hoffman et al., 2012). However, despite the probability of increased TP and DRP loads, WR is topographically confined to depressions suitable for their restoration, and in the Grand River watershed, these depressions could only potentially intercept and treat 48% of agricultural runoff. Based on the results of the BBN analysis, with evidence from the literature, this thesis recommends watershed managers educate farmers on the lifespan of phosphorus trapping and retention BMPs as their implementation for effective reduction of DRP load appears to be temporally constrained, and if ignored may become

a source of DRP rather than a sink (Dodd and Sharpley, 2016; Kleinman et al. 2000; Kleinman et al. 2010).

Nutrient application management: Despite studies advocating NAM as an effective strategy for DRP load reduction and prevention of legacy phosphorus (Sharpley et al. 2014), the BBN analysis indicated its potential to increase DRP load by 0.26−fold. The effectiveness of a BMP relies on its correct implementation, where Hanrahan et al. (2009) and Walter et al. (2001) suggested that a reduction in the amount of phosphorus applied, could result in increased load when consideration to the timing of application before runoff events is neglected, or the magnitude of the slope receiving application is not considered. This research recommends watershed managers develop and offer enhanced education and outreach programs like the "4Rs for nutrient Stewardship" (Mikkelsen, 2011). This could lead to greater, more probable reductions with NAM and the management system itself, by reducing the probability of increased DRP load stemming from a lack of knowledge causing poor implementation (Henry, 2014; Kleinman et al. 2015).

When nutrient management is implemented correctly, studies have shown a lag between their implementation and reductions in phosphorus load from the watershed (Meals et al. 2009; Sharpley et al. 2009). In the modeling study by Scavia et al. (2016), the implementation of NAM to 100% of cropland resulted in the greatest average reduction of DRP load from the Maumee river. In the Catskill Mountains of New York state, avoiding application of manure to hydrologically sensitive areas did not yield significant load reductions from the watershed in a modeling study by Rao et al. (2009) as the considerable phosphorus already accumulated in the landscape supressed the effect of reduced application to hydrologically sensitive areas. The researchers also explained that reducing application to phosphorus saturated soil will allow soil phosphorus levels to decline and eventually lead to TP and DRP load reductions from the watershed. The effectiveness distributions for BMPs with the potential to increase DRP load, might have reflected the effect of phosphorus saturated soils from past management. Therefore, with better implementation of NAM, the probability of increased TP and DRP load from other BMPs could decline.

5.2.4 DRP reduction with alternative strategies

The low probability of achieving the DRP load reduction objective with the all BMPs and the most common BMPs strategy meant these management system configurations were not suitable. A similar conclusion was reached in a study by Smith et al. (2015) who monitored phosphorus losses from agricultural operations implementing BMPs over a 9−year period. They concluded that most of the BMPs were engineered for soil conservation to meet TP objectives and, it did not seem likely that a 41% reduction in DRP load to Lake Erie was feasible with the current management system, therefore alternative strategies must be considered. The BBN analysis results for these two strategies are also complimented in a study by Kalcic et al. (2016) who reported that achieving the DRP objective in the Maumee River watershed would require the implementation of BMPs at adoption rates greater than what farmers consider feasible, while the TP objective would be achieved moderately well.

Achieving the DRP objective: The BBN model was implemented to analyze the effect of alternative management strategies on DRP load reduction, namely a TP effective BMP strategy and a DRP effective BMP strategy. If achieving the DRP reduction objective with minimal further adoption (<20%) is the watershed management priority, the BBN analysis recommends avoiding further implementation of RT and WR with the TP effective strategy. The probability of increased DRP load drops considerably supporting of speculation that has attributed recent increased DRP load to the widespread adoption of RT specifically (Baker et al. 2014; Kleinman et al. 2015; Richards et al. 2002). However, this contrasts with modeling results by Scavia et al. (2016) who reported considerable DRP load reduction, surpassing the objective, when no-tillage and subsurface phosphorus application were implemented as a management strategy on 50% of cropland in the Maumee watershed. The increased DRP load from TP effective strategy provides evidence in support of the first hypothesis but, it is the optimal approach to simultaneously achieve both TP and DRP load reduction objectives, contradicting the second hypothesis.

If eliminating the potential for increased DRP load is the watershed management priority, only the DRP effective strategy is recommended, but at a cost with considerably lower probability of achieving the 40% reduction objective at low and moderate further adoption. This suggests watershed managers need to consider what the management priorities are as the BBN analysis indicates the greatest probability for achieving the objective may not translate to the lowest probability for antagonistic effects at further adoption <40%. However, in the unlikely scenario of further adoption exceeding 39%, as discussed by Kalcic et al. (2016), the BBN analysis indicates the DRP effective strategy is the optimal approach to achieve the DRP objective and eliminate the probability of increased DRP load simultaneously.

5.3 BBN suitability for management analysis and achieving objectives

For management system analysis, the ability of BBNs to represent the uncertainty with a visual graphical interface, for management variables like BMP effectiveness, performance and resulting distribution of plausible discharged load, was a considerable advantage for easy interpretation, better communication and enhanced transparency. Furthermore, the ability of BBNs to accommodate expert opinion when data are lacking is also advantageous as too often environmental management requires a considerable amount of data to inform policy that is not always available. However, our experts were uncomfortable providing effectiveness estimates for tile drainage due to the considerable variability.

Too often science provides evidence for management options using complicated models that are high risk for policy dependence (Kim et al. 2011). In contrast, BBNs are more simplistic cause and effect models that are easily interpreted and provide management authorities with the necessary information, providing insight to multiple possible outcomes of management decisions and their probabilities of being observed. While BMP effectiveness coefficients provide a single value representing the expected reductions if implemented, the BBN model was used to construct probability distributions of expected reductions for each BMP and as a management system. This method provided insight into

the uncertainty of management outcomes that is poorly accommodated with coefficients and further increases risk for policy dependence.

Altering and updating the BBN model with new information to consider different management strategies was an easy and efficient process that did not require specialized skills or great time investment. Therefore, new evidence of BMP effectiveness and adoption can easily be incorporated into the BBN necessary for adaptive management. Furthermore, sensitivity analysis was particularly helpful in testing the models conformity to environmental behaviour.

In general, the application of BBN analysis to a system of management measures relying on the structure of the ISO 31010:2009 BRAT achieved the research objectives by probabilistically quantifying the performance of BMPs individually and as an integrated management system. In addition, the BBN analysis was suitable for analyzing the effect of BMP management strategies for achieving the phosphorus load reduction objectives while uncovering management strengths, vulnerabilities and sources of uncertainty necessary to inform and guide watershed management decisions toward achieving their policy objectives.

Chapter 6: Conclusions

6.1 Scientific findings and management implications

The recurrence of Lake Erie's harmful algal blooms despite TP loads remaining below the objective in most years since 1994 suggests a deficient policy objective incapable of preventing eutrophication effects from high risk tributary loads. Since the mid−1990s, loads of DRP from agricultural tributaries have been on the rise, coincidently with the widespread adoption of land management practices favouring soil conservation that have effectively reduced PP and TP loads (Baker et al. 2014; Dolan and Chapra, 2012; Kleinman et al 2015). With Lake Erie returning to a eutrophic state and threatening to compromise valued ecosystem services, governments from Canada and the United States have once again mobilized to tackle the issue from a perspective that considers both TP and DRP management. Based on tributary loading and in-lake eutrophication modeling, the Annex 4 Nutrient Objectives and Targets Task Team recommended a 40% reduction in TP and DRP load relative to 2008 from all western basin tributaries and the Thames River.

A new tool using BBN modeling was developed to quantify the performance of a system of management measures (focusing on BMPs), as well as analyze it for; (1) strengths, effective BMPs and combination of BMPs; (2) vulnerabilities, BMPs with potential to increase phosphorus load and have antagonistic effects on other BMPs. The management system was dominated by effective BMPs for TP load reduction with only two of the eight BMPs having antagonistic effects yielding increased loads. For DRP reduction, five of the eight BMPs imposed antagonistic effects with considerable probability and higher potential magnitude. The relative influence of BMPs on TP load discharged from agricultural landscapes decreased with distance from receiving surface waters. However, despite this relative position of BMPs, RT, having the greatest probability for increased DRP load, also had the greatest influence on discharged DRP load, drastically supressing the effect of preceding, and subsequent BMPs in the management system. Other antagonistic BMPs for DRP reduction with considerable relative influence was VFS whose effectiveness decline with age and increased loads become more probable, and

NAM that requires extensive farmer education and outreach programs to ensure its appropriate implementation to reduce the probability of increased loads yielded in the BBN analysis. Management trade-offs, with considerable magnitude and probability for increased DRP load was indicated in the BBN analysis which further supported speculation that the agricultural phosphorus management system itself may be a dominant contributor to the re-eutrophication of Lake Erie and subsequent impacts from harmful algal blooms.

The BBN tool was implemented in the Grand River watershed to simulate different BMP management strategies and analyze their effect for increasing the probability of achieving the objective as well reducing the uncertainty associated with alternative high risk load scenarios. The BBN analysis suggested traditional approaches to phosphorus management favouring implementation of soil conservation BMPs continues to be a suitable strategy for achieving the TP objective. However, their management trade-offs have the highest probability and magnitude of increased DRP load. The BBN analysis suggested that alternative management strategies that; (1) avoid further adoption of BMPs that increase TP load; or (2) avoid further adoption of BMPs that increase DRP load, are more suitable for achieving the more critical DRP objective and reducing the risk of increased loads, but reduces the probability of achieving the less critical TP objective.

The four most significant outcomes from this research suggested; (1) traditional approaches to phosphorus management that is effective for TP reduction, appears to result in trade-offs and antagonistic effects for increased DRP loads, suggesting the phosphorus management system itself is a significant contributor to phosphorus related impacts in Lake Erie. (2) The BBN analysis has identified RT as the most vulnerable management system weakness and dominant contributor to DRP loading risk from the management system analyzed. Preventing its further adoption yielded the most significant increase in probability of achieving the DRP objective and substantial reduced probability of increased loads. And (3), the highest probability for achieving the policy objectives does not always translate to the lowest probability of antagonistic effects, decision makers and watershed managers need to establish whether achieving policy objectives is the

management priority or reducing the probability of antagonistic effects, and then develop management systems and a program for the implementation accordingly.

Finally, with so much uncertainty in regards to the performance of management measures and their effect for achieving policy objectives, the BBN model provides a method to do so that communicates the uncertainty to decision makers. Although this initial model is limited in its regional application, future research can enhance its suitability. Nonetheless, this research has demonstrated that Bowtie risk analysis structured, BBN models are a good visual, probabilistic tool and method for management system analysis and making recommendations to decision makers in the context of achieving policy objectives.

6.2 Future research

The model developed was a first attempt using BBNs to analyze a management system for strengths and vulnerabilities and then using it to simulate a range of possible TP and DRP loading scenarios for different management strategies. The model was applied for TP and DRP load reduction in the context of a new policy objective; however, the non-specific configuration allows it to be applied to any type of pollutant and any type of management measure that can reduce the pollutant. More science is required to make the model more relevant for local applications. Future research should focus on compiling the conditional probability data using contextually based, region specific data for the effectiveness and adoption distributions, or combine the BBN with physically-based distributed simulation models. Such physically based models that can consider site-specific behaviour of BMPs could lead to better estimates of the performance of the management system.

Currently, the state of BMP effectiveness science is not well developed in the Grand River watershed or even the Great Lakes basin and therefore the BBN model that was developed is not specific for the Great Lakes basin. This is advantageous for application to any watershed in Canada or the United States as the data is that broad however, it is a disadvantage because BMP effectiveness is highly influenced by local condition.

One of the strengths of BBN models uses Bayes theorem to calculate the necessary conditions of BBN nodes to achieve a desired state. By plugging into the model output a hypothetical 90% probability of achieving phosphorus reductions ≥40%, the required adoption for each BMP could be analyzed with multiple BMP strategies.

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Appendices

Appendix A: BMP sub-models simulating 40-59% adoption

For visual representation of the BBN model and BMP effectiveness distributions as they appear in the Netica software, Figures A1-8 are provided, one for each BMP. The figures all show the effectiveness distributions for each BMP, as well a 40-59% adoption scenario simulated in adoption nodes, and its effect on the performance distribution in the performance nodes. For TP and DRP effectiveness datasets that passed the Shapiro-Wilk test for normality, their distributions were generated in Netica using a normal distribution relying on the mean, standard deviation and maximum and minimum effectiveness values. For TP and DRP effectiveness datasets that failed the Shapiro-Wilk test for normality, (usually n > 30), then their distributions were generated in Netica using the "Learn from Cases" function which constructed their true distribution. The results of the normality tests are included above the effectiveness nodes for each BMP

Each node has three components, a title box at the top indicating the variable the node represents (i.e. effectiveness, performance, and adoption), a center states and probability box, with the lowest box indicating the mean and standard deviation of the node variable's probability distribution. The states and probability box is separated into a left side and right side. On the left are the node states representing the different intervals the variable can have, for computational purposes these identify proportional reduction or proportional adoption, rather than percent. For effectiveness, these states are 20% intervals of the range between 0 and the highest effectiveness reported in the literature, and, when applicable 20% intervals of the range between 0 and the lowest (negative values indicating load increases) effectiveness reported in the literature. Each node state has a probability of being observed based on their probability distribution, these probabilities are indicated to the right of each nod state. On the right side of the states and probability box is a graph, with one belief bar for each state visually communicating its probability. Together, all belief bars represent the probability distribution for the variable's potential states.

The probability graphs have grey interval lines representing 25% intervals between 0 and 100% probability. Probability graphs that have all three lines for 25%, 50%, and 75%

indicates the width of the graph is from 0 to 100% probability. If there is only one interval line, it is for 25% and therefore the width of the graph represents 0 to 50% probability. This was an intentional decision to maximize the size of the box to represent larger distributions fully while seeing smaller distributions more clearly.

Figure A.1: Precision feeding (PF). TP and DRP effectiveness distribution is subjected to the effect of the adoption in the performance node.
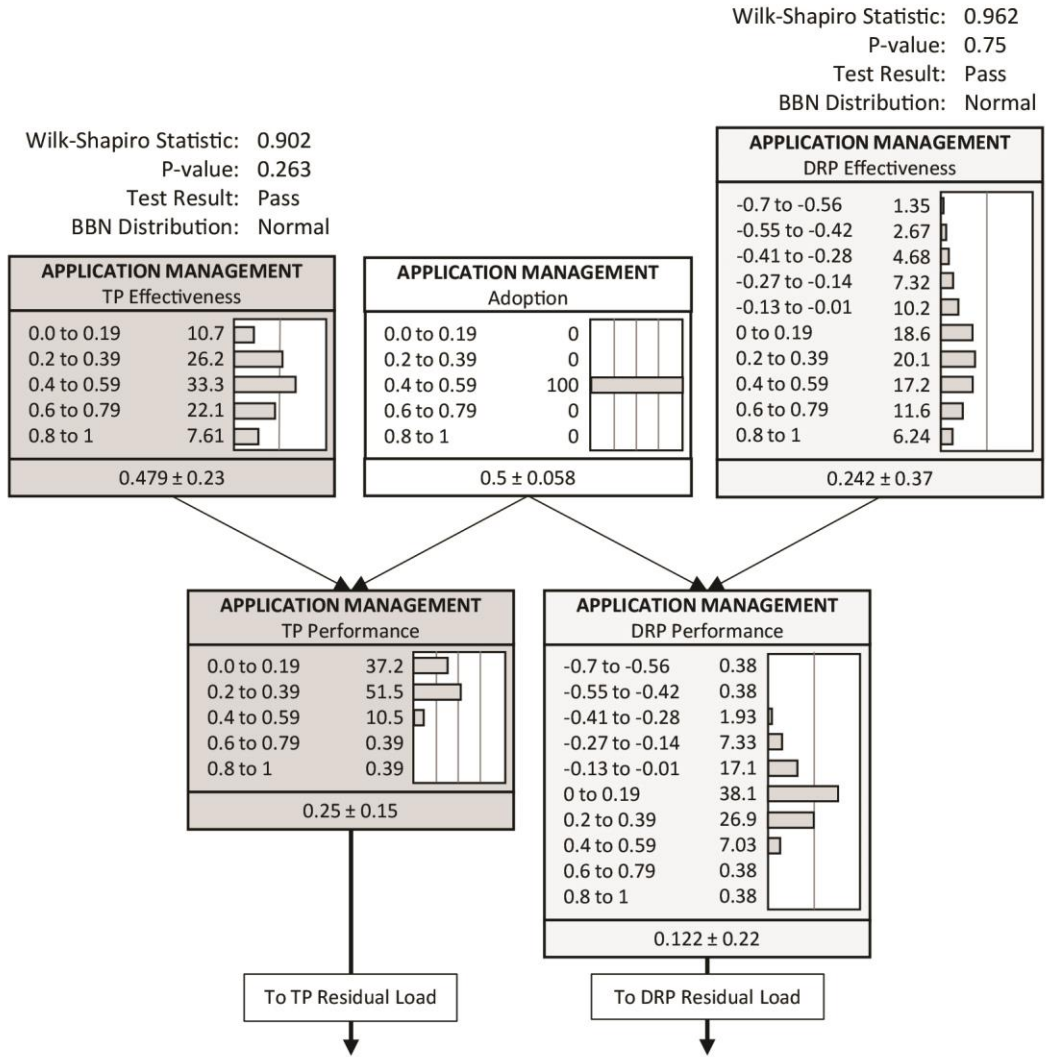
Figure A.2: Nutrient application management (NAM). TP and DRP effectiveness distribution is subjected to the effect of the adoption in the performance node.

Wilk-Shapiro Statistic: 0.864
P-value: 0.064
Test Result: Pass
BBN Distribution: Normal

Wilk-Shapiro Statistic: 0.846
P-value: 0.183
Test Result: Pass
BBN Distribution: Normal

REDUCED TILLAGE
TP Effectiveness

-0.2 to -0.16	0.53
-0.15 to -0.12	0.67
-0.11 to -0.08	0.84
-0.07 to -0.04	1.03
-0.03 to -0.01	1.26
0 to 0.19	10.6
0.2 to 0.39	18.9
0.4 to 0.59	24.9
0.6 to 0.79	24.1
0.8 to 1	17.1

0.511 ± 0.28

REDUCED TILLAGE
Adoption

0.0 to 0.19	0
0.2 to 0.39	0
0.4 to 0.59	100
0.6 to 0.79	0
0.8 to 1	0

0.5 ± 0.058

REDUCED TILLAGE
DRP Effectiveness

-5.0 to -4.0	12.2
-3.99 to -3.0	17.0
-2.99 to -2.0	20.4
-1.99 to -1.0	21.1
-0.99 to -0.01	18.7
0 to 0.19	3.25
0.2 to 0.39	3.06
0.4 to 0.59	2.87
0.6 to 0.7	1.36

-2.03 ± 1.5

REDUCED TILLAGE
TP Performance

-0.2 to -0.16	0.38
-0.15 to -0.12	0.38
-0.11 to -0.08	0.92
-0.07 to -0.04	1.82
-0.03 to -0.01	2.58
0 to 0.19	29.4
0.2 to 0.39	45.7
0.4 to 0.59	17.9
0.6 to 0.79	0.38
0.8 to 1	0.38

0.259 ± 0.17

To TP Residual Load

REDUCED TILLAGE
DRP Performance

-5.0 to -4.0	0.38
-3.99 to -3.0	0.38
-2.99 to -2.0	12.5
-1.99 to -1.0	35.8
-0.99 to -0.01	38.9
0 to 0.13	4.74
0.14 to 0.27	4.38
0.28 to 0.41	2.18
0.42 to 0.55	0.38
0.56 to 0.7	0.38

-1.05 ± 0.89

To DRP Residual Load

Figure A.3: Reduced tillage (RT). TP and DRP effectiveness distribution is subjected to the effect of the adoption in the performance node.

CROP ROTATION
Adoption

0.0 to 0.19	0	
0.2 to 0.39	0	
0.4 to 0.59	100	
0.6 to 0.79	0	
0.8 to 1	0	

0.5 ± 0.058

CROP ROTATION
TP EFFECTIVENESS

0.6 to 0.64	50.0	
0.65 to 0.7	50.0	

0.65 ± 0.029

CROP ROTATION
DRP Effectiveness

0.2 to 0.39	26.3	
0.4 to 0.59	48.9	
0.6 to 0.79	24.9	

0.497 ± 0.15

CROP ROTATION
TP Performance

0.0 to 0.13	0.39	
0.14 to 0.27	13.3	
0.28 to 0.41	85.5	
0.42 to 0.55	0.39	
0.56 to 0.7	0.39	

0.332 ± 0.068

CROP ROTATION
DRP Performance

0.0 to 0.15	17.5	
0.16 to 0.31	60.8	
0.32 to 0.47	20.9	
0.48 to 0.63	0.39	
0.64 to 0.8	0.39	

0.249 ± 0.11

To TP Residual Load

To DRP Residual Load

Figure A.4: Crop rotation (CR). TP and DRP effectiveness distribution is subjected to the effect of the adoption in the performance node.

Figure A.5: Contour strip cropping (CSC). TP and DRP effectiveness distribution is subjected to the effect of the adoption in the performance node.

VEGETATIVE FILTER STRIP
DRP Effectiveness

-2.60 to -2.08	3.66
-2.07 to -1.56	1.22
-1.55 to -1.04	2.44
-1.03 to -0.52	4.88
-0.51 to -0.01	6.10
0 to 0.19	7.32
0.2 to 0.39	11.0
0.4 to 0.59	23.2
0.6 to 0.79	25.6
0.8 to 1	14.6

0.274 ± 0.75

Wilk-Shapiro Statistic: 0.94
P-value: <0.001
Test Result: Fail
BBN Distribution: True

VEGETATIVE FILTER STRIP
TP Effectiveness

0.0 to 0.19	1.80
0.2 to 0.39	15.3
0.4 to 0.59	18.0
0.6 to 0.79	27.9
0.8 to 1	36.9

0.666 ± 0.23

VEGETATIVE FILTER STRIP
Adoption

0.0 to 0.19	0
0.2 to 0.39	0
0.4 to 0.59	100
0.6 to 0.79	0
0.8 to 1	0

0.5 ± 0.058

VEGETATIVE FILTER STRIP
TP Performance

0.0 to 0.19	17.5
0.2 to 0.39	47.5
0.4 to 0.59	34.4
0.6 to 0.79	0.39
0.8 to 1	0.39

0.338 ± 0.16

VEGETATIVE FILTER STRIP
DRP Performance

-2.60 to -2.08	0.38
-2.07 to -1.56	0.38
-1.55 to -1.04	3.32
-1.03 to -0.52	4.77
-0.51 to -0.1	10.6
0 to 0.19	19.8
0.2 to 0.39	44.0
0.4 to 0.59	16.0
0.6 to 0.79	0.38
0.8 to 1	0.38

0.114 ± 0.45

To TP Residual Load

To DRP Residual Load

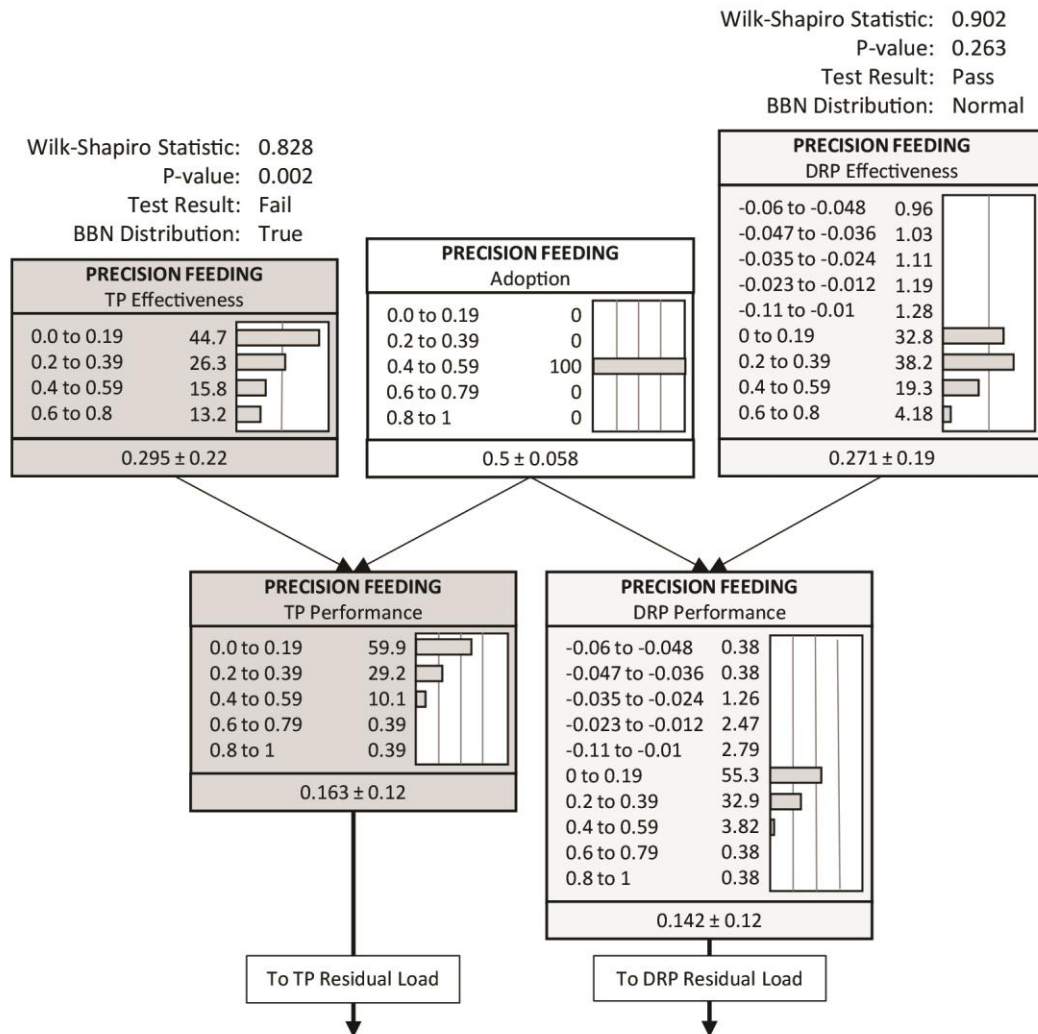**Figure A.6:** Vegetative filter strips (VFS). TP and DRP effectiveness distribution is subjected to the effect of the adoption in the performance node.

Figure A.7: Forest filter strips (FFS). TP and DRP effectiveness distribution is subjected to the effect of the adoption in the performance node.
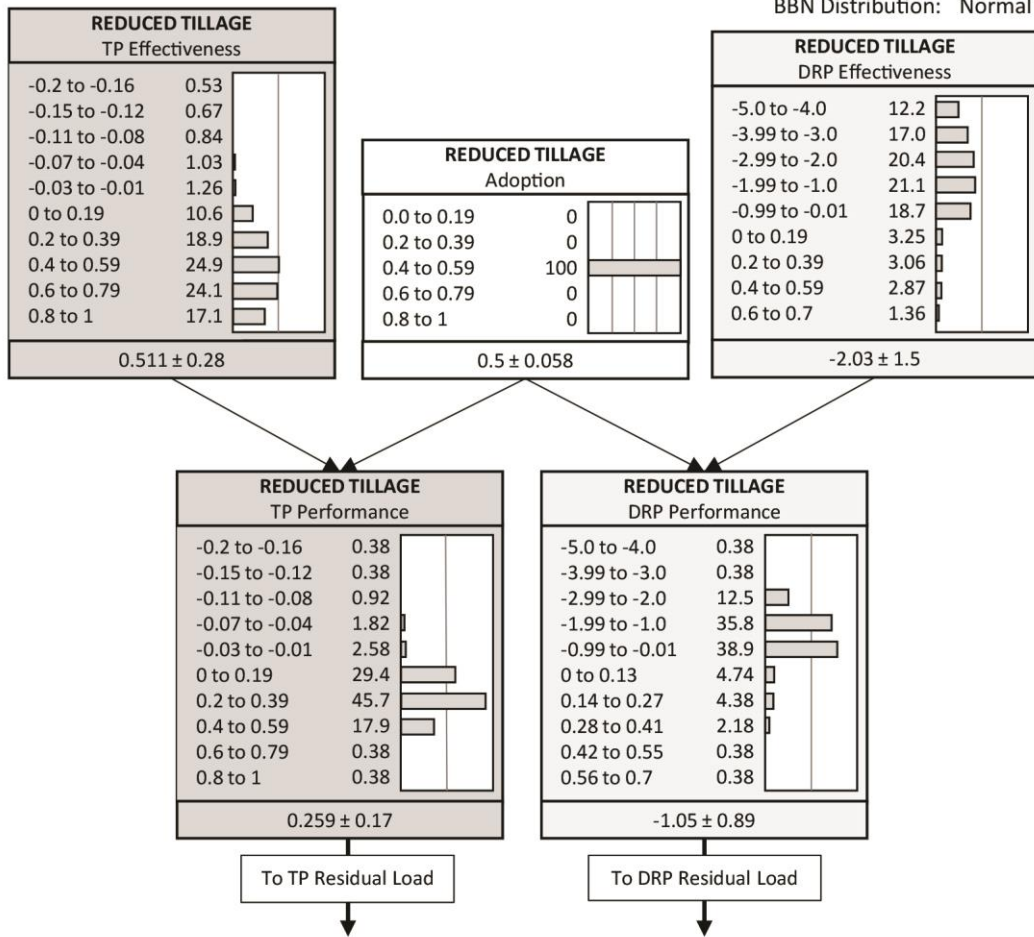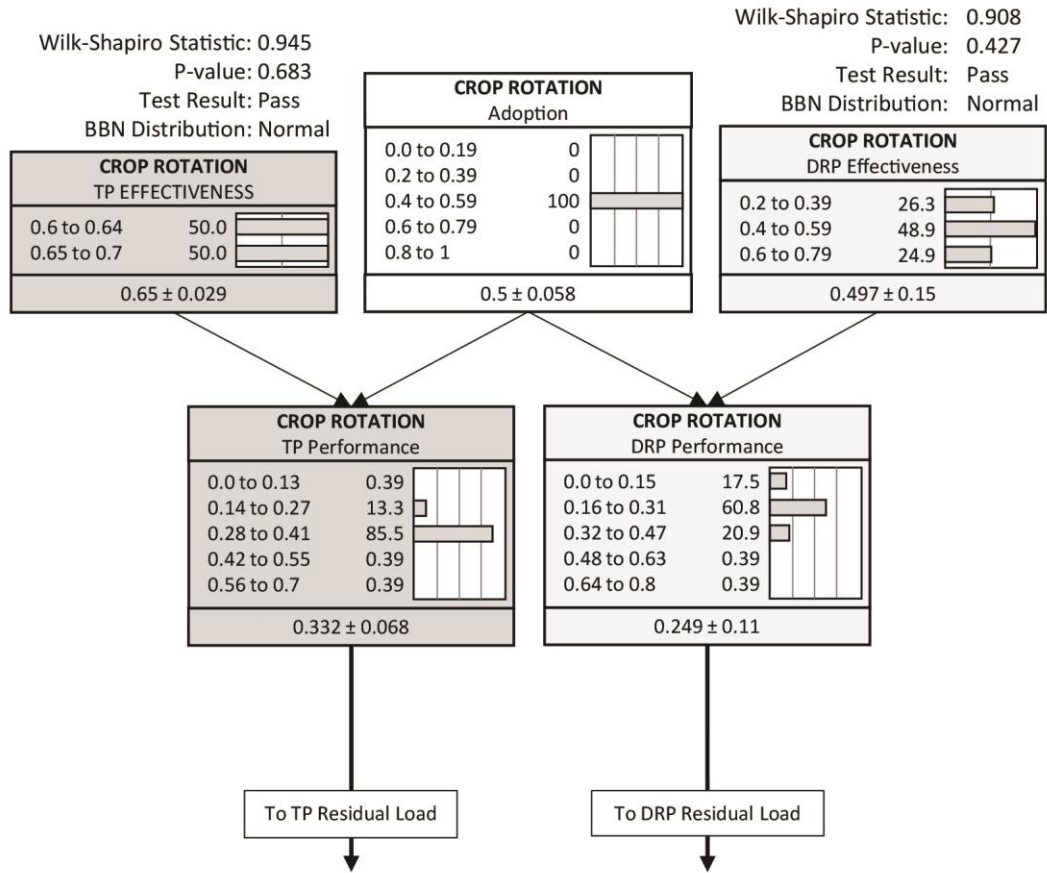
WETLAND RESTORATION
TP Effectiveness

-1.3 to -1.04	4.41	
-1.03 to -0.78	1.47	
-1.77 to -0.52	2.94	
-0.51 to -0.26	1.47	
-0.25 to -0.1	13.2	
0 to 0.19	22.1	
0.2 to 0.39	27.9	
0.4 to 0.59	7.35	
0.6 to 0.79	7.35	
0.8 to 1	11.8	

0.193 ± 0.48

WETLAND RESTORATION
DRP Effectiveness

-1.55 to -1.24	3.92	
-1.23 to -0.93	1.96	
-0.92 to -0.62	5.88	
-0.61 to -0.31	5.88	
-0.3 to -0.1	13.7	
0 to 0.19	15.7	
0.2 to 0.39	21.6	
0.4 to 0.59	21.6	
0.6 to 0.79	3.92	
0.8 to 1	5.88	

0.0984 ± 0.54

WETLAND RESTORATION
Adoption

0.0 to 0.19	0	
0.2 to 0.39	0	
0.4 to 0.47	100	

0.5 ± 0.058

WETLAND RESTORATION
TP Performance

-1.3 to -1.04	0	
-1.03 to -0.78	0	
-1.77 to -0.52	2.42	
-0.51 to -0.26	6.32	
-0.25 to -0.1	15.4	
0 to 0.19	51.3	
0.2 to 0.39	19.4	
0.4 to 0.59	5.12	
0.6 to 0.79	0	
0.8 to 1	0	

0.0747 ± 0.24

To TP Residual Load

WETLAND RESTORATION
DRP Performance

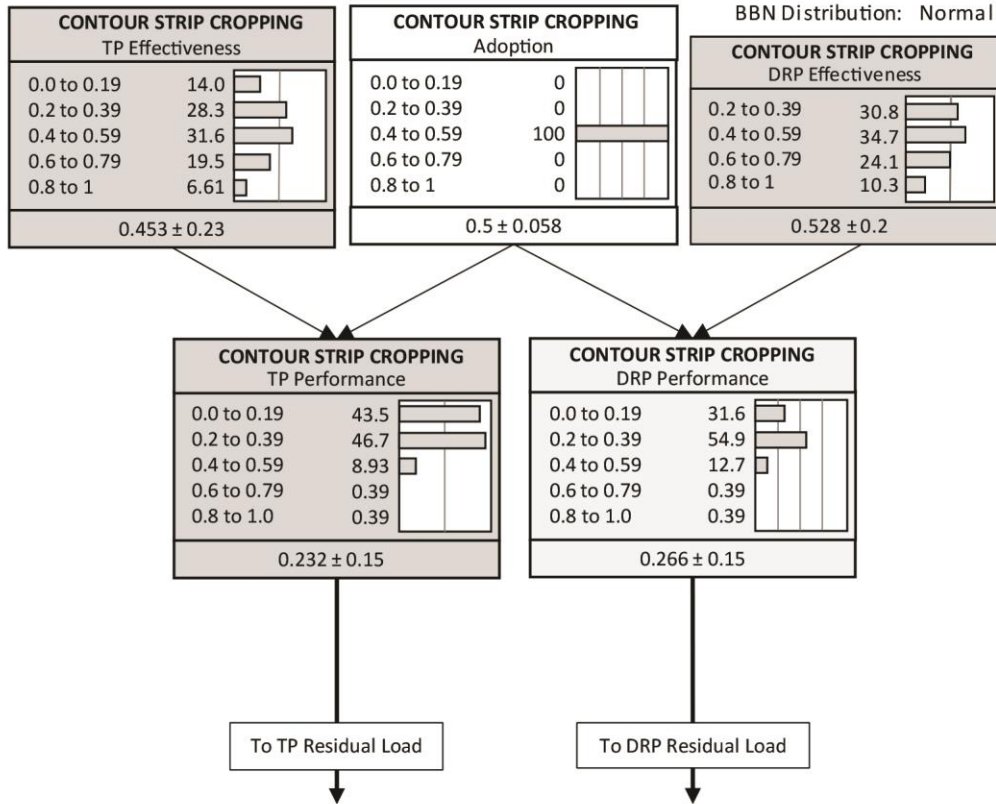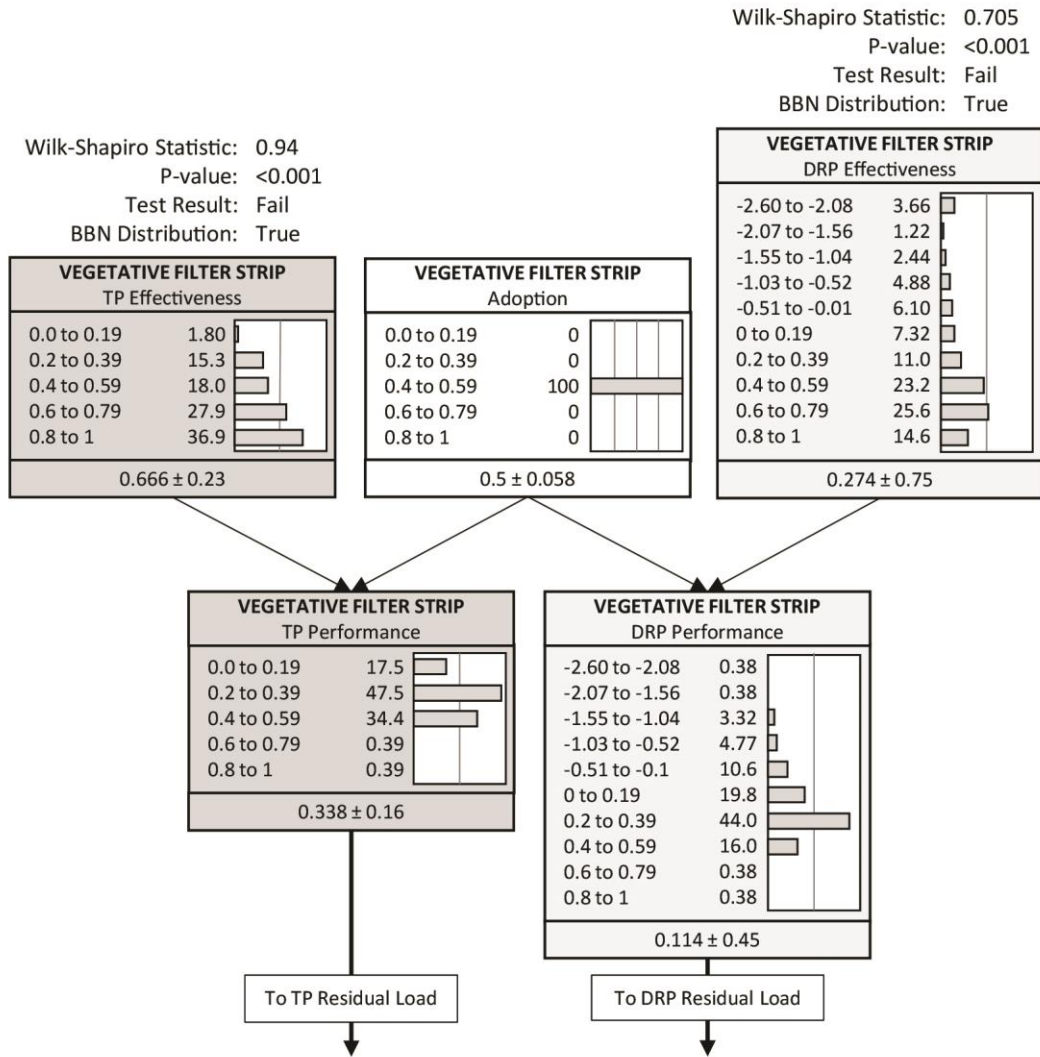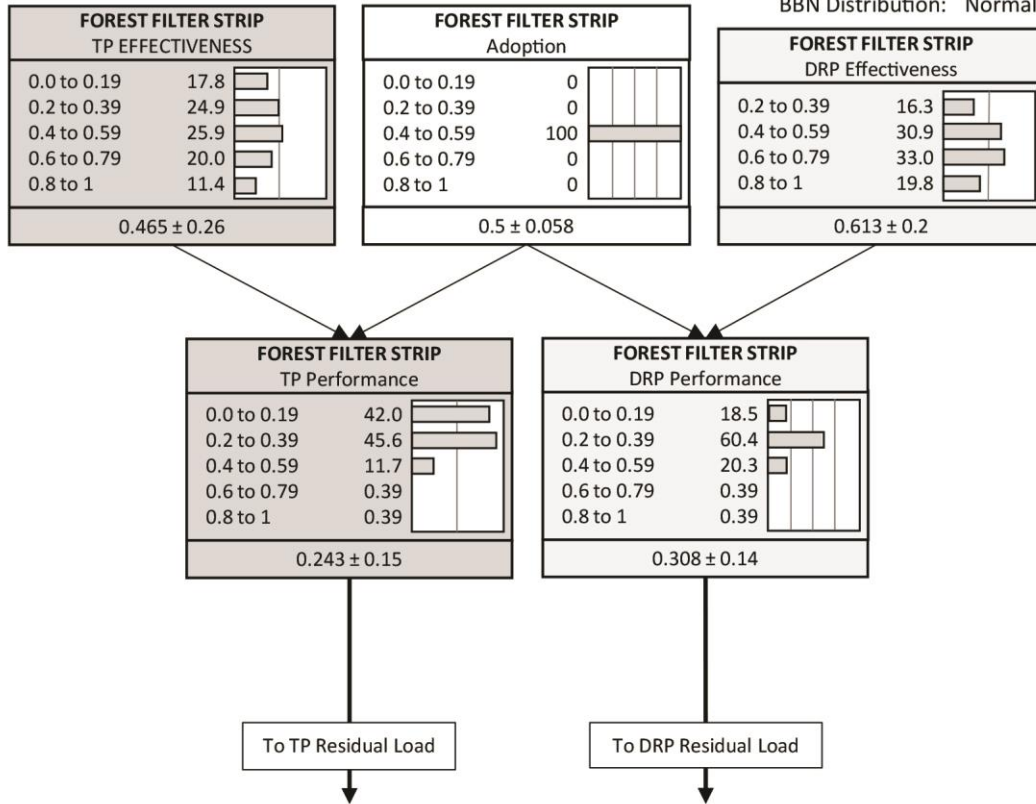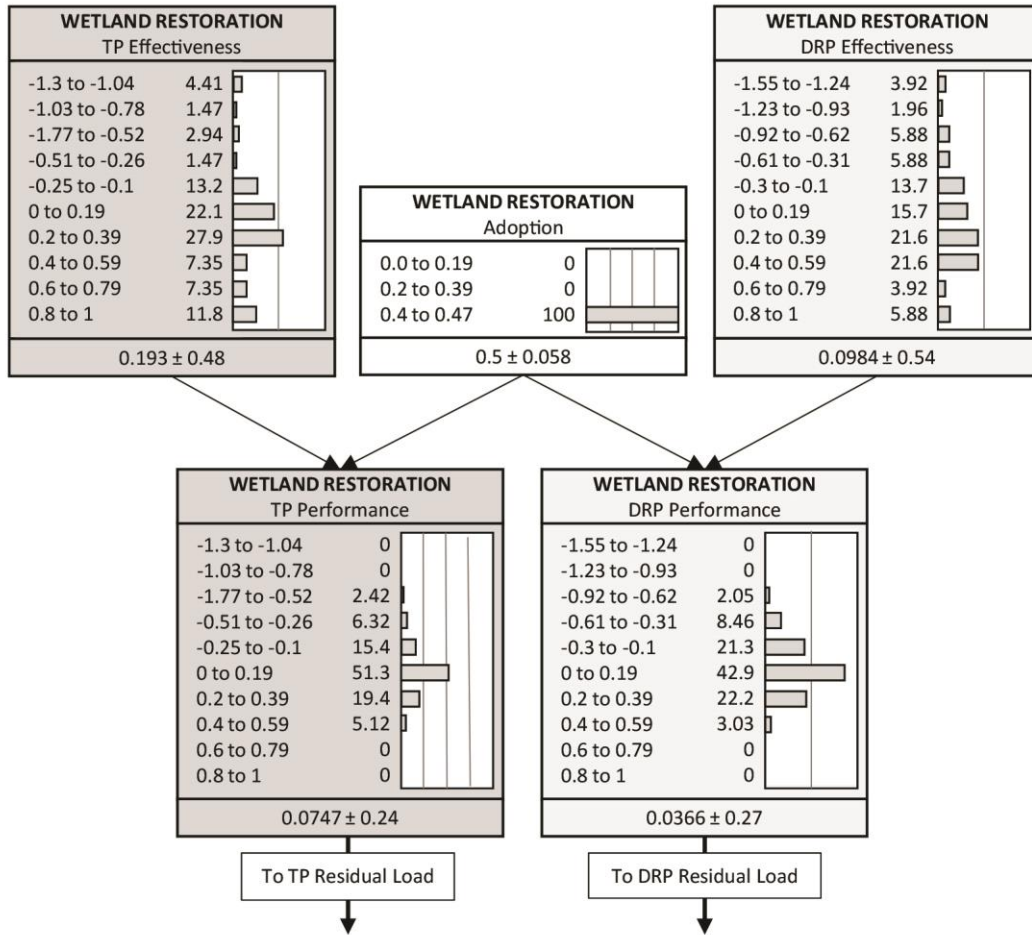|		
-1.55 to -1.24	0	
-1.23 to -0.93	0	
-0.92 to -0.62	2.05	
-0.61 to -0.31	8.46	
-0.3 to -0.1	21.3	
0 to 0.19	42.9	
0.2 to 0.39	22.2	
0.4 to 0.59	3.03	
0.6 to 0.79	0	
0.8 to 1	0	

0.0366 ± 0.27

To DRP Residual Load

Figure A.8: Wetland restoration (WR). TP and DRP effectiveness distribution is subjected to the effect of the adoption in the performance node.

Appendix B: Summary statistics for BMP effectiveness

Table B.1-8: Basic summary statistics are provided for all BMP effectiveness datasets. For TP and DRP effectiveness datasets that passed the normality test, these are the parameters used to generate their distributions, summary statistics for effectiveness datasets that failed normality are provided but not used to generate their distribution in Netica.

TP	Precision Feeding	DRP
24.45	Mean	23.65
20.65	Standard Deviation	21.04
8.55	Minimum	-5.90
70.08	Maximum	68.00
18	n	18
	Igras and Creed 2016	

TP	Nutrient App. Mgmt.	DRP
47.37	Mean	26.48
24.06	Standard Deviation	41.08
14.00	Minimum	-66.00
91.00	Maximum	94.00
9	n	14
	Gitau et al. 2005	

TP	Reduced Till	DRP
0.58	Mean	-1.79
0.36	Standard Deviation	2.57
-0.21	Minimum	-5.00
0.95	Maximum	0.68
11	n	5
	Gitau et al. 2005	

TP	Contour Strip Cropping	DRP
43.68	Mean	45.00
25.29	Standard Deviation	28.12
8.00	Minimum	20.00
93.00	Maximum	92.50
22	n	5
	Gitau et al. 2005	

TP	Forest Filter Strips	DRP
42.58	Mean	62.25
36.11	Standard Deviation	25.64
1.50	Minimum	28.00
93.00	Maximum	99.00
9	n	8
	Gitau et al. 2005	

TP (PP)	Crop Rotation	DRP
65.00	Mean	49.58
4.08	Standard Deviation	16.54
60.00	Minimum	30.00
70.00	Maximum	75.00
4	n	6
	Gitau et al. 2005	

TP	Vegetative Filter Strips	DRP
0.67	Mean	0.32
0.22	Standard Deviation	0.65
0.10	Minimum	2.58
0.98	Maximum	0.97
106	n	72
	Gitau et al. 2005 updated for this Thesis	

TP	Wetland Restoration	DRP
22.10	Mean	14.23
43.68	Standard Deviation	45.40
-127.00	Minimum	-154.00
98.00	Maximum	90.00
58	n	41
	Gitau et al. 2005 updated for this Thesis	

Appendix C: BBN model assumptions

Table C.1: BBN model assumptions.

Assumption	Context	Implication
BMP sub-model Assumptions		
Compiled BMP effectiveness coefficients represented load reductions by BMPs in the Grand River watershed.	Lack of regionally specific data; compiled effectiveness coefficients from regional and international sources.	Effectiveness distributions may not have reflected BMP load reduction in the Grand River; results may have been over or under estimated.
Similar functioning BMPs could be grouped and analyzed together. (NAM and RT).	Lack of effectiveness coefficients for individual BMPs to generate informative distributions.	Distributions do not represent expected reductions of individual BMPs in a grouping.
BMP effectiveness followed a normal distribution unless it failed the normality test.	Pragmatic decision as the shape of effectiveness distributions was evident from visual inspection.	Effectiveness distributions might have under, or over estimated the probability and magnitude of load changes from BMPs.
PP load reduction by CR ~ TP load reduction.	No TP effectiveness data for CR not found. PP traditionally represented the dominant fraction of TP load in *crop systems*.	TP reduction by CR might have been be over estimated.
BMPs managed manure and mineral phosphorus the same.	Limited effectiveness data for mineral and manure phosphorus reduction. Combined data for each BMP to generate a single effectiveness distribution.	Load reductions for manure and mineral phosphorus might have been over or under estimated.
BMP effectiveness assumed implemented BMPs intercept 100% of farm runoff and therefore 100% of phosphorus load was treated.	BMP effectiveness coefficients were generated in the literature based on input/output loads or present/absent BMP studies.	Probability and magnitude of load changes might have been over estimated by BMP effectiveness, unless farmers do spatially implement BMPs to treat 100% of the hydrological flow path.
BMP performance would equal BMP effectiveness, if the BMP treated 100% of the hydrological flow path in all agricultural areas (100% adoption), otherwise performance resulted in supressed influence on residual load.	Equation to estimate performance is Effectiveness*(Adoption), and if adoption = 1 (100%), then performance = effectiveness.	BMP performance might have over or under estimated load reductions in watershed discharge, BMP management at the scale of the watershed is considerably uncertain.

If BMP implementation is spatially random, then a *considerably small probability (<1%)* is assumed for higher magnitudes of phosphorus changes with lower adoption.	The "chance" that minimal BMP adoption might be randomly implemented to achieve treatment of greater proportions the phosphorus load despite minimal treatment of the hydrological flow path.	Small probabilities might have over or under estimated the likelihood of higher magnitude load changes by BMPs as they were manually defined; not based on empirical data or an equation.
Phosphorus Load Assumptions		
Area of agricultural land receiving phosphorus application was representative of the load of phosphorus in discharged from the Grand River agricultural areas.	Relative contribution of phosphorus load from agricultural activities data did not exist. Area of application proportioned the 2008 load among the three agricultural activity pressures.	Proportions might have been over or under estimated and therefore the mass of initial phosphorus load might be weighted inaccurately for the three agricultural activity pressures.
"1-phosphorus recoverability" was the residual proportion of phosphorus that is lost in runoff from livestock operations.	Recoverability; proportion of phosphorus in manure on livestock operations collected for *manure phosphorus application to crops*. 1-phosphorus recoverability was thus used to proportion the 2008 load among the three activity pressures.	The recovery coefficients used were not generated for the Grand River watershed. Might have over or under estimated the proportion of initial phosphorus load from the Grand River contributed by manure application and livestock manure losses.
The average annual proportion of TP that is DRP since 2009 in Grand River discharge ~ the proportion of TP that is DRP in 2008.	Data was unavailable for 2008 DRP load.	The average proportion of TP that is DRP may have over or under estimated the true proportion for 2008.

Curriculum Vitae

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Post-Secondary Education and Degrees:

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Graduate Teaching Assistant – University of Western Ontario
2014-2016
Watershed Survey Technician – Civica Infrastructure Inc
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Field Survey Technician – TBT Engineering Consultants
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Image Processing and GIS Technician – Lakehead University
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Presentations:

Igras, J.D.; Creed, I.F., (2016). Analyzing Great Lakes management system performance and uncertainty of agricultural best management practices to achieve phosphorus load reduction objectives. Oral Presentation. International Association for Great Lakes Research Conference. Guelph, Ontario.

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Igras, J.D.; Creed, I.F., (2016). Quantifying best management practices for phosphorus reduction to surface water. Oral Presentation. Great Lakes Risk Management Workshop. University of Western Ontario. London, Ontario.

Igras, J.D.; Creed, I.F., (2016). Using ISO 31010:2009 Bowtie Risk Analysis to manage multiple stressors and their cumulative effects in the Great Lakes. Oral Presentation. NSERC Great Lakes CREATE Multiple Stressors and Cumulative Effects in the Great Lakes course. University of Guelph. Guelph, Ontario.

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