The Lake Fletcher Phosphorus Model

Environmental Science Undergraduate Thesis

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Chapter 1 - Introduction

Motivation

Lake Fletcher in Nova Scotia has faced increasing pressures of development in recent years (Jaques Whitford Ltd., 2009). The Halifax Regional Municipality (HRM) has regulated that in order for future developments to take place at this location, the decision-making process must consider any possible increase in the Lake Fletcher phosphorus concentration due to proposed development. This decision was situated in the HRM Municipal Planning Strategy: Planning Districts 14/17 (Shubenacadie Lakes) to prevent this lake, which is already at the oligo-mesotrophic boundary, from becoming subjected to eutrophication (Jacques Whitford Ltd., 2009; HRM, 2014). Thus, all new development proposals must first consider whether they will risk causing an increase in trophic status of Lake Fletcher. The lake is used by the local community as a recreation site, for drinking water (both central extraction and distribution and well-water use), and as an aquatic habitat for local species (Jacques Whitford Ltd., 2009).

In order to enforce the HRM's law, there must be a tool to predict changes in lake phosphorus given new development proposals. For this thesis, I will examine the extent to which the "Lakeshore Capacity Model" (Dillon et. al., 1994) can be adapted using "User's Manual for Prediction of Phosphorus Concentrations in Nova Scotia Lakes: A Tool for Decision Making" (Brylinsky, 2004) to accurately predict phosphorus concentrations in Lake Fletcher. Additionally, I will critically examine the performance of this model and its resulting suitability for use in land-use planning. The desired outcome of this study is to provide a reliable and uniform planning tool for use by the HRM to assess the impact on phosphorus concentration from changing land uses surrounding Lake Fletcher.

Background, Context, and Definitions

Eutrophication is the over-enrichment of nutrients in water. Its opposite is to be oligotrophic, where water is nutrient-poor (Lund, 1967). Eutrophication is a naturally occurring phenomenon, however humankind has had a hand in altering the frequency and intensity to which it occurs (Reavie et al., 2000; Hasler & Swenson, 1967; Henderson-Sellers et al., 1987). Cultural eutrophication refers to the phenomenon of eutrophication occurring due to anthropogenic causes. Such anthropogenic causes often include human sewage, industrial wastes, phosphate detergents, drainage from farmlands, and run-off from impervious roadways (Hasler & Swenson, 1967). It can be predicted that increased human presence in areas where bodies of water occur would augment the probability of cultural eutrophication occurring.

Aquatic plant growth can only occur to the extent that limiting nutrients are available. A limiting nutrient is a chemical compound that participates in a reaction, but no matter how much of the other reagents are added, the reaction will not form more products. Only the addition of more of the limiting nutrient for the reaction will allow more products to form. Common limiting nutrients to aquatic ecosystems are nitrogen and phosphorus, but studies have evaluated that in general phosphorus is the limiting nutrient for freshwater systems such as lakes (Hasler & Swenson, 1967).

Phosphorus loading of a natural system is thought of as negative for various reasons, one of the most important being that it acts as a limiting nutrient for algal growth. This may dramatically shift the species composition and trophic structure of a freshwater body. In addition, the algae may release toxic substances and reduce the aesthetic quality of the water. Most importantly, when the abundant algae dies and degrades, massive amounts of dissolved oxygen are used up in the decomposition process, reducing available dissolved oxygen in the water and often killing fish that require a minimum amount of oxygen to survive (Environment Canada, 2004).

Jacques Whitford's study for the Halifax Regional Municipality (HRM) described Lake Fletcher as falling within the "Fall River Growth Area", naming it a location of significant urban development and expansion (2009). Since that time, the area continues to expand, and as urban development stretches farther from city centres, the pressure on Lake Fletcher has intensified. The HRM has issued the Municipal Planning Strategy: Planning Districts 14/17 (Shubenacadie Lakes) (2014) regulating what development may occur in the vicinity of Lake Fletcher with respect to how that development will impact phosphorus concentrations. This has left developers and city officials looking for a uniform and meaningful tool to properly assess how varying land uses will impact phosphorus concentrations of water.

When planning a development project, the Canadian Environmental Assessment Act (2012) considers cumulative effects in the assessment. Cumulative effects can be understood as an effect or impact on the environment that is caused by many sources, so that the cumulative effect has a greater degree of magnitude than any of the individual effects contributing to it. In this study, there will be a necessary implication wherein an increase in phosphorus concentration will be considered "significant". When considering significance in the context of anthropogenic phosphorus pollution, the term relates to a cumulative effect. Thus, the term "significant" for this study is defined as an increase in the phosphorus concentration of Lake Fletcher that would increase the trophic state of the water to be eutrophic.

Summary of Literature

Lake Fletcher is situated in the vicinity of Fall River in the Halifax Regional Municipality, Nova Scotia, Canada (Figure 1). It is part of the Shubenacadie watershed as one of the headwater lakes (Mudroch, 1987). Lake Fletcher falls within the Fall River Growth Area, and thus faces numerous anthropogenic development pressures in the future (Jaques Whitford Ltd., 2009; HRM, 2014).

Eutrophication is a naturally occurring process, however much like the concept of anthropogenic climate change; there is likewise anthropogenic eutrophication. Such eutrophication is termed cultural eutrophication. This effect is caused by an accelerated rate of addition of nutrients into a water system which alters the trophic state faster than the natural system can mitigate the increased nutrient levels (Reavie et al., 2000; Hasler & Swenson, 1967; Henderson-Sellers et al., 1987). It has been seen that limiting inputs of phosphorus into freshwater systems has had success in reducing anthropogenic eutrophication (Schindler, 2012). Thus selecting for developments that do not cause a significant increase in phosphorus concentrations can prove to be an effective tool against eutrophication.

Cultural eutrophication of lakes is due to anthropogenic inputs of phosphorus from human sewage, agricultural fertilizers, and excrement of livestock (Schindler, 2012). As urban development expands farther from city centres, the intensity of anthropogenic impacts on lakes that were previously in relative isolation has the potential to increase.

Anthropogenic chemical inputs may increase the nutrient load, allowing the occurrence of algal blooms that alter the ability of other species to exist in the lake (Schindler, 2012).

The Canadian Council of Ministers of the Environment published *Phosphorus: Canadian Guidance Framework for the Management of Freshwater Systems* (2004), which outlined a framework for management of phosphorus in freshwater in Canada. This report gives a foundational background for freshwater phosphorus management in Canada, but does not give any quantifiable means to calculate future phosphorus concentrations nor an objective valuation of acceptable phosphorus concentration increases for use in development planning (CCME, 2004).

The "Lakeshore Capacity Model" (Dillon & Rigler, 1975) is an established and widely used model for predicting phosphorous concentrations of Ontario lakes. The model takes into account inputs such as per capita phosphorus load, usage and occupancy of residences, and attenuation of septic tanks, as well as biophysical parameters such as lake morphology, precipitation, and vegetation. This is seen as the go-to model for Ontario lakes. It is however, not suitable for Nova Scotia lakes due to spatial variability of the various biophysical parameters and phosphorus export coefficients. Thus the "User's Manual for Prediction of Phosphorus Concentration in Nova Scotia Lakes: A Tool for Decision Making Version 1.0" was created as a roadmap for scientists to adapt the Ontario model to suit Nova Scotia environments (Brylinksy, 2004). Despite these tools, the selection of phosphorus export coefficients for the various land-uses in the watershed is highly subjective and not often uniformly applied within the scientific and development communities (Brylinksy, 2004). More work remains to be done in creating an established way to implement this model in a uniform way for a given body of water.

Lake Fletcher is near Fall River and parallel to Highway 2 in the HRM of Nova Scotia. It is one of several headwater lakes to the Shubenacadie River (Underwood et. al., 1987). Development has intensified and expanded in the Fall River area (Jaques Whitford Ltd., 2009). If such development alters or contaminates the water quality of Lake Fletcher then uses such as drinking water, recreational activities, and aquatic habitat may be compromised. The HRM Municipal Planning Strategy: Planning Districts 14/17 (Shubenacadie Lakes) (2014) has implemented limits to development surrounding Lake Fletcher so that no developments may occur that pose a threat to increasing the trophic status of the lake. The HRM and developers seek a uniform tool to evaluate whether proposed development projects would be projected to create a net phosphorus concentration increase in Lake Fletcher. There is no uniform method for achieving this currently.

Introduction to Study

This study aims to adapt Dillon's & Rigler's "Ontario Lakeshore Capacity Model" (1975) using "User's Manual for Prediction of Phosphorus Concentration in Nova Scotia Lakes: A Tool for Decision Making Version 1.0" (Brylinsky, 2004) and regional data to create export coefficients for the model to suit phosphorus concentration predictions for Lake Fletcher, Nova Scotia, Canada. This model is then intended for use by the HRM for establishing acceptable land uses and developments in the Lake Fletcher area that will not create a net increase in phosphorus concentration (HRM, 2014). The research question guiding this study is as follows:

- Can an adapted version of Dillon & Rigler's "Lakeshore Capacity Model" (1975) be used to predict phosphorus concentrations in Lake Fletcher?

- Should an adapted version of Dillon & Rigler's "Lakeshore Capacity Model" (1975) be used for planning purposes?

The scope of this study is that it will look at Lake Fletcher, Nova Scotia and its current land uses and biophysical parameters. The study will rely on sourcing data from various government publications and reports to determine these biophysical parameters and on evaluating scientific publications in order to determine suitable phosphorus export coefficients for the model.

Summary of Approach

The first research questions will be answered by creating new export coefficients for the model by selecting appropriate values from an acceptable range as stated in "User's Manual for Prediction of Phosphorus Concentration in Nova Scotia Lakes: A Tool for Decision Making Version 1.0" (Brylinsky, 2004) based on scientific studies on similar watersheds, and then using that model to predict the phosphorus concentration of Lake Fletcher. In order to validate the model and its phosphorus prediction value for Lake Fletcher, the predicted phosphorus concentration will be compared to recent measured values. The second research question will be answered by taking a critical view of the model's extent and validity by evaluating the available phosphorus export coefficient data and model application. The final deliverable of this study will be a complete model to predict the phosphorus concentration in Lake Fletcher relative to a new development proposal.

Chapter 2 – Literature Review

Introduction

Eutrophication of lakes has become a common topic of discussion in the scientific community since the 1960s (Hasler & Swenson, 1967). Numerous studies have been conducted, and eutrophication of lakes has become well studied worldwide. What appears to lack is a uniform method of implementation of policies in order to manage anthropogenic effects on phosphorus concentrations of freshwater systems. There is no Canadian national phosphorus management policy, and implementation across provinces varies greatly (CCME, 2004). The following sections will first outline the environment of Lake Fletcher in Nova Scotia, Canada to establish the environmental context of eutrophication at this site. The literature review will also discuss what constitutes cultural eutrophication and provide an overview of phosphorus models and how they have been established over time. Finally, the Halifax Regional Municipality (HRM) bylaw that describes the way in which new developments must consider Lake Fletcher phosphorus concentrations will be outlined. From these, it will become apparent that a uniform model to predict phosphorus concentrations in Lake Fletcher given different development scenarios is necessary for responsible management decisions.

Overview of Lake Fletcher

i. Environment

The biophysical characteristics of the environment at and surrounding Lake Fletcher make it a unique lake system from Ontario lakes. The region is principally characterized by soils of the Halifax and Wolfville series, however also includes soils from other groups such as Rockland, Gibraltar, Bridgewater, Peat, Mahone, and Hantsport. The underlying rock types are Cambrian Goldenville and Ordovician Halifax formations, Devonian granite, and various Pleistocene glacial deposits. These rock types correspond to deep-sea sediments, greywacke, quartzite, gneiss, slate, and schist (Mudroch, 1987; Jacques Whitford Ltd., 2009). Nova Scotia forest cover is primary softwood, with some mixed wood and hard wood. Such tree types include spruce, balsam fir, eastern hemlock, white pine, and larch (Department of Natural Resources, 2008). The climate at Lake Fletcher is impacted by the proximity to the Atlantic Ocean, which stabilizes temperatures to a smaller, less extreme range than would be observed in more central areas of Canada (Mudroch, 1987). Lake Fletcher is part of the Shubenacadie headwater lakes basin in the HRM. Additionally, the Shubenacadie River headwaters area has approximately 80 wetlands, most of which are less than 20 hectares large (Mudroch, 1987). In 2007, the trophic state of Lake Fletcher was evaluated to be near the oligo-mesotrophic boundary based on total phosphorus measurements (Jacques Whitford Ltd., 2009). In sum, these natural characteristics of the Lake Fletcher area define the context in which natural and anthropogenic processes interact.

Figure 1. Aerial photograph of headwater lakes of Lake Fletcher, Nova Scotia, including Lake Charles, Lake William, Powder Mill Lake, Lake Thomas, and Lake Fletcher. Arrow indicates direction of flow (Adapted from: maps.google.com).

ii. Geography

Lake Fletcher is situated in Fall River, Nova Scotia and is poised to face increasing anthropogenic pressures thereby increasing susceptibility of the lake to eutrophication. Figure 2 depicts a map of the Lake Fletcher area, in which city streets and roadways can be seen in close proximity to the lake. It is in close proximity to the Halifax International Airport, a major highway system, industrial parks, and urban and commercial development (Mudroch, 1987). The land along the shorelines of Lake Fletcher is entirely clear-cut for 1-2 km extending from the water, exemplifying the degree of anthropogenic alteration this region experiences (Jacques Whitford Ltd., 2009). Lake Fletcher was classified in 2009 as part of the "Fall River Growth Area" by the HRM, and this name was termed once more in 2014 in the HRM Municipal Planning Strategy: Planning Districts 14/17 (Shubenacadie Lakes). This term implies that the region is facing increased urban development and expansion (Jacques Whitford Ltd., 2009; HRM, 2014). Thus, Lake Fletcher, Nova Scotia exists in environmental conditions that incorporate both natural and anthropogenic influences. These influences will provide information to evaluate appropriate coefficients for use in phosphorus concentration modeling.

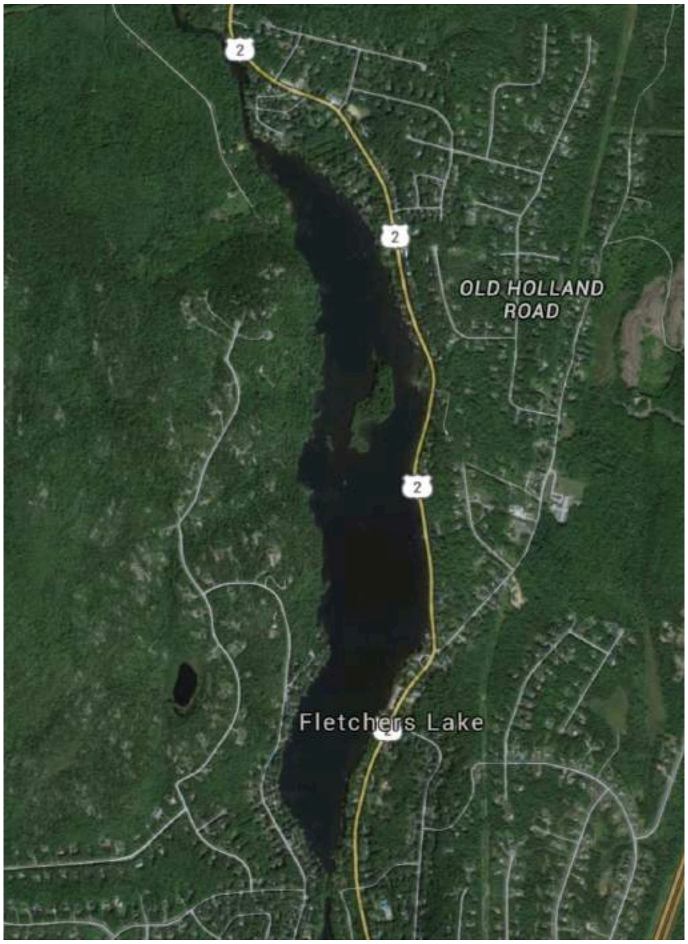

Figure 2. Aerial map of Lake Fletcher, Nova Scotia, Canada. (Source: maps.google.com)

Natural Eutrophication and the Problem of Cultural Eutrophication

i. Natural Eutrophication

Eutrophication is a naturally occurring process that may take place over centuries by which an abundance of nutrients prompts increased primary production and altered trophic status of an ecosystem. In freshwater systems, the limiting nutrient for algal growth is phosphorus (Hasler & Swenson, 1967; Schindler, 2012; CCME, 2004). In Canada, it can be seen that lakes with low concentrations of phosphorus tend to support healthy and diverse ecosystems (CCME, 2004). Conversely, lakes that experience high inputs of phosphorus may over time become eutrophic, wherein the trophic status becomes less diverse and favours principally primary production. Eutrophication is characterized by excessive growth of primary producers and increased plant biomass. This may lead to decreases in biodiversity and trophic complexity, loss of ecologically sensitive species, increases in organic matter and sedimentation, increases in turbidity, anoxic water conditions, and production of toxins (Hasler & Swenson, 1967). Thus, it can be seen that natural eutrophication occurs due to increased natural phosphorus inputs that may lead to adverse ecological effects.

ii. Cultural Eutrophication

A new phenomenon of cultural eutrophication now exists, wherein anthropogenic activities accelerate and intensify natural eutrophication processes. Cultural eutrophication is the acceleration of natural eutrophication rates due to anthropogenic activities that introduce excess nutrients into lake catchment areas. This acceleration could alter a natural eutrophication process so that rather than it occurring over many centuries, the acceleration of cultural eutrophication could change the rate to occurring over a matter of decades or less (Reavie et al., 2000; Hasler & Swenson, 1967; Henderson-Sellers et al., 1987). The intensity of cultural eutrophication is in part due to the seasonality of some biological processes, such as bacterial consumption of nutrients, compared to constant anthropogenic nutrient inputs that often occur year round (Hasler & Swenson, 1967). This concept can be compared to cars driving on roads at a constant rate, but lights at an intersection only being green at certain times. We can think of the cars in this analogy as being phosphorus inputs, and the green light as being the season that bacteria and natural processes can mitigate these nutrients. During the times that the light is red, cars begin to stockpile at the intersection waiting to get through. So long as not too many cars are on the roads, almost all of the cars at the intersection should be able to get through in the time of one green light and clear the intersection. This can be thought of as what happens in natural eutrophication. However, if there is high traffic, not all cars are likely to get across the intersection during one green light, so the queue will continue to increase as more cars come to the intersection, but the length of green lights remains the same. This can be thought of as what occurs during cultural eutrophication.

A significant increase in algal blooms in Ontario (an indicator of eutrophication) has occurred over the period of 1994 to 2015. These blooms are also occurring later into the fall season since the 1990s. This rate of increase is attributed to anthropogenic activities and climate warming, indicating cultural eutrophication (Winter et. al. 2011). The control of phosphorus inputs to reduce cultural eutrophication in lakes has had widespread success, which provides a verification of the effects of cultural eutrophication (Schindler, 2012). Many freshwater systems are impacted by cultural eutrophication as the intensity of human activities increases in proximity to their catchment areas. This alters trophic status to be overtaken by primary production and may decrease dissolved oxygen availability for organisms of different trophic states. The input of excess nutrients due to anthropogenic activities must be monitored and managed to prevent further cultural eutrophication.

History of Tools and Approaches to Phosphorus Loading Models

i. Lakeshore Capacity Model

Phosphorus loading models have been relatively constant and consistent since the 1970s. Jaques Whitford Ltd. states that excess algae growth in lakes is a direct response to phosphorus loading, which may be mathematically modeled (2009). The primary phosphorus model in use is Dillon & Rigler's "Lakeshore Capacity Model", which was originally published in the article "A simple method for predicting the capacity of a lake for development based on lake trophic status" (1975). Since its advent, this model was been widely used in the scientific community (Paterson et al., 2006; Soliman et. al., 2007; Hutchison et al., 1991), lending reliability and trustworthiness to this approach. In addition, version 1.0 of the model was proposed in 1975 and since then has gone on to be adapted to version 3.0 (Paterson et al., 2006). Through these multiple versions, the model has been made to more accurately reflect natural phenomena, thereby giving it a higher level of precision. A further discussion of the practical components of the model can be found in the Methods section.

ii. The Lack of a Uniform Model

Despite the Lakeshore Capacity Model's widespread use, in its original form it is not suitable for all lake environments. This model is fairly general and was originally created for use on Ontario lakes, thus it requires adaptation to suit different environments (Dillon et al., 1994). The model is designed to be general, so does not provide specific export coefficients, but rather provides instructions through which to derive them (Paterson et al., 2006). This is logical because the environmental and land-use context of a lake on the west coast of Canada, for example, would be very different from the context of a lake on the east coast. Moreso, even if lakes are in similar spatial proximity, any lakes that exist in separate watersheds are likely to exist in varied contexts. In order to create a model that is suitable for Lake Fletcher, Nova Scotia, the "User's Manual for Prediction of Phosphorus Concentration in Nova Scotia Lakes: A Tool for Decision Making Version 1.0" (Brylinsky,

2004) must be employed to adapt the Lakeshore Capacity Model to be suitable for application through the selection of appropriate phosphorus export coefficients for Lake Fletcher and its watershed. However, the selection and creation of these export coefficients may still be subjective and may vary depending on the individual that uses the model. No uniform set of coefficients is currently established for Lake Fletcher. Therefore, a space exists in which a consistent set of coefficients must be established to create a uniform model for policy use.

CCME - Phosphorus: Canadian Guidance Framework for the Management of Freshwater Systems

i. Model Framework

The Canadian Council of Ministers of the Environment (CCME) report, *Phosphorus: Canadian Guidance Framework for the Management of Freshwater Systems* (2004), provides context for freshwater phosphorus management, but does not provide a uniform method to identify allowable phosphorus concentrations given proposed developments. This study calls for the creation of phosphorus concentration prediction models for specific bodies of water in order to accurately apply the guidance framework (CCME, 2004). Although this guidance framework takes good preliminary steps to account for the integration of phosphorus thresholds in management decisions, it lacks a specific and consistent method to predict allowable phosphorus concentrations in a specific body of water.

ii. Decision-Making Application

The CCME report provides a framework for management decisions about phosphorus concentrations based on evaluating if changes from baseline values are acceptable to the stakeholder. A guidance framework consistent with CCME 1991 guidance principles was created for phosphorus concentrations based upon a tiered approach in which sites are marked for further assessment based upon whether their trophic status falls within specific trigger ranges. Trigger ranges are evaluated relative to baseline trophic condition for each site. The upper concentration limit of this trigger range indicates the maximum allowable phosphorus concentration for the water body. Additionally, if phosphorus concentration increases by more than 50% from the baseline value, even if the trigger range has not been exceeded, that development is not allowable. In order to make management decisions, results are compared to original goals and baseline conditions to determine whether changes are acceptable to the decision-maker (CCME, 2004). Despite the optimistic nature of this report, no systematic way to evaluate whether changes are acceptable is provided. This means that even if a trigger range is met and trophic state changes as a result, this could be deemed acceptable in a subjective valuation, particularly if bias is involved. For land development use, this framework is inadequate to provide a hard quantifiable measure for what phosphorus concentration is allowable for water bodies. Thus, a more definitive quantifiable model is needed to rationalize management decisions regarding freshwater systems.

HRM Municipal Planning Strategy: Planning Districts 14/17 (Shubenacadie Lakes)

The HRM passed a bylaw indicating that increased development around Lake Fletcher would compromise the trophic state of the lake, giving the potential for it to become eutrophic. Thus, all new developments must prove that they will not increase the phosphorus concentration of Lake Fletcher. The community in Fall River is concerned about maintaining water quality as development occurs in the region. Thus, the HRM has named minimizing the increase in phosphorus concentration in Lake Fletcher as an environmental priority (HRM, 2014). Lake Fletcher is currently identified to be oligotrophic, with fears that further development will cause it to become mesotrophic (Jacques Whitford Ltd., 2009; HRM, 2014). The bylaw defines that the upper limit for annual phosphorus loading is 10 µg/L if a lake is to be at an oligotrophic state and upon exceeding 20 µg/L the lake would become eutrophic (HRM, 2014). Under this bylaw, any new development of a size greater than eight units/lots must adhere to the "no net increase phosphorus export policy" (HRM, 2014). The details of this bylaw are as follows:

> "As part of the assessment process for a development agreement, applicants shall be required to submit a study by a qualified person demonstrating that the proposed development will not export any more phosphorus from the site than what may be exported from the site prior to the development taking place. The total amount of phosphorus that is expected to be exported from the site prior to the undertaking of a development shall in effect become the phosphorus budget or limit for the amount of phosphorus that may be allowed to be exported from the site under the proposed development for that area. If the amount of phosphorus for a proposed development exceeds the phosphorus budget for the site, then the density of development will have to be adjusted to reduce the phosphorus impacts on the receiving environment." (HRM, 2014, p. 127).

Thus, all new developments must be modeled to indicate that there will be a no net increase in phosphorus inputs to Lake Fletcher. However, no model with uniform coefficients exists to provide consistent predictions. Dillon & Rigler's "Lakeshore Capacity Model" (1975) is the best available tool, but the selection of phosphorus export coefficients for land-uses captured under the model are highly subjective. This means that any environmental consultants running the model on proposed developments will come up with inconsistent and incomparable values. In order to require developers to prove a no net increase in phosphorus export from a development site, an adequate tool for phosphorus concentration prediction must be presented to them. The HRM requires a model with appropriate export coefficients be created for use in all future Lake Fletcher developments.

Conclusion

In summary, although well-established models exist to predict phosphorus concentrations in lakes, the model may not be consistent depending on the user. Rather, a model for predicting phosphorus concentrations in Lake Fletcher given proposed developments must be created that has set phosphorus export coefficients that are appropriate to Lake Fletcher and its watershed specifically. In this way, developers and the municipality will have a reliable tool that gives accurate results with which they may establish phosphorus concentrations given new development projects so that they may conform to regulations outlined in the HRM Municipal Planning Strategy: Planning Districts 14/17 (Shubenacadie Lakes) (HRM, 2014). An appropriate tool will aid in ensuring that responsible management actions are taken to prevent eutrophication of Lake Fletcher.

Chapter 3 – Methods

Introduction

The creation of a model to predict the phosphorus concentration of Lake Fletcher relies on the adaptation of Dillon & Rigler's "Lakeshore Capacity Model" (1975) using Brylinsky's "User's Manual for Prediction of Phosphorus Concentration in Nova Scotia Lakes: A Tool for Decision Making Version 1.0" (2004). This project focused on reviewing and selecting appropriate phosphorus export coefficients by performing a literature review of available government publications and scientific data.

Lakeshore Capacity Model

Dillon & Rigler's "A simple method for predicting the capacity of a lake for development based on lake trophic status" (1975) gained popularity in the scientific and planning communities to an extent that it is now referred to as simply the "Lakeshore Capacity Model". As described previously in the Literature Review section, this model was created for use on Ontario lakes in order to predict the change in phosphorus concentration that would occur in a lake accompanying new developments nearby. The mass-balance model is most easily reduced to the following equation (Dillon & Rigler, 1975):

$$[TP]_{\text{ice-free}}=L_T * (1-R_p) * (1.965 * q_s)^{-1}$$

- $[TP]$ = total phosphorus concentration ($g\ P\ m^{-2}\ yr^{-1}$)
- L_T = total area loading rate ($m^3\ yr^{-1}$)
- R_p = retention coefficient
- q_s = areal water load ($m\ yr^{-1}$)

The above equation may appear relatively tidy and simple, but in reality each variable in the equation is calculated from a series of other variables. The equation and calculations take the form of multi-page linked Excel spreadsheets that link cell values through equations in order to produce a final predicted phosphorus concentration. As stated in the literature review, this model exhibits pronounced spatial and temporal variability, particularly when used outside of the context of Ontario Lakes (Dillon & Rigler, 1975). Therefore, some form of adaptation must be done to improve the suitability of this model for Lake Fletcher.

Nova Scotia Phosphorus Model

Brylinsky created "User's Manual for Prediction of Phosphorus Concentration in Nova Scotia Lakes: A Tool for Decision Making Version 1.0" (2004) in order to adapt biophysical parameters and phosphorus export coefficients for Nova Scotia lakes from Dillon & Rigler's 1975 model. For ease of referral, I will now refer to Brylinsky's model as the Nova Scotia Phosphorus (NSP) Model. This model is designed as a mass-balance, steady-state model. Mass-balance means that the model is a budget of what phosphorus is entering and leaving the lake. Steady-state means that phosphorus input is equal to the sum of the amount that remains in the lake plus that which leaves as output. The NSP model is, in essence, the Nova Scotia edition of the Lakeshore Capacity Model. It provides instruction for adaptation of all parameters that were intended in the Lakeshore Capacity Model as specific to Ontario lakes so that they may be appropriate for application with Nova Scotia lakes. Through the NSP model, areas of land uses and biogeochemical cycling constants are evaluated for the environment in question and suggested phosphorus export coefficient ranges are provided (Brylinsky, 2004). This model employs linked Excel spreadsheets, where values are assessed through literature review, entered into the spreadsheet for each variable, and then those variables may be used to establish coefficients for the Lake Fletcher Phosphorus Model (Brylinsky, 2004). A sample worksheet is attached as Appendix 1. Figure 3 depicts the branched nature of sourcing many values for biophysical data in order to create a phosphorus concentration prediction.

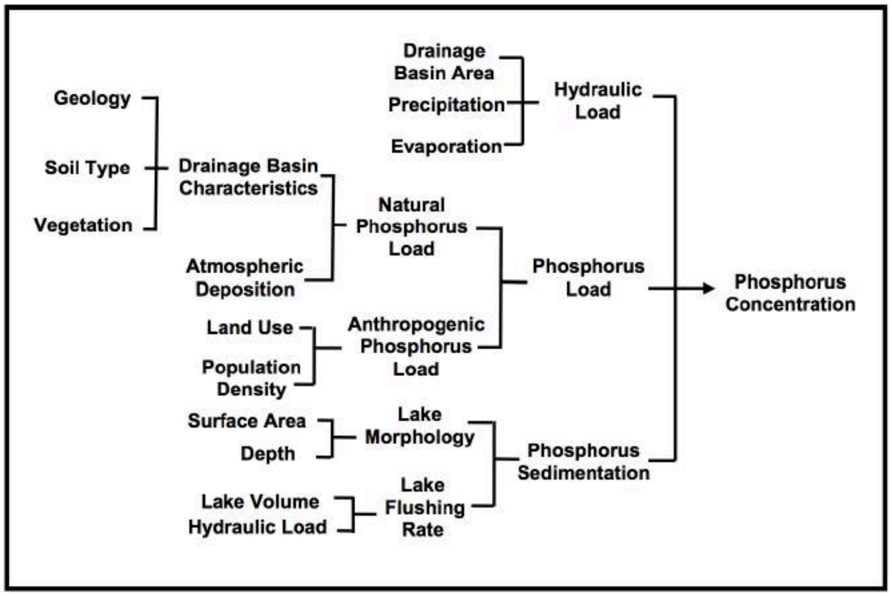

Figure 3. Biophysical and land-use parameters to consider in the establishment of the NSP model. Image source: (Brylinksy, 2004).

Spreadsheet Creation

In this thesis, the Excel spreadsheets (see Appendix 2) were hand-formulated through referral to pre-existing functioning spreadsheets in the “Fall River-Shubenacadie Lakes Watershed Study” (Jacques Whitford Ltd., 2009). The pre-existing spreadsheets were used to establish the equations that were necessary for linking cells when building the model. The Excel document is composed of linked spreadsheets for Lake Charles, Lake William, Lake Thomas, and Lake Fletcher. Also included within the Lake William land areas is the land area use of the region surrounding Powder Mill Lake: a small lake the feeds into Lake William but is too complicated by division of sub-catchment areas to receive its own spreadsheet (Jacques Whitford Ltd., 2009). The total phosphorus outflow from the spreadsheet for an upstream lake is linked to become the upstream phosphorus input to its subsequent downstream lake. For example, the total outflow of the phosphorus budget of Lake Thomas becomes the upstream phosphorus input (Pi) to Lake Fletcher.

Land Use & Biophysical Parameters

This phosphorus prediction model requires the designation of different land use areas which each have their own associated phosphorus export coefficient. The "Fall River-Shubenacadie Lakes Watershed Study" (Jacques Whitford Ltd., 2009), which was reported for the HRM, had done extensive research in delineating the different land use areas using GIS. The types of land use identified for the Fall River-Shubenacadie Lakes area were Forest, Forest/Cleared, Urban, Commercial, Industrial, Green Space, and Institutional. Each land use type was given a corresponding valuation of area through GIS analysis. Additionally, an evaluation of the hydrology for these lakes was conducted, providing all the necessary values for the hydrology inputs component of the model (see Appendix 2). Thus, all values for Morphology, Hydrology Inputs, and Phosphorus Inputs, excluding the phosphorus export coefficients (E1-E10) and upstream phosphorus input (Pi) were sourced from Jacques Whitford Ltd., 2009.

Photo Survey

The various land use categories given for the Shubenacadie Lakes area are not clearly defined within the "Fall River-Shubenacadie Lakes Watershed Study" (Jacques

Whitford Ltd., 2009) nor does the report provide GIS maps delineating where the specific land use categories are considered to be within the watershed. Further clarification from the authors of the report combined with personal judgment calls on reasonable definitions for land use categories provided the following definitions, as summarized by Table 1. These definitions of the land use categories were verified through a purposive photo survey of areas in the watershed that may be characteristic examples of each land use category. Examples of photo survey data are available in Appendix 3.

Table 1. Definitions of the land use categories employed in the Lake Fletcher Phosphorus Model as established through photo survey and further clarification with report authors.

Land Use Category	Definition
Forest	Undeveloped forested land
Forest/Cleared	Any undeveloped forested land that has at least 15% of its area barren (e.g. harvested, barren, sparsely treed, etc.)
Urban	Residential and mixed-use residential, low-medium density, low-medium traffic, often very sloped
Commercial	Business park with high proportion of impervious surfaces and moderate-high traffic
Industrial	Land developed for mines, factories, with little to no vegetative cover
Green Space	Areas devoted to park space or grass cover (e.g. sports field)
Institutional	Hospitals, schools, etc. (not explicitly defined because the lakes don't implicate any area dedicated to this land use category)

Phosphorus Export Coefficient Literature Review

The creation of the phosphorus export coefficients for the model depended on an evaluation of the results of studies that determined phosphorus export coefficients for other watersheds and then determining which of those coefficients were most suitable for the Shubenacadie Lakes. Factors in evaluating the suitability of a phosphorus export coefficient from other studies for use with the Shubenacadie Lakes included similarities in ecology, soil and geology, rate and quality of precipitation, human population, density of housing and commercial spaces, presence of roadways and volume of traffic. When ranges of possible coefficient values were provided in a paper, a subjective valuation was performed as to where in the range the Shubenacadie Lakes would fall when considering other possible coefficients and the biogeochemistry of the watershed. The suggested ranges for export coefficients in the NSP Report were used as guidance for what values from other sources may be appropriate. Literature sources for the phosphorus export coefficient data included Dillon & Molot, 1997; Lowe & Brylinsky, 2002; Reckhow et al., 1980; Brylinsky, 2004; Scott et al., 2000; Duan et al., 2012; Winter et al., 2000; Waller & Hart, 1986; Maine Department of Environmental Protection, 2000; and Johnes, 1996.

Calculation of Phosphorus Export Coefficients

All seemingly suitable values for phosphorus export coefficients for the specific land use categories of the Shubenacadie Lakes were amassed for consideration in calculating the coefficients. For each land use category, a mean was taken of all of the phosphorus export coefficients that were collected in order to establish the phosphorus export coefficient for that land use that would be inputted into the model (Table 2). These values were maintained initially, and then upon model validation were tweaked by removing certain values that could be skewing the phosphorus export coefficient from its correct value. Thus in the development of the model, calculation of coefficients and model validation were a somewhat iterative process wherein the results of one was able to inform improvement in the other.

Model Validation

In order to validate the Lake Fletcher Phosphorus Model, the predicted phosphorus concentration value generated by the model must be compared to a measured phosphorus concentration value. The HRM Lakes Water Quality Sampling Program has collected water quality data of lakes in the HRM from the period of 2006-2011 during spring, summer, and fall seasons (HRM, 2006-2011). Thus, the total phosphorus concentrations at 1 meter depth in Lake Charles, Lake William, Lake Thomas, and Lake Fletcher have been recorded over a five year time period and can be used for validation purposes. In order to accommodate for possible temporal variation and fluctuations in total phosphorus concentration in any of the lakes, an average was taken of all available data points of total phosphorus concentration for each of these lakes, excluding values that appear as outliers. For the upstream lakes of Lake Fletcher, the HRM water quality data is the most current reliable data available. However, more recent total phosphorus concentration data is available for Lake Fletcher. Joanna Poltarowicz, Dalhousie University MASc student, sampled the total phosphorus concentration of Lake Fletcher in August 2015 and has provided her data for use in this report. Five samples were taken, each with a second replicate, at both the input of Lake Fletcher and the output of Lake Fletcher. This thesis took the average of these twenty total data points in order to establish the most recent total phosphorus in Lake Fletcher, as of August 2015. The model is then tested against the measured values, and if the prediction and measured value do not differ by more than 20%, the model may be considered valid. This 20% validation interval is established because it reflects the typical uncertainties of laboratory and field measurements (Brylinsky, 2004). Due to the admittedly large range of 20% for this validation between the measured and predicted values, the model was validated within the 20% range, but was required to be an overestimate within that 20% range. This provision allows that the phosphorus concentration prediction of the model employs the precautionary principle by accounting for a potential worst-case scenario phosphorus concentration prediction.

Limitations and Delimitations

The principal limitation of this study is that it involves the creation of a model. Models are simplifications of natural processes and rely on assumptions, and thereby never exactly reflect natural phenomena. However, a model is only considered as good as its ability to closely match natural phenomena. Therefore, there will always be some error involved in model predictions. In order to improve upon the issues of this limitation, the Lake Fletcher Phosphorus Model should be used to predict the upper limit of a phosphorus concentration, thereby giving the worst-case scenario. This allows for environmental responsibility, through the employment of the precautionary principle, and thus less uncertainty of environmental effect that could result from the underestimation of a phosphorus concentration resulting from development.

The delimitations of this study are that the model is only applicable to the watershed Lake Fletcher, Nova Scotia and considers developments in direct proximity to Lake Fletcher and its upstream lakes.

Chapter 4 – Results

Phosphorus Export Coefficients

Table 2 presents the results of the literature review for Shubenacadie Lakes phosphorus export coefficients. The following pieces of literature were employed in order to deduce appropriate phosphorus export coefficient values for the model. The subsequent text describes the relationship between the literature and their suitability for the use in the Shubenacadie Lakes watershed.

Dillon & Molot's "Effect of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments" provided phosphorus export coefficients for metamorphic, forested watersheds in central Ontario (1997). The comparison of forest with peatland cover, which yields a higher phosphorus export value, versus forest with no peatland cover, which yields a lower phosphorus export value, indicates that the presence of wetlands will increase the phosphorus export of a land use category. However, the wetland cover for the watershed of the Shubenacadie Lakes is only 6.8% (Nova Scotia Groundwater Atlas, 2016). Thus, values of forests with 0% peatland cover are more representative of the phosphorus export of this watershed than would be the case for forests with 25% peatland cover (Dillon & Molot, 1997).

Table 2. Results of the literature review phosphorus export coefficients to be selected for the Shubenacadie Lakes in Nova Scotia.

Land Cover Type	Export Coefficient Source	Export Coefficient Description	Phosphorus Export Value (g P m^{-2} yr^{-1})	Mean Value (g P m^{-2} yr^{-1})
Forest	(Dillon & Molot, 1997)	Forest with 0% peatland cover	0.0018	0.00686
	(Lowe, 2002)	Metamorphic forested watershed	0.0191	
	(Reckhow et al., 1980)	Forest	0.0024	
	(Scott et al., 2000)	Nova Scotia forest, Igneous rock, Coarse soil, 18.3% wetland	0.0041	
	(Scott et al., 2000)	Nova Scotia Igneous Forested watersheds	0.0069	
Forest/Cleared	(Duan et al., 2012)	80% forest cover	0.006897	0.007832
	(Scott et al., 2000)	Igneous rock, medium-coarse soil, 76.4% forest, 19.5% clear-cut)	0.0083	
	(Scott et al., 2000)	Nova Scotia Igneous Forested Watershed with >15% cleared/wetland	0.0083	
Urban	(Jacques Whitford Ltd., 2009)	Nova Scotia Urban	0.0520	0.04733
	(Duan et al., 2012)	30% impervious cover	0.040	
	(Winter & Duthie, 2000)	Mixed low-density and medium-density residential	0.050	
Commercial	(Waller & Hart, 1986)	Commercial, no vegetation, high traffic	0.202	0.158
	(Maine Department of Environmental Protection, 2000)	Public highways	0.35	
	(Jacques Whitford Ltd., 2009)	Commercial	0.0400	
Industrial	(Duan et al., 2012)	Industrial, 72% impervious cover	0.12665	0.07398
	(Brylinsky, 2004)	Little known about industrial phosphorus run off, so often treated just as urban	0.07525	
	(Waller & Hart, 1986)	Institutional, No vegetation, Low traffic	0.042	
	(Jacques Whitford Ltd., 2009)	Industrial	0.0520	
Green Space	(Reckhow et al., 1980)	Grazing/pasture land	0.0150	0.013208
	(Winter & Duthie, 2000)	Pasture	0.02	
	(Johnes, 1996)	Permanent grass	0.01	
	(Brylinsky, 2004)	Treat as forest/cleared	0.007832	
Institutional	(Waller & Hart, 1986)	Institutional, No vegetation, Low traffic	0.042	0.042

Lowe's thesis "Overland phosphorus export in the Gaspereau River watershed: application to a lake capacity model" analyzed the phosphorus export coefficients associated with the Gaspereau River in Nova Scotia (2002). The proximity of this area to the Shubenacadie Lakes watershed lends reliability to the use of its values. However, it is noted in the thesis that observed phosphorus export was higher than anticipated, which may be due to the highly coloured nature of the waters in the river. Thus, the values from this thesis were tested in the model, but many of them rejected because the model validation recognized that they were contributing to an over-prediction of total phosphorus (Lowe, 2002).

Reckhow et al. composed the study "Modeling phosphorus loading and lake response under uncertainty: A manual and compilation of export coefficients" in order to compile one of the more extensive surveys of phosphorus export coefficients across diverse land use categories (1980). The NSP Model relies heavily on data from this study as a source of export coefficients for forested land uses and anthropogenic land uses alike (Brylinsky, 2004). Although it is a challenge to interpret the suitability of these values based on similarities in biophysical environments, their incorporation in the NSP Model and similarity to other amassed values for Shubenacadie Lakes land use categories garnered them a place among this model.

Scott et al.'s internal report "Phosphorus export from stream catchments in Nova Scotia" comprises the most extensive study of phosphorus export coefficients produced from a variety of watersheds in Nova Scotia (2000). The in depth analysis of the effects of soils, geology, and the percent cover of various land uses on phosphorus export coefficients in a watershed allow for a highly reliable set of values for use with the Shubenacadie Lakes.

Duan et al.'s "Phosphorus export across an urban to rural gradient in the Chesapeake Bay watershed" is a study composed in Chesapeake Bay near Maryland and

Virginia, USA (2012). This differing climate and biogeochemistry bring into question the suitability of the phosphorus export coefficients from the study for use in Nova Scotia. However, a serious gap in knowledge exists with regards to the behaviour of phosphorus export across urban and industrial environments in the literature in Nova Scotia, thus requiring the interpretation of Duan et al.'s values that may be representative of the Shubenacadie Lakes watershed to an uncertain degree. The characteristic of Duan et al.'s study which is of particular interest is that it analyzes phosphorus export across a gradient of differing land uses (2002). This relates well to the Fall River area which is shifting in land uses over time to incorporate more development, yet has many areas of mixed land use and low density development (HRM, 2014; Appendix 3). Thus, the Duan et al. values for phosphorus export were used under caution and continuously compared in order to see if they were congruous with other collected export values.

Jacques Whitford's "Fall River-Shubenacadie Lakes Watershed Study" (2009) for the HRM implicated the creation of phosphorus prediction models, such as the model of this thesis, for various Nova Scotia lakes. Although the phosphorus export coefficients supplied by these models did not cause most of the predicted phosphorus concentrations of the Shubenacadie Lakes to fall within the validation range, in cases where reliable export coefficients were lacking in other literature, such as with the urban land use category, the export coefficient created by Jacques Whitford Ltd. was employed (Jacques Whitford Ltd., 2009).

In "Report No. DEPLW-112, Final Lakes TDML Report", the Maine Department of Environmental Protection performed a survey of available phosphorus export coefficients in literature that would be considered suitable for watersheds in Maine (2000). Maine has similar climate, soil, and geology to Nova Scotia, and thus is considered to be comparable in terms of phosphorus export coefficients (Brylinsky, 2004). This report provided values that could be considered when calculating the phosphorus export coefficients for the urban and commercial land use categories. However, it is challenging to rely on such values of phosphorus export from a different region because although the biogeochemistry may be similar in terms of geology and hydrology, the level and quality of anthropogenic development may differ. There is a knowledge gap among the literature of how differing covers in urban and commercial areas may affect phosphorus export, and challenges may arise when considering high density, medium density, and low density developments across varying municipalities with varying zoning regulations.

Winter & Duthie's "Export coefficient modeling to assess phosphorus loading in an urban watershed" implicates a study site in Southern Ontario in which agriculture is predominant and the encroachment of urban development is increasing on undeveloped land (2000). The estimates of phosphorus export from these regions for urban and green space land use categories are among the higher values of those amassed. This may be due to the differing geology, soil, climate, and morphology of Southern Ontario in comparison to Nova Scotia, causing the values of phosphorus export to be higher than those expected for Nova Scotia. However, this thesis implicates the assumption that in the absence of definitive phosphorus export coefficients for a parkland/green space land use category, values for the forest/cleared land use may be considered, as well as literature citing phosphorus export coefficients for grassland, permanent grass, or pasture land. This assumption is justified through similar comparisons being made in other literature (Brylinsky, 2004; Jacques Whitford Ltd., 2009) as well as the observation through photo survey that green space in this watershed is primarily composed of grassed areas and little other vegetation (Appendix 3).

Waller & Hart's paper, "Solids, nutrients and chlorides in urban run off", estimates urban run off in Ontario watersheds and extrapolates further to predict run off values for Halifax watersheds (1986). The values provided by this study are used cautiously because they appear to exist on the high end of predicted ranges for urban run off in Nova Scotia (Brylinsky, 2004). Additionally, the predicted urban run off value for Ontario is 0.11 g P m^{-2} yr^{-1}, and yet the predicted values for Halifax in this study are higher than this Ontario value. This seems to be in conflict with other predictions in the literature, which often indicate a generally lower phosphorus export in Nova Scotia in comparison to Ontario (Brylinsky, 2004; Dillon & Molot, 1997). However, once more a lack of available data describing phosphorus export across developed land uses in Nova Scotia limits the certainty of these predictions and comparisons.

Johnes' "Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modeling approach" depicts phosphorus export in the Thames catchment in England (1996). Despite implicating a study site of markedly different geology and hydrology from that of Nova Scotia, this study is one of the few available resources that discusses a sort of green space land use category. In the rest of the literature, the closest that any land use category approaches green space is in the capacity of referring to pasture land, which can not definitively be said to have any true relationship with the phosphorus export of a green space land use category. Other models have simply treated green space with the same phosphorus export coefficient determined for the forest/cleared land use category (Jacques

Whitford Ltd., 2009; Brylinsky, 2004). Despite its geographical disparity with Nova Scotia, the concept of a permanent grass land use category produces a similar phosphorus export coefficient to that of what is produced by simply replicating the determined forest/cleared phosphorus export coefficient (Johnes, 1996).

Thus, in summary, phosphorus export coefficients that were applicable to the watershed of Lake Fletcher were sourced from the literature. If multiple export coefficients were found among the literature for one land use, then a mean was taken of all the applicable export coefficients to determine the phosphorus export coefficient that would be used in the model for that land use. These phosphorus export coefficients stated as mean values in Table 2 are re-stated as a summary of results below in Table 3.

Table 3. Lake Fletcher Phosphorus Model Export Coefficients

Land Use Category	Phosphorus Export Coefficient (g P m^{-2} yr^{-1})
Forest	0.00686
Forest/Cleared	0.007832
Urban	0.04733
Commercial	0.158
Industrial	0.07398
Green Space	0.013208
Institutional	0.042

Lake Fletcher Phosphorus Model

The full model is attached as Appendix 2. The model predicted phosphorus values given the selected phosphorus export coefficients for Lake Charles, Lake William, Lake

Thomas, and Lake Fletcher that were compared to measured values in order to validate the model. For Lake Charles, the predicted phosphorus concentration was 0.0116 mg/L, which exhibited a 0.87% difference greater than the measured value. Lake William gave a prediction of 0.0096 mg/L and had a 0.69% difference less than the measured value. Lake Thomas gave a prediction of 0.0135 mg/L and had a 4.46% difference greater than the measured value. Lake Fletcher's predicted phosphorus concentration was 0.0167 mg/L, which is a 39.17% difference greater than the measured value. A comparison of the predicted values from the measured phosphorus concentrations is presented in Figure 4. Thus, the model proved valid, by consideration of the acceptable percent difference of 20% or less, for Lake Charles, Lake William, and Lake Thomas, but not for Lake Fletcher.

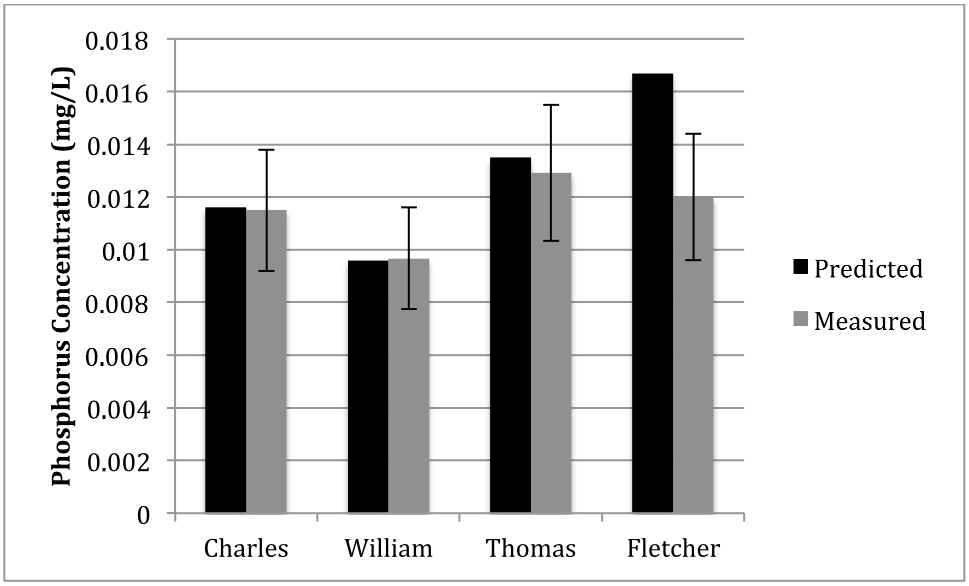

Figure 4. Comparison of predicted and measured phosphorus concentrations (mg L^{-1}) for Lake Charles, Lake William, Lake Thomas, and Lake Fletcher. Error bars depict whether a predicted phosphorus concentration falls within the 20% validation range of the measured phosphorus concentration.

Phosphorus Concentration in Lake Fletcher Over Time

Figure 5 depicts the total phosphorus concentration (mg/L) in Lake Fletcher, Nova Scotia from the period of Spring 2006 to Summer 2015. The total phosphorus measured in the period of Spring 2006 to Fall 2011 was sampled and recorded as part of the HRM Lakes Water Quality Sampling Program (2006-2011). The data for Summer 2015 was collected through the Dalhousie University Masters thesis research of Joanna Poltarowicz. It can be seen that the total phosphorus concentration in Lake Fletcher is not only variable from year to year, but also from season to season. This is due to high variability of trace phosphorus concentrations in lakes during the ice-free season, which are challenging to quantify.

In order to circumvent the variability of phosphorus concentrations between seasons and among layers, common practice is to observe the spring turnover phosphorus concentration as the most accurate measurement of lake total phosphorus (Clark et al., 2010). Thus, Figure 6 depicts the total phosphorus concentrations in Lake Fletcher during spring turnover measurements from 2006 to 2010. 2011 spring turnover measurements were unavailable for this dataset due to incomplete sampling during that time period by the HRM (HRM, 2006-2011). It can be seen by the trend line in Figure 6 that phosphorus concentrations are on a trajectory of increase during the period of Spring 2006 to Spring 2010. This five-year dataset is small and thus inconclusive, however it may be suggested that the increased urban development in the Fall River Growth Center may be increasing the phosphorus concentration in Lake Fletcher. However, the Spring 2010 total phosphorus measurement of 0.03 mg/L is by far the highest value out of all samples, so that year could have been an anomaly and further measurements should be taken to put the value into further context. This trend of phosphorus increase in Lake Fletcher reinforces the importance of a model for phosphorus export alteration by new development in the Fall River area.

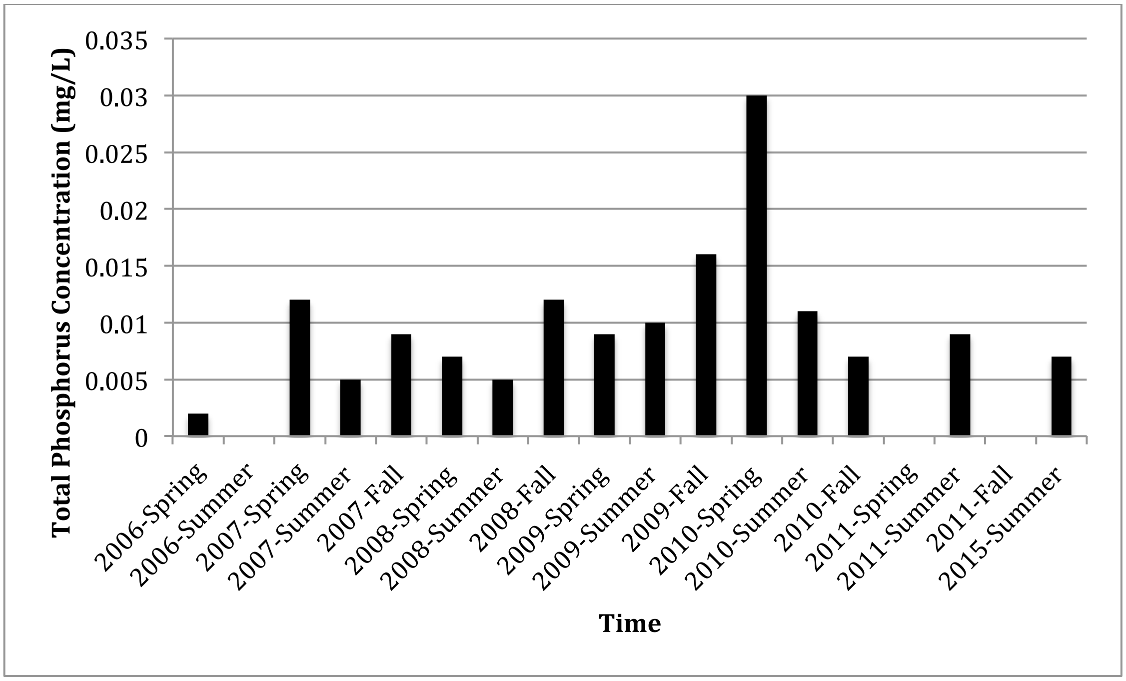

Figure 5. Total phosphorus concentration (mg/L) at 1 meter depth in Lake Fletcher over time, ranging from Spring 2006 to Summer 2015. Seasons with no total phosphorus concentration value displayed either had no phosphorus detected upon sampling or sampling was incomplete during that season. Data sourced from HRM (2006-2011) and Joanna Poltarowicz (2015).

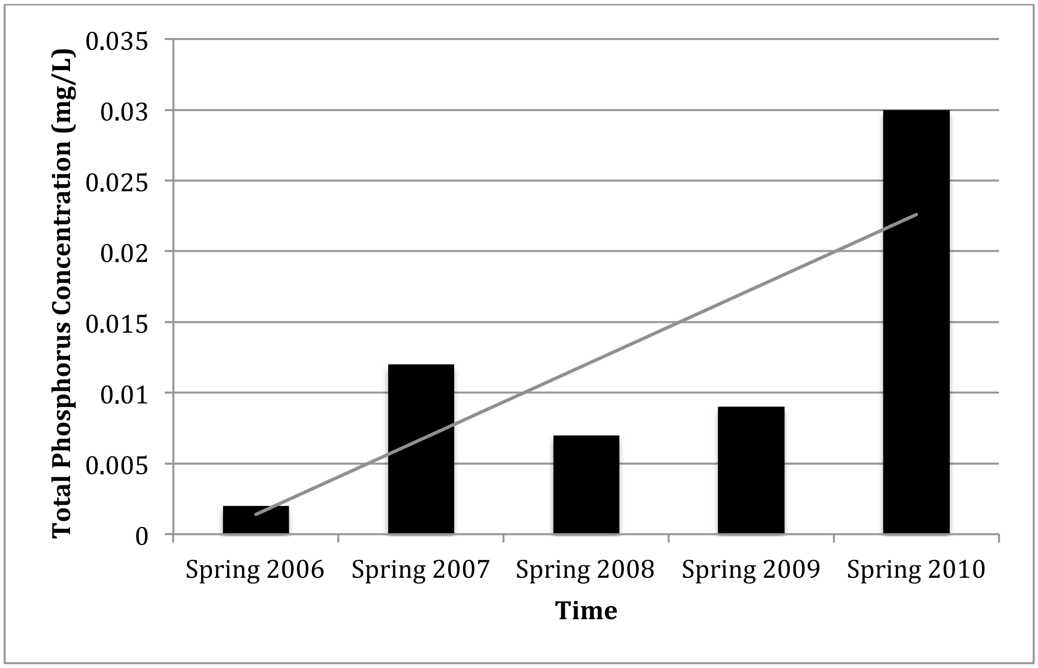

Figure 6. Total phosphorus concentration (mg/L) at 1 meter depth in Lake Fletcher over time, ranging from Spring 2006 to Spring 2010. No data was obtained for the sampling season of Spring 2011. The trend line displays the increase in spring total phosphorus measurements over the five years of sampling. Data sourced from HRM (2006-2011).

Chapter 5 – Discussion

Can the Model Predict Phosphorus Concentrations in Lake Fletcher?

Although the model has proven valid within the 20% difference interval for predicting the phosphorus concentration in Lake Charles, Lake William, and Lake Thomas, it has not been proven valid for Lake Fletcher, which is the lake of concern with regards to development practices (Appendix 2; HRM, 2014). Two factors influencing the validity of the model prediction for Lake Fletcher are the validity of individual phosphorus export coefficients and the assignment and definition of land use categories.

The first factor for this model invalidity is that the phosphorus export coefficients may be incorrect. Brylinsky notes in the NSP Report that the selection of the phosphorus export coefficients is the most sensitive aspect of this model creation (2004). Due to the subjective nature of export coefficient selection, there is no quantitative means of verifying whether the export coefficients have been selected correctly apart from justifying the selections with literature, as is the goal of this thesis, or by conducting a whole watershed study in order to measure the phosphorus export from the named land use categories. Within the context of this study, the only measure of ensuring the validity of the phosphorus export coefficients for each individual land use category is through checking the validity of the group by means of the 20% difference validation. However, in this there is no way to check the validity of the individuals, only the group as a whole (Brylinsky, 2004). There is, in fact, a study being performed at the time of this writing by Joanna Poltarowicz to sample and analyze phosphorus inputs to Lake Fletcher. Thus, the validity of the phosphorus export coefficients is a current gap in the knowledge, to which further research will hopefully continue to contribute.

The second factor influencing the validity of the model could be the assignment of land use areas to the watershed and the associated definitions of these land use categories. The division of the land into the categories Forest, Forest/Cleared, Urban, Commercial, Industrial, Green Space, and Institutional once more introduces a level of subjectivity into the model. These land use categories appear to be standard categories used for this model; however just as every different watershed needs different phosphorus export coefficients (Brylinsky, 2004; Dillon & Rigler, 1975), every different watershed may need a consideration of its own unique land use categories. For example, the land use categories use Urban as a category that refers to residential areas. However, Fall River and the residential areas surrounding the Shubenacadie Lakes are composed of varying types of residential areas. Some may be higher density and suburb-like, whereas many are medium- to low-density with large yards and plenty of surrounding green space (Jacques-Whitford Ltd., 2009; Appendix 3). The application of one phosphorus export coefficient across the varying sub-categories of land use within a given land use category may create an oversimplification that could invalidate the model results.

This oversimplification within the land use categories is also apparent when trying to compare phosphorus export coefficients from the literature to the Shubenacadie Lakes area. Many studies make use of simple descriptor phrases in order to encapsulate the characteristics of a land use category for which phosphorus export occurs (Jacques Whitford Ltd., 2009; Dillon & Molot, 1997; Lowe, 2002; Reckhow et al., 1980; Scott et al., 2000; Winter & Duthie, 2000; Johnes, 1996). However as seen previously, the phosphorus export coefficients in the model are observed to be the most sensitive model aspect. It seems counterintuitive to make broad generalizations about what land use a phosphorus export coefficient may apply to when it is a set of values that significantly impacts the validity of the model (Brylinsky, 2004). Many such land use category definitions may depend on municipal zoning regulations for the area in question (Jacques Whitford Ltd., 2009), yet this creates challenges when transferring phosphorus export coefficients between municipalities. When these definitions of land use categories are implicit within municipal land use bylaws and zoning regulations rather than explicitly stated the transfer of an export coefficient from one municipality to another may result in model error.

These impacts of uncertainty and subjectivity cause the model to be subject to possible error. The lack of quantitative validation for individual phosphorus export coefficients within the literature contributes to this uncertainty. These uncertainties and resulting errors create challenges in the implementation of this model for land use planning purposes.

Is the Model a Suitable Tool for Phosphorus Prediction in Lake Fletcher?

Throughout the construction and validation of this model, it was seen that the "Lakeshore Capacity Model" (Dillon & Rigler, 1975) and its application to the Lake Fletcher Phosphorus Model was not necessarily always an effective means for predicting phosphorus concentrations in the Shubenacadie lakes. The ineffectiveness of the model is due to gaps in the knowledge and literature, the subjective nature of export coefficient selection, and ill-qualified validation procedure. However, it was seen that despite these shortcomings of the model, through the implementation of the precautionary principle in order to select phosphorus export coefficients in a conservative manner, the model is valuable in its contribution to preservation efforts against eutrophication.

Knowledge Gaps

Despite the moderate availability of literature discussing phosphorus and its impact on freshwater systems, eutrophication remains a fairly new scientific field that has not been thoroughly explored as of yet. The first conference to consolidate knowledge regarding eutrophication of freshwater systems did not occur until 1967 (Hasler & Swenson, 1967). Since then, great strides have been made in the field of eutrophication, particularly with the Experimental Lakes Area study conducted by David Schindler and the development of the Lakeshore Capacity Model (1975) by Dillon & Rigler.

However, land uses are rapidly changing as humans alter the natural environment for development and industry, leaving the research struggling to keep up. One of the most pronounced issues among selecting phosphorus export coefficients under this model is that operators of the model are unsure how to treat land use categories such as Green Space and Industrial. This may be due to the previously discussed lack of clarity in the definitions of these terms, yet even subjective definitions come up dry when searching for phosphorus export coefficient values for these categories among the literature. Some studies were unsure how to treat these categories, and thus just treated them as the categories of next closest character for which phosphorus export coefficients could be found. For Green Space, the category was interpreted as equivalent to Forest/Cleared, and for Industrial, the category was interpreted as Urban (Jacques Whitford Ltd., 2009; Brylinsky, 2004). However, if land uses are differing in character enough to earn their own individual land use category, then they likely should receive a different phosphorus export coefficient than that of their next closest neighbour.

Across the literature surveyed, only one study was able to provide an export coefficient for an Industrial land use category (Duan et al., 2012), and no studies were able to attribute an export coefficient to Green Space nor any similar type of category. If these land use categories, as assessed by the HRM, are appropriate for this watershed, then there must be accompanying phosphorus export coefficient values to attribute to them in order to allow this model to function as an effective tool for phosphorus concentration prediction.

Subjectivity in Export Coefficient Selection

For Lake Fletcher and its associated upstream lakes in the watershed, phosphorus export coefficients were selected as previously outlined in Table 3. However, subjectivity exists in the establishment of these phosphorus export coefficients, as no protocol exists for the selection of phosphorus export coefficients. Essentially, the coefficients must either be measured for the watershed in question through sampling and analysis or they must be sourced from secondary data that provides export coefficients for similar land uses (Brylinsky, 2004). Every environmental consultant and scientist will bring a personal bias and subjectivity to the selection of phosphorus export coefficients, as is human nature. There is no protocol or set of guidelines in place to ensure that the phosphorus coefficients that are selected are the most appropriate option. In this thesis, a variety of coefficients were often found in the literature as possibilities to be the phosphorus export coefficient value for a given land use category. In cases where many coefficients were possible, a mean value of all of the coefficients was taken to determine the phosphorus export coefficient to input into the model. However, this may not give the appropriate weight to a value that may be more correct than the others. Through this, an increased presence of subjectivity appears in the Lakeshore Capacity Model (Dillon & Rigler, 1975) and its adaptation to the Lake Fletcher Phosphorus Model.

Validation Procedure

The NSP Report states that in order to validate a phosphorus prediction model, the predicted value of phosphorus must be no more than 20% different from the measured value of phosphorus for that lake. This validation percentage is based off of common scientific uncertainties associated with sampling measurements and instrumentation (Brylinsky, 2004). However, when employing a "No Net Phosphorus Export Policy" (HRM, 2014), a fluctuation of up to 20% between the measured phosphorus value and the predicted one could misinform development decisions. Ideally, the model would predict a phosphorus concentration that had a 0% difference from the measured value, thus rendering the model prediction perfect. However, it can be seen in this thesis and other literature that rather than achieving percent differences close to 0%, or even less than 20%, the percent difference values are exceedingly large and often more than 50% percent different (Jacques Whitford Ltd., 2009). Two explanations can be suggested for this phenomenon. First, that there is an error in the formulation of the model or oversimplifications which are causing the model to produce invalid predictions despite an effective percent difference validation procedure. Second, that the percent validation procedure is ineffective and should be replaced by a superior means of validation, such as statistical analysis of significant differences (e.g. T-tests). Whether any of these explanations are influencing the performance of the model requires further research to explore and assess, and would likely improve the accurate phosphorus prediction capacity of the model.

The discussion of whether the Lake Fletcher Phosphorus Model is able to predict phosphorus concentrations in Lake Fletcher, and further whether it is a suitable tool for phosphorus prediction, yielded an exposure of the shortcomings of the application of this model. The Lakeshore Capacity Model (Dillon & Rigler, 1975) has been employed for development decision-making in Canada for many years, and yet it may not be an effective model. However, it is certainly the best tool available currently. Future research should work to address the division and definition of land use categories employed in the model, knowledge gaps in phosphorus export across different land uses, the subjective nature of export coefficient selection, and improving the validation procedure both for individual export coefficients and for the model as a whole.

Implementation of the Lake Fletcher Phosphorus Model

The Lake Fletcher Phosphorus Model was constructed for the purpose of advising land development decision-making in Fall River, Nova Scotia. Several steps are advised for the effective implementation of this model. Firstly, the model must be conducted under the precautionary principle to maintain the integrity of its purpose under the municipal bylaws. Under this, all phosphorus export coefficients must be maintained as conservative estimates so that they will not result in under-predictions and contradiction of the precautionary principle. Secondly, a re-evaluation of land use categories appropriate to the Shubenacadie Lakes watershed should be considered. Third, further study must be done to "ground-truth" the establishment of land use categories and their associated areas in order to improve their precision. Finally, the model has its most effective use in creating a baseline phosphorus concentration prediction for which future phosphorus export of development proposals may be measured against.

Precautionary Principle

The precautionary principle was first established in Canadian environmental law under the Canadian Environmental Protection Act (CEPA) (1999). This legislation states "a lack of full scientific uncertainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (CEPA, 1999). The rationale of the Lake Fletcher Phosphorus Model is that its use may allow a prediction of potential development impacts on phosphorus concentration even if they are not known with scientific certainty. The pragmatic approach to ensuring that the phosphorus predictions of the model employ the precautionary principle is that although predicted values are desired to be as close to measured values as possible, within the 20% validation range (Brylinsky, 2004), any variation from the measured value should be an overestimation of the phosphorus concentration. Thus, the phosphorus export impacts of development in the watershed will not be underestimated and undue environmental degradation will not occur in Lake Fletcher. When new development areas and their associated phosphorus export coefficients are inputted into the model, the phosphorus export coefficients must predict the upper end of the range of possible phosphorus export from that development, so as to once more avoid undue environmental damage to Lake Fletcher.

Re-evaluation of Land Use Categories

As previously discussed, the establishment of land use categories and their associated areas in the watershed is problematic within this model. The land uses in Fall

River and the Shubenacadie Lakes watershed are far more nuanced than the division of land use into Forest, Forest/Cleared, Urban, Commercial, Industrial, Green Space, and Institutional allow for. For example, urban lands contain a gradient from fairly high-density subdivision housing to homes on large lots with plentiful green space and vegetated land (Appendix 3). Based on the findings of this thesis, it would be suggested that the HRM create further subdivisions for categories such as Urban, Commercial, and Green Space in order to better capture the true nature of the land uses that fall under these categories. Some suggestions would be to subdivide Urban into High-density Urban and Moderate/Low-density Urban, Commercial into High Traffic Commercial and Low Traffic Commercial, and Green Space into Vegetated Parkland and Grassed Space/Fields.

However, it becomes a delicate balance between what is precise and what is practical in terms of land use planning. Although it is important to accurately represent the different land use areas, over-complication of these land use category divisions could reduce the ease with which this model may be implemented. Additionally, it was challenging to find phosphorus export coefficients even for the reduced level of specificity of land use categories already employed in this model, so it could provide some serious challenges in finding more specific phosphorus export coefficients to describe this natural to urban gradient of land use categories. However, this provides opportunities for some fascinating and useful research that could make a significant contribution to the accuracy of understanding of phosphorus loading within Nova Scotia watersheds. Thus, the HRM and future researchers should consider the feasibility of improving the specificity of the land use categories within the Shubenacadie Lakes watershed in order to improve the Lake Fletcher Phosphorus Model.

Ground-Truth

An important aspect of the land use category establishment within this model relies on "ground-truthing" the GIS analysis. This entails visiting the sites that are delineated as being of certain land use categories in order to ensure that the land use category assigned to that land area is correct based on the GIS analysis. In some instances through the development of this model it was seen that there are apparent inconsistencies between the land use category areas assigned by the GIS analysis and what is observed to be present through Google Maps satellite images as well as site visits for the photo surveys. These inconsistencies could be contributing to issues with accuracy in the Lake Fletcher Phosphorus Model, particularly for the Lake Fletcher phosphorus prediction, which exceeds the measured value by 39.17% (Appendix 2D). Thus, the HRM should employ "ground-truthing" in their land use delineations in order to improve the accuracy of the Lake Fletcher Phosphorus Model.

Baseline Prediction

Finally, the true value of the Lake Fletcher Phosphorus Model and its implementation lies in that now that a uniform set of phosphorus export coefficients have been created; a baseline phosphorus concentration prediction has been established so that phosphorus export from proposed developments may be measured against this baseline prediction. Despite the Lake Fletcher phosphorus prediction varying from the measured value by 39.17% (Appendix 2D), the addition of a new development with its own land area and phosphorus export coefficient will still demonstrate whether the new development creates a net phosphorus export and resulting increase in the Lake Fletcher phosphorus concentration, thus fulfilling the goal of the model for its development decision-making context. Efforts should still be made to implement the above measures to improve the model's phosphorus prediction accuracy against the measured value. However, the model as it is has great value as a baseline against which phosphorus export from developments may be measured, and is a strong protector against environmental degradation through its employment of the precautionary principle.

Conclusion

The HRM identified a concern that Lake Fletcher may increase from an oligotrophic state to a mestotrophic state, so to limit this possibility implemented a Municipal Planning Strategy that enforced a "no net phosphorus export policy" on new developments around Lake Fletcher (HRM, 2014). In order to implement this policy, a tool is needed to model the impact on Lake Fletcher's phosphorus concentration from proposed developments. Thus, Dillon & Rigler's "Lakeshore Capacity Model" (1975) was adapted using the NSP model (Brylinsky, 2004) using secondary data from government documents and scientific literature to create the Lake Fletcher Phosphorus Model with phosphorus export coefficients specific to Lake Fletcher and the Shubenacadie Lakes. This model was subjected to the validation procedure, wherein the predicted phosphorus concentrations of Lake Charles, Lake William, and Lake Thomas were considered valid, whereas the predicted phosphorus concentration of Lake Fletcher was invalid under the model. Therefore, the Lake Fletcher Phosphorus Model was unable to be made to predict the phosphorus concentration in Lake Fletcher. Additionally, this model was considered under discussion to exhibit many shortcomings that impact its accuracy and precision, yet is currently the best available option. The precautionary principle should be implemented through this model in land use planning to establish a baseline phosphorus concentration prediction against which predictions of proposed developments may be measured to ensure that the uncertainties of this model do not further cultural eutrophication of Lake Fletcher.

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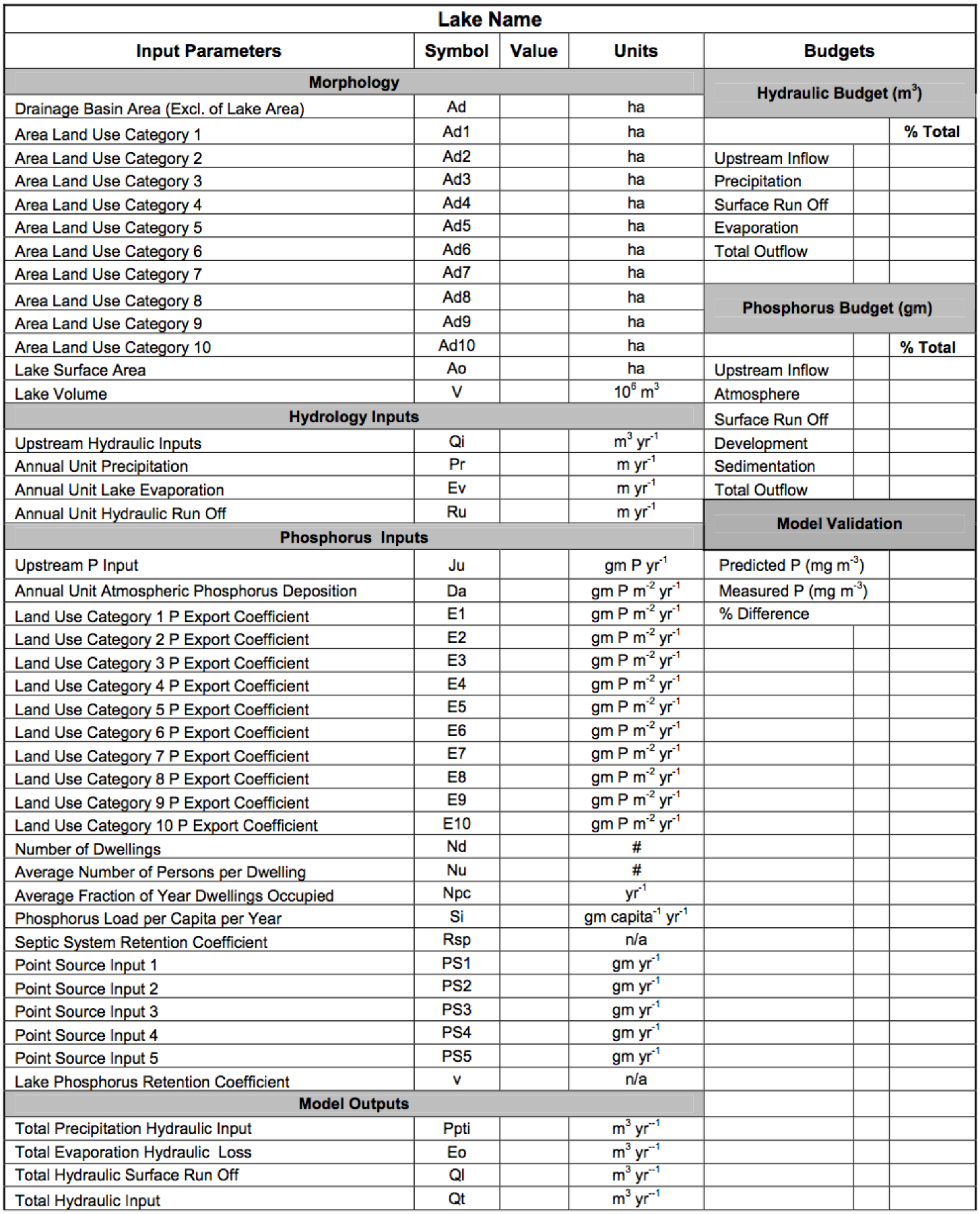
Appendix 1



Lake Name

Input Parameters	Symbol	Value	Units
Morphology			
Drainage Basin Area (Excl. of Lake Area)	Ad		ha
Area Land Use Category 1	Ad1		ha
Area Land Use Category 2	Ad2		ha
Area Land Use Category 3	Ad3		ha
Area Land Use Category 4	Ad4		ha
Area Land Use Category 5	Ad5		ha
Area Land Use Category 6	Ad6		ha
Area Land Use Category 7	Ad7		ha
Area Land Use Category 8	Ad8		ha
Area Land Use Category 9	Ad9		ha
Area Land Use Category 10	Ad10		ha
Lake Surface Area	Ao		ha
Lake Volume	V		10^6 m^3
Hydrology Inputs			
Upstream Hydraulic Inputs	Qi		m^3 yr^{-1}
Annual Unit Precipitation	Pr		m yr^{-1}
Annual Unit Lake Evaporation	Ev		m yr^{-1}
Annual Unit Hydraulic Run Off	Ru		m yr^{-1}
Phosphorus Inputs			
Upstream P Input	Ju		gm P yr^{-1}
Annual Unit Atmospheric Phosphorus Deposition	Da		gm P m^{-2} yr^{-1}
Land Use Category 1 P Export Coefficient	E1		gm P m^{-2} yr^{-1}
Land Use Category 2 P Export Coefficient	E2		gm P m^{-2} yr^{-1}
Land Use Category 3 P Export Coefficient	E3		gm P m^{-2} yr^{-1}
Land Use Category 4 P Export Coefficient	E4		gm P m^{-2} yr^{-1}
Land Use Category 5 P Export Coefficient	E5		gm P m^{-2} yr^{-1}
Land Use Category 6 P Export Coefficient	E6		gm P m^{-2} yr^{-1}
Land Use Category 7 P Export Coefficient	E7		gm P m^{-2} yr^{-1}
Land Use Category 8 P Export Coefficient	E8		gm P m^{-2} yr^{-1}
Land Use Category 9 P Export Coefficient	E9		gm P m^{-2} yr^{-1}
Land Use Category 10 P Export Coefficient	E10		gm P m^{-2} yr^{-1}
Number of Dwellings	Nd		#
Average Number of Persons per Dwelling	Nu		#
Average Fraction of Year Dwellings Occupied	Npc		yr^{-1}
Phosphorus Load per Capita per Year	Si		gm $capita^{-1}$ yr^{-1}
Septic System Retention Coefficient	Rsp		n/a
Point Source Input 1	PS1		gm yr^{-1}
Point Source Input 2	PS2		gm yr^{-1}
Point Source Input 3	PS3		gm yr^{-1}
Point Source Input 4	PS4		gm yr^{-1}
Point Source Input 5	PS5		gm yr^{-1}
Lake Phosphorus Retention Coefficient	v		n/a
Model Outputs			
Total Precipitation Hydraulic Input	Ppti		m^3 yr^{-1}
Total Evaporation Hydraulic Loss	Eo		m^3 yr^{-1}
Total Hydraulic Surface Run Off	Ql		m^3 yr^{-1}
Total Hydraulic Input	Qt		m^3 yr^{-1}

Budgets		
Hydraulic Budget (m^3)		
		% Total
Upstream Inflow		
Precipitation		
Surface Run Off		
Evaporation		
Total Outflow		
Phosphorus Budget (gm)		
		% Total
Upstream Inflow		
Atmosphere		
Surface Run Off		
Development		
Sedimentation		
Total Outflow		
Model Validation		
Predicted P (mg m^{-3})		
Measured P (mg m^{-3})		
% Difference		

(Brylinsky, 2004)

Appendix 2A: Lake Charles Model

Input Parameters	Symbol	Value	Units
Morphology			
Drainage Basin Area (Excl. of Lake Area)	Ad	1731.9	ha
Area Land Use Category 1 (Forest)	Ad1	447.4	ha
Area Land Use Category 2 (Forest/Cleared)	Ad2	749.4	ha
Area Land Use Category 3 (Urban)	Ad3	355.8	ha
Area Land Use Category 4 (Commercial)	Ad4	49.6	ha
Area Land Use Category 5 (Industrial)	Ad5	68	ha
Area Land Use Category 6 (Green Space)	Ad6	61.6	ha
Area Land Use Category 7 (Institutional)	Ad7	0	ha
Area Land Use Category 8	Ad8	0	ha
Area Land Use Category 9	Ad9	0	ha
Area Land Use Category 10	Ad10	0	ha
Lake Surface Area	Ao	141.4	ha
Lake Volume	V	11.2	10^6 m^3
Hydrology Inputs			
Upstream Hydraulic Inputs	Qi	0	m^3 yr^-1
Annual Unit Precipitation	Pr	1.452	m yr^-1
Annual Unit Lake Evaporation	Ev	0.552	m yr^-1
Point Source Hydraulic Input (2 STPs)	Qps	0	m^3 yr^-1
Annual Unit Hydraulic Run Off - Developed	Ruv	1.33	m yr^-1
Annual Unit Hydraulic Run Off - Non-Developed	Ruu	1.02	m yr^-1
Phosphorus Inputs			
Upstream P Input	Pi	0	gm P yr^-1
Annual Unit Atmospheric Phosphorus Deposition	Da	0.0173	gm P m^-2 yr^-1
Land Use Category 1 P Export Coefficient	E1	0.00686	gm P m^-2 yr^-1
Land Use Category 2 P Export Coefficient	E2	0.007832	gm P m^-2 yr^-1
Land Use Category 3 P Export Coefficient	E3	0.04733	gm P m^-2 yr^-1
Land Use Category 4 P Export Coefficient	E4	0.1973	gm P m^-2 yr^-1
Land Use Category 5 P Export Coefficient	E5	0.07398	gm P m^-2 yr^-1
Land Use Category 6 P Export Coefficient	E6	0.013208	gm P m^-2 yr^-1
Land Use Category 7 P Export Coefficient	E7	0.042	gm P m^-2 yr^-1
Land Use Category 8 P Export Coefficient	E8	0	gm P m^-2 yr^-1
Land Use Category 9 P Export Coefficient	E9	0	gm P m^-2 yr^-1
Land Use Category 10 P Export Coefficient	E10	0	gm P m^-2 yr^-1
Number of Dwellings	Nd	0	#
Average Number of Persons per Dwelling	Nu	2.9	#
Average Fraction of Year Dwellings Occupied	Npc	1	yr^-1
Phosphorus Load per Capita per Year	Si	800	gm capita^-1 yr^-1
Septic System Retention Coefficient	Rsp	0.5	n/a
Point Source Input 1	PS1	0	gm yr^-1
Point Source Input 2	PS2	0	gm yr^-1
Point Source Input 3	PS3	0	gm yr^-1
Point Source Input 4	PS4	0	gm yr^-1
Point Source Input 5	PS5	0	gm yr^-1
Lake Phosphorus Retention Coefficient	v	12.4	n/a
Model Outputs			
Total Precipitation Hydraulic Input	Ppti	2053128	m^3 yr^-1
Total Evaporation Hydraulic Loss	Eo	780528	m^3 yr^-1
Total Hydraulic Surface Run Off	Ql	19131900	m^3 yr^-1
Total Hydraulic Input	Qt	21185028	m^3 yr^-1
Areal Hydraulic Input	qs	14.43	m yr^-1
Total Hydraulic Outflow	Qo	20404500	m^3 yr^-1
Upstream P Input	Ju	0	gm yr^-1
Total Atmospheric P Input	Jd	24462.2	gm yr^-1
Total surface Run Off P Input	Je	414088	gm yr^-1
Total Development P Input	Jr	0	gm yr^-1
Total P Input	Jt	438550	gm yr^-1
Lake P Retention Factor	Rp	0.46	-
Lake P Retention	Ps	201733	gm yr^-1
Predicted Lake P Concentration	[P]	0.0116	mg L^-1
Lake P Outflow	Jo	236817	gm yr^-1
Lake Mean Depth	z	7.9	m
Lake Flushing Rate	FR	1.82	times yr^-1
Lake Turnover Time	TT	0.55	yr
Lake Response Time	RT(1/2)	0.22	yr

Budgets		
Hydraulic Budget (m^-3)		
		% Total
Upstream Inflow	0	0
Precipitation	2053128	9.69
Surface Run Off	19131900	90.31
Evaporation	-780528	3.68
Point Sources	0	
Total Outflow	20404500	96.32
Total Check		100

Phosphorus Budget (gm yr^-1)		
		% Total
Upstream Inflow	0	0
Atmosphere	24462.2	5.58
Land Run Off	414088	94.42
Development	0	0
Sedimentation	-201733	46
Total Outflow	236817	54
Total Check		100

Model Validation	
Predicted P (mg L^-1)	0.0116
Measured P (mg L^-1)	0.0115
% Difference	0.87

Appendix 2B: Lake William Model

Input Parameters	Symbol	Value	Units
Morphology			
Drainage Basin Area (Excl. of Lake Area)	Ad	2931.6	ha
Area Land Use Category 1 (Forest)	Ad1	1667.6	ha
Area Land Use Category 2 (Forest/Cleared)	Ad2	1187.1	ha
Area Land Use Category 3 (Urban)	Ad3	0	ha
Area Land Use Category 4 (Commercial)	Ad4	22	ha
Area Land Use Category 5 (Industrial)	Ad5	29.5	ha
Area Land Use Category 6 (Green Space)	Ad6	25.4	ha
Area Land Use Category 7 (Institutional)	Ad7	0	ha
Area Land Use Category 8	Ad8	0	ha
Area Land Use Category 9	Ad9	0	ha
Area Land Use Category 10	Ad10	0	ha
Lake Surface Area	Ao	305.8	ha
Lake Volume	V	34.8	10^6 m^3
Hydrology Inputs			
Upstream Hydraulic Inputs	Qi	44225550	m^3 yr^-1
Annual Unit Precipitation	Pr	1.452	m yr^-1
Annual Unit Lake Evaporation	Ev	0.552	m yr^-1
Point Source Hydraulic Input (2 STPs)	Qps	29200	m^3 yr^-1
Annual Unit Hydraulic Run Off - Developed	Ruv	1.33	m yr^-1
Annual Unit Hydraulic Run Off - Non-Developed	Ruu	1.02	m yr^-1
Phosphorus Inputs			
Upstream P Input	Pi	118408.5	gm P yr^-1
Annual Unit Atmospheric Phosphorus Deposition	Da	0.0173	gm P m^-2 yr^-1
Land Use Category 1 P Export Coefficient	E1	0.00686	gm P m^-2 yr^-1
Land Use Category 2 P Export Coefficient	E2	0.007832	gm P m^-2 yr^-1
Land Use Category 3 P Export Coefficient	E3	0.04733	gm P m^-2 yr^-1
Land Use Category 4 P Export Coefficient	E4	0.1973	gm P m^-2 yr^-1
Land Use Category 5 P Export Coefficient	E5	0.07398	gm P m^-2 yr^-1
Land Use Category 6 P Export Coefficient	E6	0.013208	gm P m^-2 yr^-1
Land Use Category 7 P Export Coefficient	E7	0	gm P m^-2 yr^-1
Land Use Category 8 P Export Coefficient	E8	0	gm P m^-2 yr^-1
Land Use Category 9 P Export Coefficient	E9	0	gm P m^-2 yr^-1
Land Use Category 10 P Export Coefficient	E10	0	gm P m^-2 yr^-1
Number of Dwellings	Nd	553	#
Average Number of Persons per Dwelling	Nu	2.9	#
Average Fraction of Year Dwellings Occupied	Npc	1	yr^-1
Phosphorus Load per Capita per Year	Si	800	gm capita^-1 yr^-1
Septic System Retention Coefficient	Rsp	0.5	n/a
Point Source Input 1 Frame STP	PS1	14600	gm yr^-1
Point Source Input 2	PS2	0	gm yr^-1
Point Source Input 3	PS3	0	gm yr^-1
Point Source Input 4	PS4	0	gm yr^-1
Point Source Input 5	PS5	0	gm yr^-1
Lake Phosphorus Retention Coefficient	v	12.4	n/a
Model Outputs			
Total Precipitation Hydraulic Input	Ppti	4440216	m^3 yr^-1
Total Evaporation Hydraulic Loss	Eo	1688016	m^3 yr^-1
Total Hydraulic Surface Run Off	Ql	30061970	m^3 yr^-1
Total Hydraulic Input	Qt	78756936	m^3 yr^-1
Areal Hydraulic Input	qs	25.2	m yr^-1
Total Hydraulic Outflow	Qo	77068920	m^3 yr^-1
Upstream P Input	Ju	118408.5	gm yr^-1
Total Atmospheric P Input	Jd	52903.4	gm yr^-1
Total surface Run Off P Input	Je	275956	gm yr^-1
Total Development P Input	Jr	656080	gm yr^-1
Total P Input	Jt	1103348	gm yr^-1
Lake P Retention Factor	Rp	0.33	-
Lake P Retention	Ps	364105	gm yr^-1
Predicted Lake P Concentration	[P]	0.0096	mg L^-1
Lake P Outflow	Jo	739243	gm yr^-1
Lake Mean Depth	z	11.4	m
Lake Flushing Rate	FR	2.14	times yr^-1
Lake Turnover Time	TT	0.47	yr
Lake Response Time	RT(1/2)	0.23	yr

Budgets		
Hydraulic Budget (m^-3)		
		% Total
Upstream Inflow	44225550	56.15
Precipitation	4440216	5.64
Surface Run Off	30061970	38.17
Evaporation	-1688016	2.14
Point Sources	29200	
Total Outflow	77068920	97.86
Total Check		99.96
Phosphorus Budget (gm yr^-1)		
		% Total
Upstream Inflow	118408.5	10.73
Atmosphere	52903.4	4.79
Land Run Off	275956	25.01
Development	656080	59.46
Sedimentation	-364105	33
Total Outflow	739243	66.9999855
Total Check		99.99
Model Validation		
Predicted P (mg L^-1)		0.0096
Measured P (mg L^-1)		0.00966667
% Difference		-0.69

Appendix 2C: Lake Thomas Model

Input Parameters	Symbol	Value	Units
Morphology			
Drainage Basin Area (Excl. of Lake Area)	Ad	4867.8	ha
Area Land Use Category 1 (Forest)	Ad1	1631.4	ha
Area Land Use Category 2 (Forest/Cleared)	Ad2	1703.9	ha
Area Land Use Category 3 (Urban)	Ad3	0	ha
Area Land Use Category 4 (Commercial)	Ad4	116.2	ha
Area Land Use Category 5 (Industrial)	Ad5	156.7	ha
Area Land Use Category 6 (Green Space)	Ad6	1259.6	ha
Area Land Use Category 7 (Institutional)	Ad7	0	ha
Area Land Use Category 8	Ad8	0	ha
Area Land Use Category 9	Ad9	0	ha
Area Land Use Category 10	Ad10	0	ha
Lake Surface Area	Ao	114	ha
Lake Volume	V	5.4	10^6 m^3
Hydrology Inputs			
Upstream Hydraulic Inputs	Qi	74391420	m^3 yr^-1
Annual Unit Precipitation	Pr	1.452	m yr^-1
Annual Unit Lake Evaporation	Ev	0.552	m yr^-1
Point Source Hydraulic Input (2 STPs)	Qps	273385	m^3 yr^-1
Annual Unit Hydraulic Run Off - Developed	Ruv	1.33	m yr^-1
Annual Unit Hydraulic Run Off - Non-Developed	Ruu	1.02	m yr^-1
Phosphorus Inputs			
Upstream P Input	Pi	739243	gm P yr^-1
Annual Unit Atmospheric Phosphorus Deposition	Da	0.0173	gm P m^-2 yr^-1
Land Use Category 1 P Export Coefficient	E1	0.00686	gm P m^-2 yr^-1
Land Use Category 2 P Export Coefficient	E2	0.007832	gm P m^-2 yr^-1
Land Use Category 3 P Export Coefficient	E3	0.04733	gm P m^-2 yr^-1
Land Use Category 4 P Export Coefficient	E4	0.1973	gm P m^-2 yr^-1
Land Use Category 5 P Export Coefficient	E5	0.07398	gm P m^-2 yr^-1
Land Use Category 6 P Export Coefficient	E6	0.013208	gm P m^-2 yr^-1
Land Use Category 7 P Export Coefficient	E7	0	gm P m^-2 yr^-1
Land Use Category 8 P Export Coefficient	E8	0	gm P m^-2 yr^-1
Land Use Category 9 P Export Coefficient	E9	0	gm P m^-2 yr^-1
Land Use Category 10 P Export Coefficient	E10	0	gm P m^-2 yr^-1
Number of Dwellings	Nd	328	#
Average Number of Persons per Dwelling	Nu	2.9	#
Average Fraction of Year Dwellings Occupied	Npc	1	yr^-1
Phosphorus Load per Capita per Year	Si	800	gm capita^-1 yr^-1
Septic System Retention Coefficient	Rsp	0.5	n/a
Point Source 1 Input Septic Systems in Area 8	PS1	214.6	gm yr^-1
Point Source Input Wellington STP	PS2	0	gm yr^-1
Point Source Input 3	PS3	0	gm yr^-1
Point Source Input 4	PS4	0	gm yr^-1
Point Source Input 5	PS5	0	gm yr^-1
Lake Phosphorus Retention Coefficient	v	12.4	n/a
Model Outputs			
Total Precipitation Hydraulic Input	Ppti	1655280	m^3 yr^-1
Total Evaporation Hydraulic Loss	Eo	629280	m^3 yr^-1
Total Hydraulic Surface Run Off	Ql	50497550	m^3 yr^-1
Total Hydraulic Input	Qt	126817635	m^3 yr^-1
Areal Hydraulic Input	qs	110.69	m yr^-1
Total Hydraulic Outflow	Qo	126188355	m^3 yr^-1
Upstream P Input	Ju	739243	gm yr^-1
Total Atmospheric P Input	Jd	19722	gm yr^-1
Total surface Run Off P Input	Je	756921	gm yr^-1
Total Development P Input	Jr	380694.6	gm yr^-1
Total P Input	Jt	1896581	gm yr^-1
Lake P Retention Factor	Rp	0.1	-
Lake P Retention	Ps	189658	gm yr^-1
Predicted Lake P Concentration	[P]	0.0135	mg L^-1
Lake P Outflow	Jo	1706923	gm yr^-1
Lake Mean Depth	z	4.7	m
Lake Flushing Rate	FR	23.32	times yr^-1
Lake Turnover Time	TT	0.04	yr
Lake Response Time	RT(1/2)	0.03	yr

Budgets		
Hydraulic Budget (m^-3)		
		% Total
Upstream Inflow	74391420	58.66
Precipitation	1655280	1.31
Surface Run Off	50497550	39.82
Evaporation	-629280	0.5
Point Sources	273385	
Total Outflow	126188355	99.5
Total Check		99.79
Phosphorus Budget (gm yr^-1)		
		% Total
Upstream Inflow	739243	38.98
Atmosphere	19722	1.04
Land Run Off	756921	39.91
Development	380694.6	20.07
Sedimentation	-189658	10
Total Outflow	1706923	90.0000053
Total Check		100
Model Validation		
Predicted P (mg L^-1)		0.0135
Measured P (mg L^-1)		0.01292308
% Difference		4.46

Appendix 2D: Lake Fletcher Model

Input Parameters	Symbol	Value	Units
Morphology			
Drainage Basin Area (Excl. of Lake Area)	Ad	1472.5	ha
Area Land Use Category 1 (Forest)	Ad1	549.3	ha
Area Land Use Category 2 (Forest/Cleared)	Ad2	910.3	ha
Area Land Use Category 3 (Urban)	Ad3	0	ha
Area Land Use Category 4 (Commercial)	Ad4	8.1	ha
Area Land Use Category 5 (Industrial)	Ad5	2.3	ha
Area Land Use Category 6 (Green Space)	Ad6	2.6	ha
Area Land Use Category 7 (Institutional)	Ad7	0	ha
Area Land Use Category 8	Ad8	0	ha
Area Land Use Category 9	Ad9	0	ha
Area Land Use Category 10	Ad10	0	ha
Lake Surface Area	Ao	107.7	ha
Lake Volume	V	4	10^6 m^3
Hydrology Inputs			
Upstream Hydraulic Inputs	Qi	125914970	m^3 yr^-1
Annual Unit Precipitation	Pr	1.452	m yr^-1
Annual Unit Lake Evaporation	Ev	0.552	m yr^-1
Point Source Hydraulic Input (2 STPs)	Qps	190530	m^3 yr^-1
Annual Unit Hydraulic Run Off - Developed	Ruv	1.33	m yr^-1
Annual Unit Hydraulic Run Off - Non-Developed	Ruu	1.02	m yr^-1
Phosphorus Inputs			
Upstream P Input	Pi	1706923	gm P yr^-1
Annual Unit Atmospheric Phosphorus Deposition	Da	0.0173	gm P m^-2 yr^-1
Land Use Category 1 P Export Coefficient	E1	0.00686	gm P m^-2 yr^-1
Land Use Category 2 P Export Coefficient	E2	0.007832	gm P m^-2 yr^-1
Land Use Category 3 P Export Coefficient	E3	0.04733	gm P m^-2 yr^-1
Land Use Category 4 P Export Coefficient	E4	0.1973	gm P m^-2 yr^-1
Land Use Category 5 P Export Coefficient	E5	0.07398	gm P m^-2 yr^-1
Land Use Category 6 P Export Coefficient	E6	0.013208	gm P m^-2 yr^-1
Land Use Category 7 P Export Coefficient	E7	0	gm P m^-2 yr^-1
Land Use Category 8 P Export Coefficient	E8	0	gm P m^-2 yr^-1
Land Use Category 9 P Export Coefficient	E9	0	gm P m^-2 yr^-1
Land Use Category 10 P Export Coefficient	E10	0	gm P m^-2 yr^-1
Number of Dwellings	Nd	568	#
Average Number of Persons per Dwelling	Nu	2.9	#
Average Fraction of Year Dwellings Occupied	Npc	1	yr^-1
Phosphorus Load per Capita per Year	Si	800	gm capita^-1 yr^-1
Septic System Retention Coefficient	Rsp	0.5	n/a
Point Source Input Lockview STP	PS1	82855	gm yr^-1
Point Source Input Wellington STP	PS2	12410	gm yr^-1
Point Source Input 3	PS3	0	gm yr^-1
Point Source Input 4	PS4	0	gm yr^-1
Point Source Input 5	PS5	0	gm yr^-1
Lake Phosphorus Retention Coefficient	v	12.4	n/a
Model Outputs			
Total Precipitation Hydraulic Input	Ppti	1563804	m^3 yr^-1
Total Evaporation Hydraulic Loss	Eo	594504	m^3 yr^-1
Total Hydraulic Surface Run Off	Ql	15052760	m^3 yr^-1
Total Hydraulic Input	Qt	142722064	m^3 yr^-1
Areal Hydraulic Input	qs	131.97	m yr^-1
Total Hydraulic Outflow	Qo	142127560	m^3 yr^-1
Upstream P Input	Ju	1706923	gm yr^-1
Total Atmospheric P Input	Jd	18632.1	gm yr^-1
Total surface Run Off P Input	Je	127003	gm yr^-1
Total Development P Input	Jr	754145	gm yr^-1
Total P Input	Jt	2606703	gm yr^-1
Lake P Retention Factor	Rp	0.09	-
Lake P Retention	Ps	234603	gm yr^-1
Predicted Lake P Concentration	[P]	0.0167	mg L^-1
Lake P Outflow	Jo	2372100	gm yr^-1
Lake Mean Depth	z	3.7	m
Lake Flushing Rate	FR	35.53	times yr^-1
Lake Turnover Time	TT	0.03	yr
Lake Response Time	RT(1/2)	0.02	yr

Budgets		
Hydraulic Budget (m^-3)		
		% Total
Upstream Inflow	125914970	88.22
Precipitation	1563804	1.1
Surface Run Off	15052760	10.55
Evaporation	-594504	0.42
Point Sources	190530	
Total Outflow	142127560	99.58
Total Check		99.87
Phosphorus Budget (gm yr^-1)		
		% Total
Upstream Inflow	1706923	65.48
Atmosphere	18632.1	0.71
Land Run Off	127003	4.87
Development	754145	28.93
Sedimentation	-234603	9
Total Outflow	2372100	91.0000104
Total Check		99.99
Model Validation		
Predicted P (mg L^-1)		0.0167
Measured P (mg L^-1)		0.012
% Difference		39.17

Appendix 3: Photo Survey Examples

Land Use Category 3: Urban

Land Use Category 4: Commercial

Land Use Category 6: Green Space