User's Manual for Prediction of Phosphorus Concentration In Nova Scotia Lakes: A Tool for Decision Making

Version 1.0

Prepared For

The Nova Scotia Water Quality Objectives and Model Development Steering Committee

Nova Scotia Department of Environment and Labour

By

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SUMMARY

Increasing demands on our freshwater resources to provide clean water for industrial, domestic, agricultural and recreational purposes, together with increasing development of watersheds, has raised concerns about the kind and amount of development that can be tolerated in watersheds containing these resources. Of major concern are watershed activities that result in increased inputs of phosphorus to lakes, the nutrient most important in controlling lake productivity and, when present in high concentrations, the major cause of lake eutrophication. As a result, considerable effort has been extended by various agencies to develop methods that can be used to determine the extent to which a watershed can be altered before the aquatic ecosystems it contains begin to exhibit impaired water quality.

This manual documents a simple modeling procedure that has been widely used to predict the amount of phosphorus present in the water column of a lake based on its morphological, hydrological and drainage basin characteristics. This model has proven to be a useful tool in decision making and assessments of the effect of various alterations within a watershed with respect to how they may influence lake phosphorus concentrations. The intended users of the manual include federal and provincial resource management agencies, provincial regulatory officers, municipal planners, consulting agencies and non-governmental organizations and individuals.

Table of Contents

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1. Introduction

Increasing pressure on our freshwater resources to provide clean water for industrial, domestic, agricultural and recreational purposes has raised concerns about the kind and amount of development that can be tolerated in watersheds containing these resources. In many areas of the world, freshwater systems have been severely degraded as a result of poor watershed management and lack of land use planning. Although Nova Scotia contains many relatively pristine watersheds, concern about threats to the quality of our freshwater resources from increased development, and the land use changes that accompany development, has been raised in the past (Waller 1971), and many believe that it is now time to develop procedures for determining the kind and level of development that can be endured within Nova Scotia watersheds before water quality becomes impaired.

Over the last three decades, considerable effort has been extended by many agencies to develop a simple procedure that can be used to determine the extent to which a watershed can be altered before the aquatic ecosystems it contains begin to exhibit impaired water quality as a result of excessive nutrient enrichment. In North America, many provinces and states are in the process of developing nutrient criteria designed to protect freshwater systems from nutrient overenrichment.

Of major concern is human activity that results in alterations of the tropic status of lakes. The term ***trophic*** literally means 'nourish', and when applied to a water body it refers to its level of biological productivity. Three commonly used terms to define the trophic status of a water body are ***oligotrophic*** (little nourishment), ***mesotrophic*** (moderate nourishment) and ***eutrophic*** (much nourishment). Oligotrophic systems are characterized by relatively pristine conditions and low levels of production. Eutrophic systems are characterized by a high biomass of plants, especially algae, and in many instances, low levels of dissolved oxygen which can result in the build up of toxic products such as methane, hydrogen sulphide and ammonia. Eutrophic conditions can lead to fish kills and species shifts of both plants and animals. A fourth trophic term, ***dystrophic***, literally means abnormal nourishment, and is used to describe systems that do not fall into the above categories. Dystrophic water bodies are characterized by colored water, mostly as a result of receiving run off containing dissolved humic compounds that originate from peatlands or leachates produced from the breakdown of coniferous vegetation within a watershed.

Because lakes lie in depressions within the land, they are natural traps for particulate materials containing nutrients that enter via their inflows. As a result, all lakes gradually accumulate nutrients and at some point will become eutrophic. This ***natural eutrophication*** is a slow process, on the order of tens of centuries in most cases, but it is often accelerated by the activities of humans, a process referred to as ***cultural eutrophication***, through land use alterations within a lake's drainage basin, or by the direct discharge of sewage, or other effluents containing nutrients, into a lake.

Although freshwater algae require a number of nutrients in order to grow, the two that are most commonly present in limiting amounts are phosphorus and nitrogen. Of these, phosphorus is the nutrient that most often limits the growth of aquatic plants in freshwater systems and, when present in high concentrations, is most often responsible for lake eutrophication. A general rule of thumb used by limnologists is that phosphorus is considered the limiting nutrient when the ratio of total nitrogen to total phosphorus concentration (by weight) is greater than about 7. Although there is considerable variation, on a global scale the concentration of phosphorus that results in oligotrophic, mesotrophic, and eutrophic conditions is about <10, 10-35 and > 35 $\mu g\ L^{-1}$, respectively.

Considerable effort has been devoted to developing quantitative empirical relationships between the concentration of phosphorus in a lake and water quality parameters that provide an indication of the trophic status of a lake. The two most commonly used parameters for this purpose are chlorophyll *a* concentration, an index of the amount of algae contained within the water column of the lake, and Secchi Disk depth, a measure of the lake’s water clarity. Table 1 contains an example of one set of guidelines commonly employed to determine the trophic status of a lake.

Table 1. Total phosphorus, chlorophyll *a* and Secchi Disk depth boundary values for determining a lake’s trophic state (Vollenweider and Kerekes 1982).

Trophic Category	TP ($\mu g\ L^{-1}$)	Mean Chlorophyll ($mg\ m^{-3}$)	Max Chlorophyll ($mg\ m^{-3}$)	Mean Secchi Depth (m)	Min Secchi Depth (m)
Ultra-oligotrophic	<4	<1	<2.5	>12	>6
Oligotrophic	<10	<2.5	<8	>6	>3
Mesotrophic	10-35	2.5-8	8-25	6-3	3-1.5
Eutrophic	35-100	8-25	25-75	3-1.5	1.5-0.7
Hyper-eutrophic	>100	>25	>75	<1.5	<0.7

Explanation of terms:
TP - mean annual in lake total phosphorus concentration;
Mean Chlorophyll - mean annual chlorophyll *a* concentration in surface waters;
Max Chlorophyll - peak annual chlorophyll *a* concentration in surface waters;
Mean Secchi Depth – mean annual Secchi Disk depth;
Min Secchi Depth – minimum annual Secchi Disk depth.

The purpose of this manual is to document a procedure that can be used to predict the amount of phosphorus that a lake will contain based on its morphological, hydrological and drainage basin characteristics. This information can then, in turn, be used to assess its susceptibility to eutrophication as a result of modifications of any of these characteristics, and particularly with respect to inputs of phosphorus resulting from human activities. The intended users of the manual include federal and provincial resource management agencies, provincial regulatory officers, municipal planners, consulting agencies and non-governmental organizations and individuals.

The general approach presented here has previously been applied within Nova Scotia for lakes associated with the Gaspereau River watershed (Horner Associates Ltd. 1995), Shubenacadie River watershed (Hart et al. 1978), Nine Mile River watershed (Dillon Consulting Ltd. 2003), a Cape Breton highlands lake (Kerekes 1983) and numerous lakes in the Halifax area (Soil and Water Conservation Society of Metro Halifax 1992; 1993).

Scott et al. (2003) carried out a study comparing these models and concluded that all of the models were essentially the same in terms of their general formulations and assumptions.

2. Some Basic Limnological Concepts

Anyone who attempts to use the model presented in this manual to predict the phosphorus concentration of a lake, or to determine the permissible loading of phosphorus to a lake, should have at least a general knowledge of the factors that cause eutrophication, as well as of the processes that determine the degree to which a particular lake is subject to becoming eutrophic. Of particular importance is an understanding of how phosphorus cycles within a lake, and the way in which lake stratification and the mixing processes occurring within the water column of a lake influence this cycle. It is also important to know something of the relationship between light availability and lake stratification in terms of how this also influences lake productivity. The discussion below provides a general description of these factors.

2.1. Lake Stratification

Lake stratification refers to the condition in which the water column of a lake becomes separated into layers of different densities as a result of differences in temperature. In temperate climates, this stratification is typically most strongly developed during the late summer and consists of three water layers (Figure 2.1).

The upper surface portion of the water column, the epilimnion, is the warmest layer, and the lower bottom layer, the hypolimnion, is the coldest. Between the two is the metalimnion, a layer of water in which a strong temperature gradient, called the thermocline, exists.

In Nova Scotia, the depth of the thermocline during the summer is generally about six metres, unless the lake is colored in which case the thermocline forms at about three metres. Aside from color, the strength and depth of the thermocline, as well as the temperature difference between the epilimnion and hypolimnion, depends on a number of factors, of which exposure to winds is one of the most important.

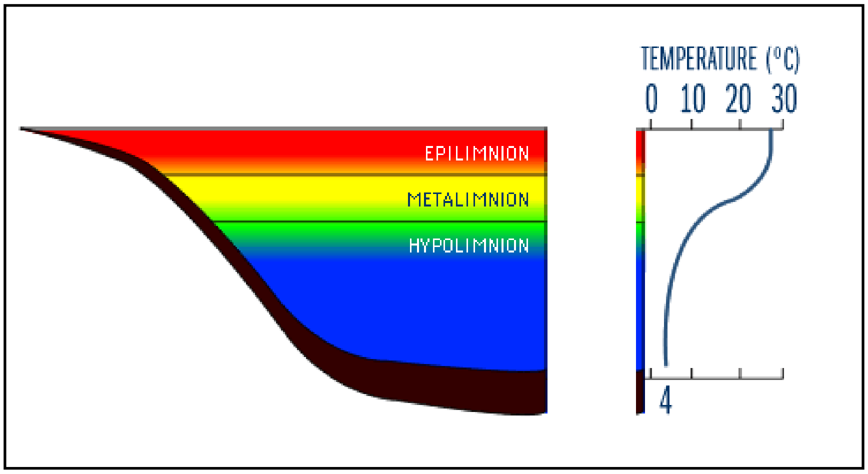

Figure 2.1. Cross section through a stratified lake showing the three water layers and a temperature-depth profile.

Lake stratification typically begins during spring when daylength increases and the lake begins to warm. It ends in the fall when daylength begins to decrease and the surface water cools causing it to sink to the bottom of the lake. At this time the lake undergoes the 'fall overturn' and the bottom waters rise to the surface having been displaced by the sinking surface waters. This process results in bottom waters becoming re-oxygenated in those instances when the lake has experienced a decrease in oxygen during the period of summer stratification.

Temperate zone lakes may also undergo stratification during winter if covered by ice, and this may also result in depletion of oxygen in the bottom waters. Figure 2.2 illustrates the seasonal variation in thermal structure of a lake that undergoes stratification. One of the most significant consequences of stratification is that it limits the degree to which oxygen is mixed from the surface of the lake to the hypolimnion. As a result, if the lake has a high level of algal production, the dead organic matter that eventually results settles to the bottom of the lake where it is metabolized by organisms that consume whatever oxygen was present when the lake first stratified, and the bottom waters may become anoxic.

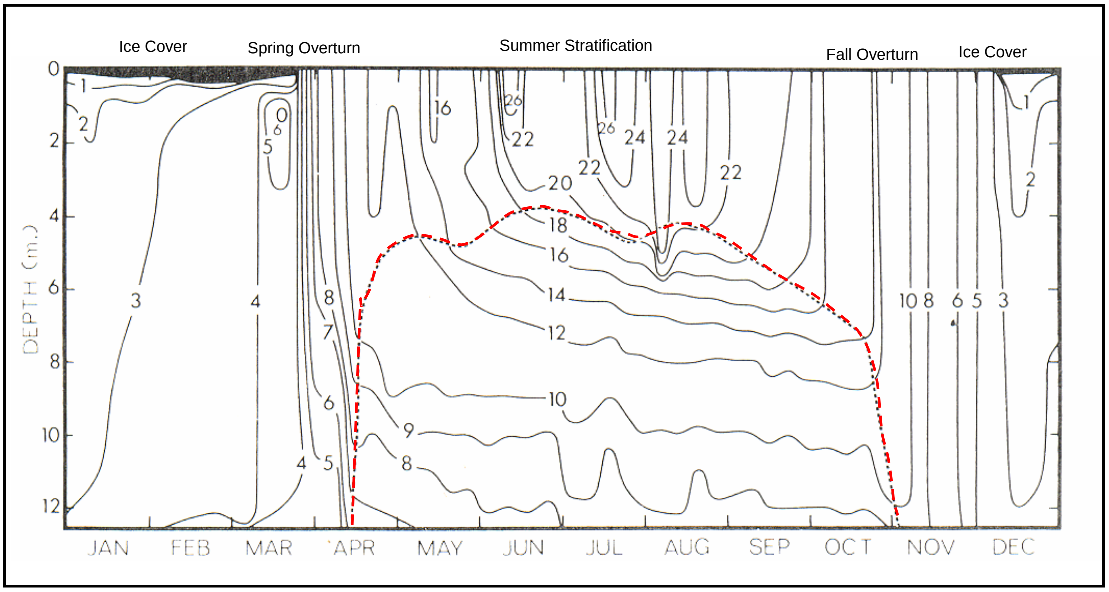

Figure 2.2. A temperature isopleth illustrating the seasonal development of stratification in a lake. The dashed line represents the position of the thermocline. (Modified from Wetzel (1983))

2.2. The Aquatic Phosphorus Cycle

The cycling of phosphorus in aquatic ecosystems is complex and involves physical, chemical and biological transformations (Figure 2.3). The major source of natural phosphorus is through weathering and erosion of rocks where phosphorus exists in a relatively insoluble, oxidized form complexed with metals such as aluminium, iron and magnesium. The resistance of these compounds to dissolution is one of the reasons why phosphorus is so often limiting in aquatic ecosystems.

Once phosphorus enters a water body it has numerous fates. If it exists as an insoluble precipitate, it may settle to the bottom where it becomes buried within the sediments with little chance of being returned to the water column. This is typically the case in an unproductive, well oxygenated lake. If, however, the lake is a productive one, and it contains an anoxic zone, either at the sediment surface or within the bottom water layer, the precipitate may be chemically transformed to a reduced state which is soluble and biologically available. In this case, the phosphorus may become resuspended into the water column where it is available for uptake by plants. This chemical transformation of insoluble phosphorus to a soluble form under anoxic conditions is one of the reasons why a lake that has accumulated phosphorus in its sediments over a long period of time, and that has an anoxic hypolimnion, may take considerable time, often on the order of decades, to respond to a reduction in phosphorus loading.

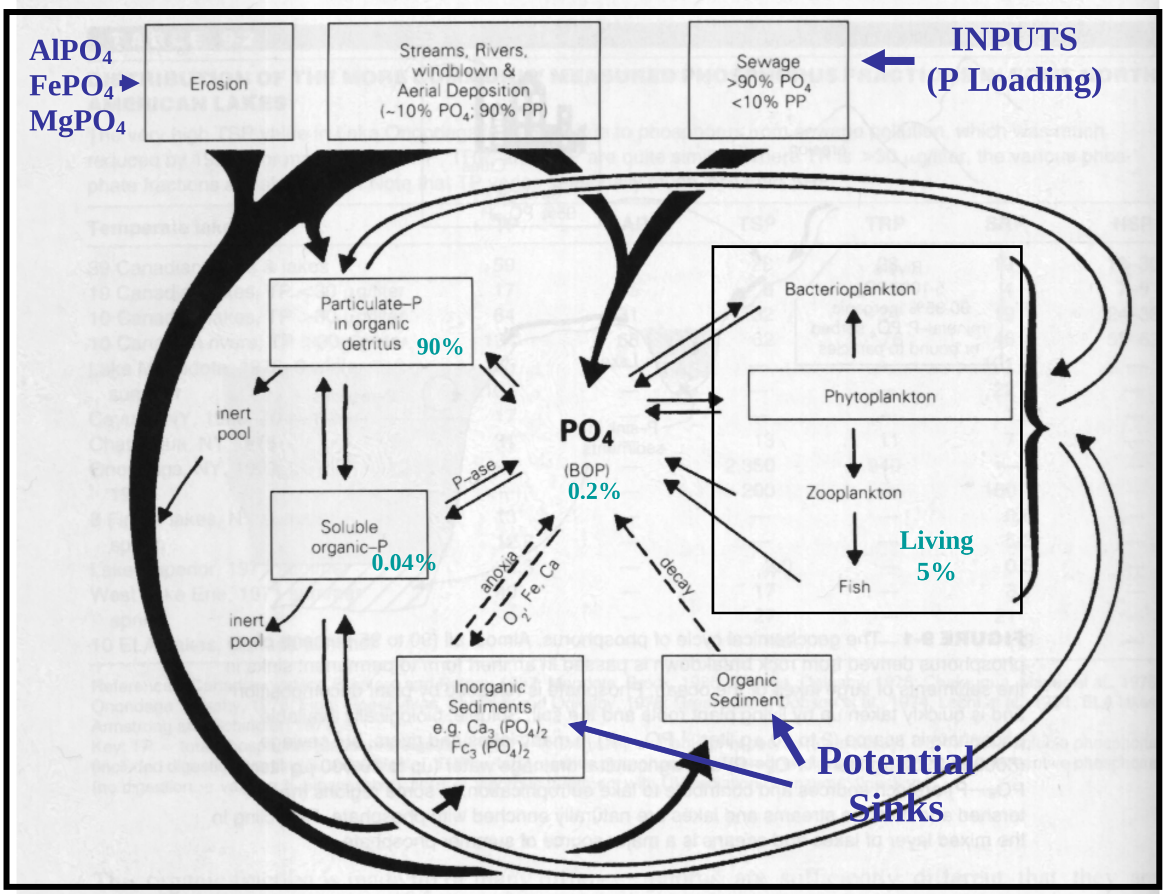

Figure 2.3. The cycle of phosphorus in a lake (percentages represent the relative amounts of phosphorus typically found in each form within the water column of a lake). Modified from Horne and Goldman (1994).

Plants can only assimilate phosphorous in the dissolved inorganic form. This form is referred to as orthophosphate and, because of the rapidity with which plants take it up, it is usually present in very low amounts. Orthophosphate that has been taken up by plants becomes incorporated into the food web as living particulate phosphorus. This pool of phosphorus is much larger than that present as orthophosphate. As organisms die and decay, the phosphorus they contain can be transformed into forms that can be recycled if they remain in the soluble form. By far the largest quantity of phosphorus present in aquatic systems is that contained in the non-living organic particulate form. This is commonly referred to as detrital phosphorus, and consists of dead aquatic organisms as well as terrestrial plants and animals that have been washed into the system. As this pool of organic matter is metabolized by bacteria and other detritus feeding organisms, phosphorus is released and may once again become available to plants to complete the cycle.

2.3. Factors Controlling Algal Growth

The two major factors that control algal growth in aquatic ecosystems are the availability of light and the availability of nutrients, both of which are strongly influenced by the amount of mixing of the water column. In stratified systems, the depth to which algae are mixed is determined by the thermocline depth. If the thermocline depth is shallow, the algae will spend most of the time within the upper portion of the water column where there is usually sufficient light for photosynthesis and, if nutrients are plentiful, will grow rapidly. If, however, the system is unstratified and relatively deep, the algae will be mixed throughout the water column and may spend a significant portion of the time in that part of the water column where light levels are too low to support photosynthesis. In this case, algal growth will be limited, even though nutrients levels may be quite high. Because of the dependency of algal growth on both light and nutrients, stratified systems are more susceptible to becoming eutrophic than are unstratified systems, unless the lake is relatively shallow and sufficient light is available throughout the water column.

3. Model Overview

Figure 3.1 is a hierarchical diagram showing the relationships between the major factors that determine the concentration of phosphorus in a lake. Climate, watershed characteristics and lake morphology are the main determinants, and information on all of these factors is required to construct the model. Climate and watershed characteristics are the main determinants of the amount of water and phosphorus that enters the lake, and the morphological characteristics of the lake determine how much phosphorus remains within the water column of the lake.

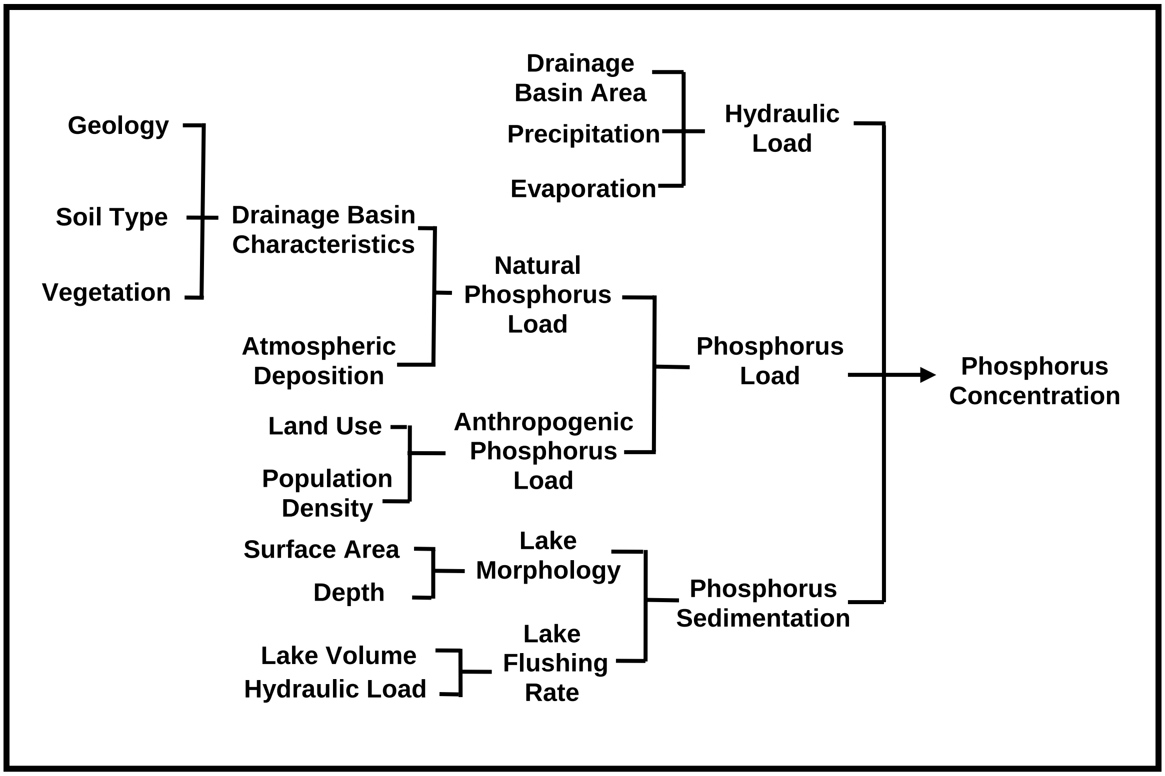

Figure 3.1. Hierarchical diagram illustrating the major factors controlling lake phosphorus concentration.

The spatial extent of the watershed required for the model depends on the relationship of the lake being modeled to other lakes. If the lake is a headwater lake, then only its watershed needs to be included in the model. If, however, the lake receives inputs from lakes located upstream, the watersheds of those lakes will also have to be included in the model.

The mathematical formulation of the model is best described as a black box, mass balance, steady-state model. The term black box implies that the model does not attempt to include any of the processes involved in determining the amount of phosphorus entering the lake, nor any of the biological or chemical processes that phosphorus goes through once it enters the lake. The term mass balance indicates that the model is essentially a budget of the amount of phosphorus entering and leaving the lake, and the term steady-state means that, on an annual time scale, the amount of phosphorus entering the lake is equal to the sum of that which sediments to the bottom and that which leaves the lake via its outflow. The model is essentially an accounting system that sums the hydraulic inputs, phosphorus inputs and amount of phosphorus lost to the sediments to estimate the phosphorus concentration of the lake. Figure 3.2 illustrates this further.

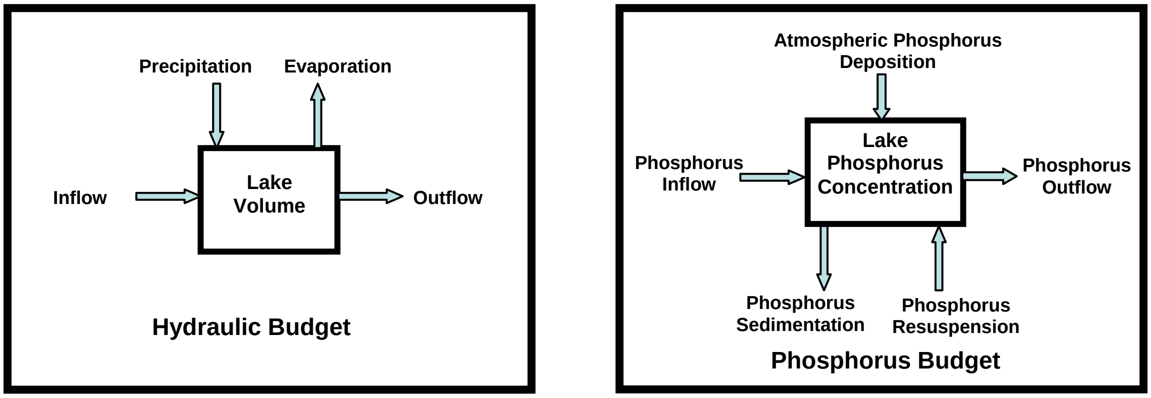

Figure 3.2. Inputs and outputs of the hydraulic and phosphorus budgets.

4. Model Formulation

The general equation used to determine the concentration of phosphorus in the lake once the hydraulic and phosphorous inputs are known is based on formulations originally proposed by Bifi (1963) and Piontelli and Tonolli (1964), and further developed by Vollenweider (1968; 1975).

The Vollenweider model assumes that the change in the amount of phosphorus in the lake over time is equal to the amount of phosphorus entering the lake minus the amount of phosphorus lost to the sediments and the outflow:

$$(\Delta PV / \Delta t) = M - (PV \times Q / V) - (\sigma \times P) \quad \text{where,}$$

PV = Total mass of phosphorus in lake (gm)
P = Lake phosphorus concentration (gm m^{-3})
V = Lake volume (m^3)
t = time
M = Annual mass of phosphorus input to lake (gm yr^{-1})
Q = Annual volume of water outflow from lake (m^{-3} yr^{-1})
σ = Sedimentation coefficient (yr^{-1})

The steady state solution (i.e., setting $\Delta PV / \Delta t = 0$) to this equation is:

$$PV = \frac{M / V}{(Q / V) + \sigma}$$

The major assumptions of the model are:

- Phosphorus entering the lake is mixed throughout the lake,
- The concentration of phosphorus in the outflow is equal to the concentration in the lake,
- The loss of phosphorus by settling to sediments is proportional to its concentration in the lake,
- Seasonal fluctuations in hydraulic and phosphorus loading can be neglected.

A major difficulty encountered in using Vollenweider's model is that it requires knowing the net sedimentation rate of phosphorus once it enters the lake. This has proven to be a difficult parameter to measure, largely because of the problems involved in separating phosphorus settling from phosphorus resuspension under experimental conditions. Based on an analysis of data from 21 temperate zone European and North American lakes, Vollenweider (1976) estimated σ, the phosphorus sedimentation rate, to be equal to approximately 10 divided by the mean depth of the lake. This formulation, however, requires that the mean depth of the lake be known which, in turn, requires a bathymetric survey of the lake. A number of studies (Larsen and Mercier 1976; Canfield and Bachmann 1980) have shown that lake phosphorus retention is highly correlated with the areal hydraulic load. One of the most commonly used formulations for phosphorus retention was developed by Kirchner and Dillon (1975) based on an analysis of Ontario lakes. In this formulation, the proportion of phosphorus lost to the sediments (Rp) is estimated as follows:

$$\mathrm{Rp} = \mathrm{v} / (\mathrm{v} + q_s) \quad \text{where,}$$

v = apparent settling velocity
q_s = areal hydraulic load

In a later study (Dillon et al. 1994), they suggested the use of different values of v depending on whether the lake contained an oxic or anoxic hypolimnion, 12.4 for the former and 7.2 for the latter.

Incorporation of this equation into the Vollenweider steady state equation results in the following equation for lake phosphorus concentration (note that this formulation does not require that the mean depth or volume of the lake be known):

$$\mathrm{P} = \frac{\mathrm{M} \times (1 - \mathrm{Rp})}{\mathrm{Q}}$$

Kalff (2002) provides an excellent discussion of the derivation of this, and other variations, of the Vollenweider formulation.

The general model formulations presented above have been widely used and applied successfully to numerous lakes (Sas 1989). Dillon and Rigler (1975) were the first to incorporate these formulations into what is commonly referred to as an export coefficient model where the phosphorus loadings are estimated using phosphorus export coefficients for the various land use characteristics of a lake's drainage basin.

There are, however, certain types of lakes for which these formulations do not appear to work well (Kalff 2002). These include: colored lakes having high concentrations of humic substances; lakes that have a low nitrogen to phosphorous ratio and are more likely to be limited by nitrogen rather than phosphorus; lakes that have high turbidity and are more likely to be limited by light than nutrients; and lakes that are very shallow and have short residence times (i.e. high flushing rates).

It should be noted that the time scale for models based on these formulations is one year which means that the models can not be used to determine average lake phosphorus concentrations for time periods shorter than this.

There are also numerous other assumptions and limitations associated with this model. In some cases, modifications can be made to the model to deal with these. Some of these limitations, and possible solutions for dealing with them, are discussed in the Supplementary Technical Report contained in Appendix VI.

5. Model Format

The model is formatted as an Excel® workbook and has been designed so that all of the data for a single lake is contained in a separate worksheet. Appendix I contains a sample of the format. If the lake being modeled is a headwater lake, only one worksheet is required. If the lake receives inputs from lakes located upstream, those lakes will also have to be modeled, each as a separate worksheet.*

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* An exception to this would be if the upstream hydraulic and phosphorus loadings were already known.

6. Modeling Procedure

Figure 3.4 illustrates the basic steps involved in constructing and applying the model.

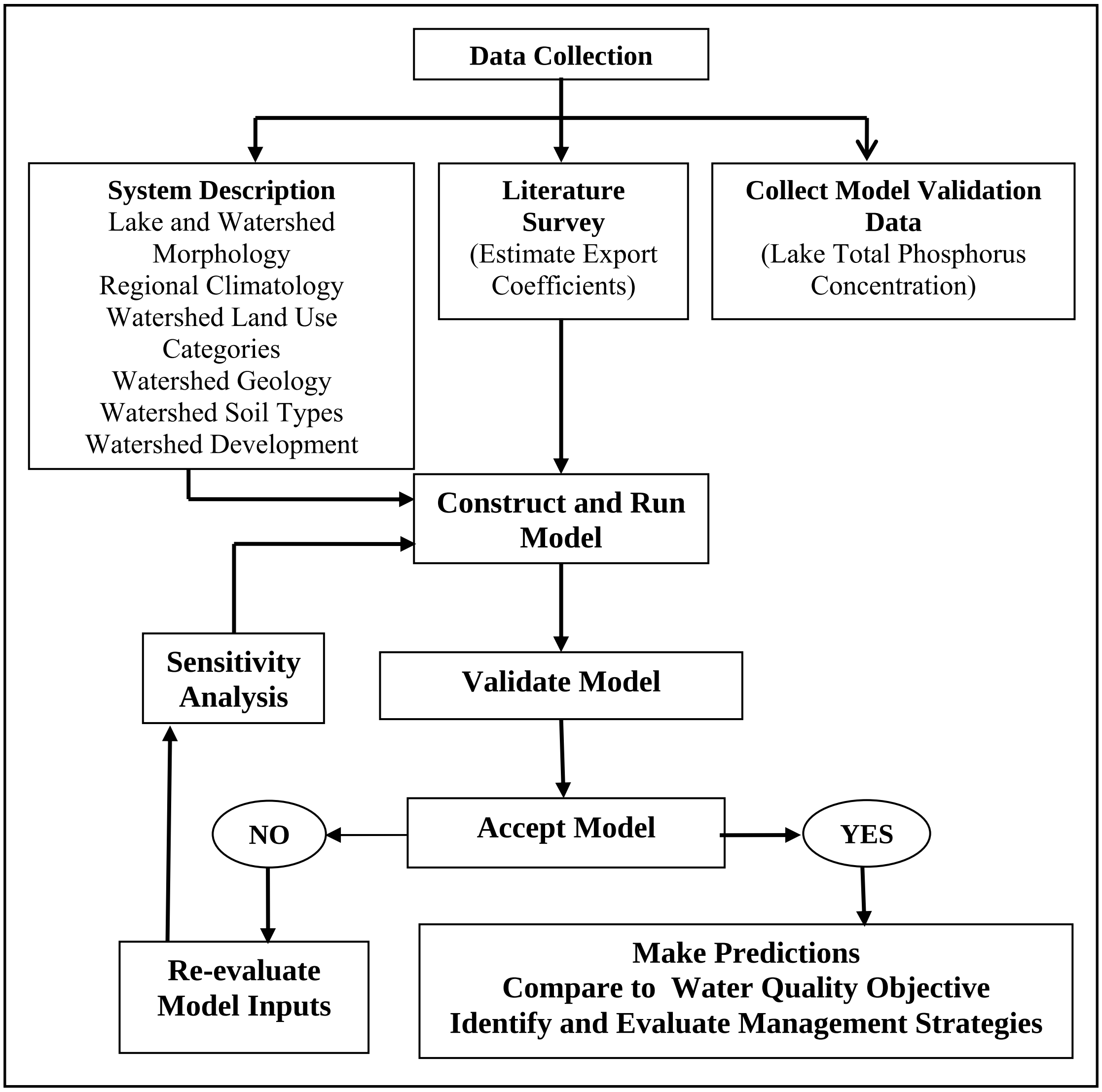

Figure 4.3. Model development and application procedure.

Data assimilated from existing literature and other sources is compiled and used to provide the necessary inputs for the model. The model is validated by comparing its prediction of the lake's total phosphorus concentration with field measurements (see Section 9). If the model prediction and field data agree, the model is considered to be validated and can then be used to determine how changes in the model's input parameters will affect the lake's total phosphorus concentration. If the model prediction and field data do not agree, it will be necessary to review and re-evaluate the data used to estimate the model inputs. In the latter case, it may prove useful to carry out a sensitivity analysis of each model input (see Section 11).

7. Model Construction

7.1. Model Inputs

The information required to construct the model falls into three general categories: (1) drainage basin and lake morphology characteristics; (2) hydraulic inputs; and (3) phosphorous inputs. The specific parameters associated with each of these categories is summarized in Table 7.1

A number of model inputs require estimation of surface areas. Examples include the surface area of the lake, the surface area of the lake's drainage basin and the surface areas of soil, geology and land use types within the drainage basin. In the past, surface areas have typically been measured using a planimeter. There are, however, other ways to estimate surface areas. One of the best and often most precise are those that use Geographic Information System (GIS) databases containing digital elevations and land use characteristics. These are often available through Municipal and Provincial planning agencies. If a GIS database is not available, it will be necessary to obtain maps containing the necessary information and to estimate areas using planimetry.[*]

There are also a number of image analysis programs that can be used to estimate surface areas. They require a digital image of the area to be estimated, which may be available from the same agencies that have GIS databases, or which can be obtained by digital scanning of an aerial photographs or maps. One potential disadvantage is that the scale of the image may be too small to obtain accurate results if the watershed or lake is large.

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[*] Wetzel and Likens (1991) is an excellent source of information on planimetric procedures.

Appendix II contains a listing of agencies that can be contacted to obtain maps and other data required to estimate model parameters.

Table 7.1. Model inputs.

Morphological Parameters	**Symbol**	**Units**
Drainage Basin Area (exclusive of lake)	Ad	m^2
Surface Area of Each Land Use Category	Adi	m^2
Lake Surface Area	Ao	m^2
Lake Volume	V	m^3
Hydraulic Input Parameters		
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 Input Parameters		
Upstream Phosphorus Input	Ji	$gm\ yr^{-1}$
Annual Unit Atmospheric Phosphorus Deposition	D	$gm\ m^{-2}\ yr^{-1}$
Annual Unit Phosphorus Export from Land*	Ei	$gm\ m^{-2}\ yr^{-1}$
Number of Dwellings	Nd	#
Average Number of Persons per Dwelling	Nu	#
Average Fraction of Year Dwellings Occupied	Npc	yr^{-1}
Phosphorus Input per Capita Year	Si	$gm\ capita^{-1}\ yr^{-1}$
Septic System Retention Coefficient	Rsp	-
Point Source Phosphorus Inputs	PSi	$gm\ yr^{-1}$
Lake Phosphorus Retention Coefficient	v	-

*A separate estimate is required for each combination of geology, soil type and land use present in the drainage basin.

7.1.1. Morphology

7.1.1.1. Drainage Basin Area (Ad)

Estimation of the drainage basin area requires using a topographic map (typically at scales of 1:10,000 or 1:50,000) to define the watershed boundary. The watershed boundary is the area between the highest points of land and the outlet of the lake. This area is outlined on the topographic map and then, by planimetry or some other available method, the area of the drainage basin is estimated. Use of the largest scale map available that includes the entire drainage basin will provide the most accurate estimates. The surface area of the lake should not be included as part of the drainage basin area.

7.1.1.2. Surface Area of Each Land Use Category (Adi)

If the drainage basin of the lake contains more than one type of land use and/or varies in geology and soil type, it will be necessary to estimate the surface area of each combination of land use and soil type since these are likely to differ in their phosphorus export coefficients.

7.1.1.3. Lake Surface Area (Ao)

The surface area of the lake is determined by planimetry using either aerial photographs, topographic maps or GIS databases. In some cases this, and other lake morphological characteristics, can be obtained from the Nova Scotia Department of Agriculture and Fisheries Lake Survey database. The Province has surveyed almost 2000 lakes in Nova Scotia and this information is readily available.

If the lake contains islands, the surface area of the islands should not be included as part of the lake's surface area, but should be included as part of the lake's drainage basin.

7.1.1.4. Lake Volume (V)

Although the volume of the lake is not, in most cases, required to predict the lake's phosphorus concentration, it is required for calculation of the lake's mean depth, residence time, turnover rate and response time (see Section 7.2.3).

Determining the volume of the lake requires having a bathymetric map that shows the area of the lake at each depth. This information is then used to construct a hypsographic curve, which represents the change in surface area with depth. The area under the curve is then integrated by planimetry to determine the volume of the lake. Alternatively, the volume of the lake can be determined using the formula for either a truncated pyramid or truncated cone (see Appendix V for an example).

7.1.2. Hydrology

7.1.2.1. Upstream Hydraulic Inputs (Qi)

If the lake being modeled is not a headwater lake, it will be necessary to determine the hydraulic input from any upstream lakes that flow into the lake. Unless this is known from field measurements of stream and river inflows into the lake, it will be necessary to estimate the hydraulic input using the same procedures as for the lake being modeled.

7.1.2.2. Annual Unit Precipitation (Pr)

An estimate of the total annual precipitation, expressed on a square metre basis, is required to account for the precipitation input that falls directly onto the lake. This information can be obtained from the Canadian Climate Normals (see Appendix II). Long-term averages (e.g., 20 year means) from the nearest weather station should be used.

7.1.2.3. Annual Unit Lake Evaporation (Ev)

Evaporation from the surface of the lake is required to estimate the lake outflow. This parameter is the evaporation rate per square metre per year. This information can be also be obtained from the Canadian Climate Normals. As is the case for precipitation, long-term averages should be used.

7.1.2.4. Annual Unit Hydraulic Run Off (Ru)

The average annual unit water run off is the amount of water, expressed as m yr^{-1}, (this is the same as m^3 m^{-2} yr^{-1}) that runs off the drainage basin and flows into the lake. It represents net run off and is the difference between precipitation and evapotranspiration. It should not include groundwater inputs to the lake.

Ideally, this should be estimated from direct measurements made at weirs located at the inputs or outputs of the lake. This information, however, is seldom available and is costly to obtain. In most cases, it will be necessary to estimate this parameter from other studies. An isorunoff map for Nova Scotia is contained in Appendix III and can be used to obtain a rough estimate when more precise data is unavailable.

7.1.3. Phosphorus Inputs

The most critical data input for the model is the phosphorus loading to the lake. This includes both point source loadings, such as the effluent of sewage treatment plants and storm sewers, and non-point inputs such as atmospheric deposition and surface run off from forested and agricultural lands. Although direct measurement of phosphorus loading to the lake would provide the most accurate data, this is often impractical to do because of the effort and cost involved. In addition, if the model is to be used to predict how the lake's phosphorus concentration would change as a result of changes in land use, it is essential that land use characteristics, and the amount of phosphorus run off associated with each land use, be incorporated into the model.

7.1.3.1. Upstream Phosphorus Input (Ju)

If the lake being modeled is not a headwater lake, phosphorus inputs from streams and rivers draining the watersheds and lakes located upstream must also be estimated (from either field measurements or model estimates) in order to determine the total phosphorus input to the lake.

7.1.3.2. Annual Unit Atmospheric Phosphorus Deposition (Da)

Atmospheric deposition includes dry deposition of particulate phosphorus transported by wind to the lake, and wet deposition of phosphorus dissolved in the precipitation falling directly onto the lake. Estimates of the dryfall portion are often 70 to 90 % of the total deposition (Likens and Loucks 1978). Sources of phosphorus transported to a lake by atmospheric deposition can originate outside of the lake's watershed. Atmospheric deposition tends to be highest in areas surrounding agricultural lands as a result of wind erosion of fertilized soils, and within urban areas as a result of the fly ash produced by burning of fossil fuels.

There have been very few measurements of atmospheric phosphorus deposition for Nova Scotia. Studies by Hart (1977), Hart et al. (1978) and Thirumurthi and Hart (1985) carried out in the Halifax area and the headwater region of the Shubenacadie River watershed suggest that a value of 0.025 gm m^{-2} $yr\text{-}^{1}$ is a reasonable estimate for Nova Scotia. Lowe (2002) estimated a value of 0.014 gm m^{-2} yr^{-1} for the Wolfville area. The lower value may be related to differences in the relative degree of urban development. Measurements made by Underwood (1984) for various areas in Nova Scotia suggest an average value of about 0.017 gm m^{-2} $yr\text{-}^{1}$.

7.1.3.3. Annual Unit Phosphorus Export from Land (Ei)

The export of phosphorus from the land is expressed as an export coefficient which is the amount of phosphorus carried into the lake by surface water run off, expressed as gm per square metre per year. The value of export coefficients vary depending on geology, soil type and land use and require analyzing the drainage basin of the lake to determine what combination of these characteristics it possesses. Phosphorus export coefficients are often the most difficult model parameter to estimate because of the diversity of climate, geology, soil type and land use activity that can occur in a watershed.

The first step is to partition the drainage basin according to its various combinations of geology, soil type, and land use and determine the area of each partition. Maps depicting geology, soil type and forest type cover are readily available from various Provincial agencies. Land use characteristics are often available from Municipal databases and in many cases are available in GIS formats. Recent aerial photography is also a useful resource for delineating land use characteristics. It is always a good idea to ground truth the results of any land use interpretations, especially if the maps or photos being used are not recent (i.e., more than 3-5 years old).

Once appropriate maps and photos have been acquired, it is necessary to determine the surface area of each land use category, along with the underlying soil type and geology. The general land use categories most often considered in the development of phosphorus loading models are forest lands, cultivated and uncultivated agricultural land, wetlands and developed urban and residential lands. While there is considerable variation in the amount of phosphorus exported from a given land use category, partly as a result of differences in climate, soil type and geology, some general patterns have emerged (Reckhow et al. 1980). These are summarized below

Climate:

- Warm climates with high rainfall have higher export coefficients than those with colder, dryer climates
- The amount, intensity and duration of precipitation have a large influence on phosphorus export coefficients

Geology and Soil Types

- Sandy soils overlying granitic igneous formations tend to have high nutrient export
- Loamy soils contain more nutrients and are more subject to erosion than sandy and gravely soils and tend to have higher export coefficients
- Clay soils are highly erosive, have poor water infiltration and a high capacity to adsorb phosphorus which results in high export

- Organic soils have high nutrient contents, poor infiltration capacity, limited phosphorus retention capacity and high export

Forestry

- Relative to other land uses, phosphorus export from forests is generally low, on the order of 0.001 to 0.015 gm m^{-2} yr^{-1}
- Forested watersheds with sandy soils overlying granitic igneous formations export about one-half the phosphorus than do forested watersheds with loamy soils overlying sedimentary formations
- Deforested watersheds have high export of phosphorus
- Young (<5 years old) forests have relatively high phosphorus export

Cultivated Lands

- Phosphorus export from cultivated lands tends to be very high and variable
- Heavily fertilized or manured lands, particularly if over-fertilized, have high phosphorus export, but this is reduced considerably if the fertilizer or manure is worked into the soil shortly after application
- Pasture and grazing land, if overgrazed or fertilized, export high amounts of nutrients
- Feedlots, especially if uncovered and exposed to precipitation, have high phosphorus export

Urbanization

- Urban run off tends to export high amounts of phosphorus and, since it is often channelled into storm drains, may contain discharges originating from more than one watershed

Because export coefficients vary depending on a multitude of factors, unless they have been measured in the watershed being modeled, the choice of the most appropriate export coefficient to use remains somewhat subjective. It is very important to attempt to match climate, geology, soil and vegetation type as closely as possible when estimates are based on studies that have been carried out in other areas,

Land Use Export Coefficients Measured in Nova Scotia

There have been a few studies carried out in Nova Scotia to determine phosphorous export coefficients from various combinations of geology, soil type and land use. Scott et al. (2000) carried out the most extensive study. The results are listed in Table 7.2.

Table 7.2. Phosphorus export coefficients measured by Scott et al. (2000) for various Nova Scotia watersheds.

Watershed Location	Geology[1]	Soil Type[2]	Land Use (%)							Phosphorus Export (gm m^{-2} yr^{-1})
			Forest	Clear Cut	Wetland	Agriculture	Barren	Urban	Other[3]	
Halifax	I	C	83.5	0.0	4.6	0.0	4.1	7.1	0.7	0.0166
Halifax	I	C	88.2	0.0	9.9	0.0	0.0	0.0	1.9	0.0137
Halifax	I	C	45.0	0.0	0.0	0.0	0.0	0.0	55.0	0.0024
Petit Etang	I	C	63.7	0.0	26.5	0.0	8.6	0.0	1.2	0.0107
Petit Etang	I	C	81.5	0.0	18.3	0.0	0.0	0.0	0.2	0.0041
Prospect	I	M-C	76.4	19.5	0.9	1.6	0.0	0.6	1.0	0.0083
Gillisdale	I	M	97.1	0.6	0.0	2.1	0.0	0.0	0.2	0.0130
Wentworth	I	M	86.1	7.9	0.5	2.5	0.0	0.8	2.3	0.0056
Wentworth	I	M	87.9	8.8	0.9	0.0	0.0	0.1	2.2	0.0041
Wentworth	I	M	85.2	11.1	0.4	0.0	0.0	0.4	2.9	0.0042
Wentworth	S	M	85.6	5.6	1.5	5.4	0.0	0.0	1.9	0.0087
Wentworth	S	M	93.1	1.8	4.8	0.0	0.0	0.0	0.3	0.0072
Wentworth	S	M	85.9	5.0	1.0	4.5	0.0	0.6	3.0	0.0108
Mount Thom	S	M	88.8	5.0	0.8	2.8	0.0	0.3	2.4	0.0058
Mount Thom	S	M	86.7	6.2	0.7	2.8	0.0	0.3	3.2	0.0061
Mount Thom	S	M	79.9	8.9	0.2	6.1	0.0	3.4	1.5	0.0143
Union Centre	S	M	81.1	5.5	0.5	7.4	0.0	0.7	1.9	0.0073
Union Centre	S	M	83.7	4.4	0.5	4.3	0.0	0.6	2.1	0.0058
Union Centre	S	M	83.3	2.4	0.6	3.2	0.0	0.4	2.3	0.0054
Union Centre	S	M	86.6	4.7	1.0	5.1	0.0	0.5	2.2	0.0058
Mount Thom	S	M	82.9	6.4	9.5	0.7	0.0	0.0	0.5	0.0116
Mount Thom	S	M	82.4	6.5	9.0	1.5	0.1	0.0	0.6	0.0104
Mount Thom	S	M	83.2	5.5	7.1	3.2	0.2	0.0	0.8	0.0126
Mount Thom	S	M	82.5	10.9	4.4	0.0	0.3	0.0	1.8	0.0061
Mount Thom	S	M	77.9	16.1	0.2	5.2	0.0	0.3	0.3	0.0195
Streets Ridge	S	F	80.0	12.1	1.5	3.5	0.0	0.1	2.9	0.0071

[1] I - Igneous; S - Sedimentary

[2] F - Fine (>15% clay); M – Medium (5 to 15% clay); C - Coarse (<5% clay)

[3] Mainly roads and open water

In a summary of their results, Scott et al. (2000) suggest the following general export values:

- Igneous Forested Watersheds – 0.0069 gm m^{-2} yr^{-1}
- Igneous Forested Watersheds with >15% cleared/wetland – 0.0083 gm m^{-2} yr^{-1}
- Sedimentary Forested Watersheds – 0.0088 gm m^{-2} yr^{-1}
- Sedimentary Forested Watersheds with >5% cleared/wetland – 0.0115 gm m^{-2} yr^{-1}

Lowe (2002) carried out a similar study for a number of stream catchments located in the Gaspereau River watershed. The estimated phosphorus export coefficients (Table 7.3) are considerably higher than those reported by Scott et al. (2000). The difference may be related to the highly colored waters typical of the lower reaches of the Gaspereau watershed where the study was carried out.

Table 7.3. Phosphorus export coefficients measured by Lowe (2002) for watersheds located in the Gaspereau River system, Kings County, Nova Scotia.

Geology	**Soil Type**	**Land Use (%)**				**Phosphorus Export (gm m^{-2} yr^{-1})**
		Forest	**Clearcut**	**Wetland**	**Agriculture**	
Igneous	Coarse	99	0	1	0	0.0327
Igneous	Coarse	85	15	0	0	0.0634
Igneous	Medium Coarse	80	14	0	6	0.0304
Sedimentary	Medium Fine	79	3	0	18	0.0354
Sedimentary	Medium Fine	80	4	0	16	0.0408
Sedimentary	Medium Fine	89	4	3	4	0.0213
Sedimentary	Fine/Coarse	98	1	0	1	0.0191
Sedimentary	Medium Fine	74	4	0	22	0.0311
Sedimentary	Medium Fine	72	8	0	20	0.0321
Igneous	Fine/Coarse	69	6	2	23	0.0624

Some phosphorus export coefficient estimates are also available for Maine which has similar climate, geological and soil characteristics to Nova Scotia. The following export coefficients were established by the Maine Department of Environmental Protection (2000) based on an extensive survey of values reported in the literature:

- Managed Forests (ca. 15 % clearcut/10% selective cut) - 0.050-0.075 gm m^{-2} yr^{-1}
- Unmanaged Forest – 0.0035-0.0050 gm m^{-2} yr^{-1}
- Agriculture (Rotation Crops) – 0.150-0.350 gm m^{-2} yr^{-1}
- Agriculture (Using Soil Conservation Practices) – 0.010-0.030 gm m^{-2} yr^{-1}
- Residential Lots – 0.025-0.035 gm m^{-2} yr^{-1}
- Logging Roads – 0.35 gm m^{-2} yr^{-1}
- Public Highways – 0.35 gm m^{-2} yr^{-1}
- Camp/Private Roads – 0.35 gm m^{-2} yr^{-1}

Reckhow et al. (1980) carried out and an extensive literature survey of export coefficients and compiled the summary listed in Table 7.4.

Table 7.4. Summary of land use phosphorus export coefficients (gm m^{-2} yr^{-1}) compiled by Reckhow et al. (1980).

Land Use	Range	Median	Mean
Forest	0.0019 - 0.0083	0.0021	0.0024
Row Crops	0.0026 - 0.1860	0.0224	0.0446
Non-row Crops	0.0010 – 0.0290	0.0076	0.0108
Grazing/Pasture Land	0.0014 - 0.0490	0.0081	0.0150

Run off coefficients for land uses other than those listed above will have to be estimated from literature containing coefficients measured in other regions of North America. (See Appendix IV for literature references of compiled export coefficients.) It should be noted that the utmost care should used in deciding if an estimate is really applicable to the situation that exists in the watershed being modeled. Export coefficients are among the most sensitive parameters determining the level of phosphorous concentration predicted by the model.

Urban Run Off

Urban areas typically have a high run off of phosphorus. Sources include run off from pavement (roads, parking lots and driveways) and lawns and leaf fall.

Reckhow et al. (1980) list a wide variety of export coefficients for urban areas, ranging from 0.0019 to 0.0623 gm m^{-2} yr^{-1}. The lowest values were for areas of low density housing and the highest for high density housing areas.

Waller and Hart (1986) estimated surface run off from urban areas in Ontario to be about 0.11 gm m^{-2} yr^{-1}. They also presented the following estimates for impervious urban areas in Halifax:

Residential/Vegetation/Low Traffic	0.186 gm m^{-2} yr^{-1}
Commercial/No Vegetation/High Traffic	0.202 gm m^{-2} yr^{-1}
Commercial/Vegetation/Moderately High Traffic	0.398 gm m^{-2} yr^{-1}
Institutional/No Vegetation/Low Traffic	0.042 gm m^{-2} yr^{-1}

7.1.3.4. Development Inputs (Nd, Nu, Npc, Si, Rsp)

Development input is the amount of phosphorus supplied to the lake from the human population present in the watershed. It is based on a determination of the number of capita-years in the watershed, the amount of phosphorus produced per capita and the proportion of the phosphorus produced that enters the lake. It also includes point source inputs of phosphorus. Although some of this information may be available from local planning offices, it will most likely have to be gathered from surveys. The information required to estimate the number of capita-years is as follows:

- **Nd -** the number of dwelling units within 300 m of the shoreline of the lake and any tributaries that enter into the lake
- **Nu -** the average number of people occupying the dwellings
- **Npc -** the average fraction of the year each dwelling is occupied

The amount of phosphorus produced per capita (**Si**) depends on the nature of the activities of the population residing in the watershed, and whether the residences are simple recreational cottages or full time residences. Factors such as the use of fertilizer for gardening and lawn maintenance, use of phosphate based detergents and prevalence of garbage grinders are some of the factors that should be considered. Estimates of the amount of phosphorus inputs to septic systems range from as low as 300 to as high as 1800 gm P capita^{-1} year^{-1} (Uttormark 19 74; Reckhow et al.1980), the higher values being for areas where phosphate detergents are used. A commonly used estimate in many models is 800 gm P capita^{-1} yr^{-1} (Dillon et al. 1986).

The final parameter required to estimate phosphorus input from residential development is a measure of the adsorption capacity (**Rsp**) of the soils in which the septic systems are located. This depends on factors such as the age of the septic system, the frequency of maintenance, the physical and chemical characteristics of the soil surrounding the system, and the degree to which the system interacts with the water table. Hart et al. (1978) estimated that septic systems on Halifax and Wolfville soils retained about 50% of the phosphorus input to septic systems. In instances where the model is being used to make conservative predictions of the potential long-term consequences of residential development, the septic system retention coefficient is often assumed to equal zero (see e.g., Horner Associates Ltd. 1995).

7.1.3.5. Point Source Inputs (PSi)

The previous discussion of phosphorus loading has dealt with non-point sources of phosphorus. There are a number of potential point sources of phosphorus that also need to be considered. Examples include inputs from sewage treatment plants, livestock feedlots and aquaculture operations.

Sewage Treatment Plants

Sewage treatment plants (STP) are often the most important point source inputs to water bodies receiving influents from domestic wastes that discharge either into a lake itself or a tributary leading into a lake. Although the quality of STP effluents is required to be monitored, the amount of phosphorus contained in STP effluents is not always included in the water quality parameters monitored. In this case, it becomes necessary to estimate the phosphorus loading based on the number of persons the plant services. Table 7.5 provides estimates of the effluent phosphorus load for Ontario STPs having various levels of treatment.

Table 7.5. Total phosphorus load in the final effluent for various levels of wastewater treatment (from Chambers et al. (2001) based on data contained in OMEE (1993)).

Treatment Type	P Removal	Number of Samples	Effluent Load (gm P capita^{-1} yr^{-1})
Primary	No	9	624.2
	Yes	19	273.5
	Average	**28**	**386.9**
Secondary	No	46	376.0
	Yes	137	153.3
	Average	**183**	**211.7**
Lagoons	No	45	284.7
	Yes	76	73.0
	Average	**121**	**153.3**
Tertiary	No	2	372.3
	Yes	33	54.8
	Average	**35**	**73.0**

Livestock Feedlots

Animal feedlots are also usually treated as point sources of phosphorus export. Measured export coefficients are very high, on the order of 30 gm m^{-2} yr^{-1} for intensive operations (Rast and Lee 1977).

Aquaculture Operations

Inland aquaculture operations are also potential point sources of phosphorus. Within Nova Scotia, salmonid aquaculture is most common. The amount of phosphorus exported depends mainly on the type and amount of food used. For salmonids, current operations use high nutrient dense feeds which contain about 1% phosphorus by weight, of which approximately one-third is assimilated by the fish and two-thirds is exported in the effluent (personal communication; J. Blanchard, Nova Scotia Department of Agriculture and Fisheries). It is therefore possible to estimate the total amount of phosphorus exported based on the amount of food used.

7.1.3.6. Lake Phosphorus Retention Coefficient (v)

The amount of phosphorus retained within the lake as a result of phosphorus settling to the sediments requires an estimate of the phosphorus retention coefficient (see Section 4 for the coefficients developed by Dillon et al (1986).

7.2. Model Outputs

The outputs of the model are listed in Table 7.6.

Table 7.6. Model outputs.

Parameter	Symbol	Units
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	$m^3\ yr^{-1}$
Areal Hydraulic Load	*qs*	$m\ yr^{-1}$
Total Hydraulic Outflow	Qo	$m^3\ yr^{-1}$
Atmospheric Phosphorus Input	Jd	$gm\ yr^{-1}$
Surface Run Off Phosphorus Input	Je	$gm\ yr^{-1}$
Development Phosphorus Input	Jr	$gm\ yr^{-1}$
Total Phosphorus Input	Jt	$gm\ yr^{-1}$
Lake Phosphorus Retention Factor	Rp	-
Lake Phosphorus Retention	Ps	$gm\ yr^{-1}$
Lake Phosphorus Concentration	[P]	$mg\ L^{-1}$
Total Phosphorus Outflow	Jo	$gm\ yr^{-1}$
Lake Mean Depth	z	m
Lake Flushing Rate	FR	$times\ yr^{-1}$
Lake Turnover Time	TT	yr
Lake Response Time	RT(1/2)	yr

7.2.1. Hydrology

7.2.1.1. Total Precipitation Hydraulic Input (Ppti)

The total amount of precipitation input to the lake is calculated as follows:

$$Ppti = Ao \times Pr$$ where,

Ao = Lake Surface Area
Pr = Annual Unit Precipitation

7.2.1.2. Total Evaporation Hydraulic Loss (Eo)

The total loss of water due to evaporation from the lake is calculated as follows:

$Eo = Ao \times Ev$ where,

Ao = Lake Surface Area
Ev = Annual Unit Lake Evaporation

7.2.1.3. Total Hydraulic Surface Run Off (Q_l)

The total amount of water entering the lake from land run off is calculated as follows:

$Q_l = Ad \times Ru$ where,

Ad = Drainage Basin Area
Ru = Annual Unit Water Run Off

7.2.1.4. Total Hydraulic Input (Qt)

The Total Hydraulic Input to the lake is calculated as the sum of all water inputs to the lake:

$Qt = P_{pti} + Q_l + Qi$ where,

P_{pti} = Total Precipitation Input
Q_l = Total Hydraulic Surface Run Off
Qi = Upstream Hydraulic Input

7.2.1.5. Areal Hydraulic Load (q_s)

The Areal Hydraulic Load to the lake is the amount of water entering the lake relative to the surface area of the lake. It is calculated as the ratio of the total annual water input minas evaporation and the lake surface area:

$qs = (Qt - Eo / A_o)$ where,

Q_t = Total Hydraulic Input
E_o = Evaporation Hydraulic Loss
A_o = Lake Surface Area

7.2.1.6. Total Hydraulic Outflow (Q_o)

The Total Annual Hydraulic Outflow is calculated as the Total Hydraulic Input minus Evaporation for the lake surface:

$$Q_o = Q_t - E_o \quad \text{where,}$$

Q_t = Total Hydraulic Input
E_o = Evaporation Loss

7.2.2. Phosphorus

7.2.2.1. Atmospheric Phosphorus Input (Jd)

The Atmospheric Phosphorus Input is calculated as the product of the Annual Unit Atmospheric Deposition and the Lake Surface Area:

$$J_d = D \times A_o \quad \text{where,}$$

D = Annual Unit Atmospheric Deposition
A_o = Lake Surface Area

7.2.2.2. Total Surface Run Off Phosphorus Input (Je)

The Total Surface Run Off Phosphorus Input is the sum of all the phosphorus export from each land use class:

$$J_e = Ad_i \times E_i \quad \text{where,}$$

Ad_i = Area of land use i
E_i = Annual unit phosphorous export from land use i

7.2.2.3. Development Phosphorus Input (Jr)

The Development Phosphorus Input is the sum of phosphorus inputs from all point sources and dwellings within the lake's drainage basin:

$$Jr = \Sigma PSi + (Nd \times Nu \times Npc \times Si \times (1 - Rsp)) \quad \text{where,}$$

PSi = Total phosphorus input from Point Source i
Nd = Number of dwellings in the drainage basin
Nu = Average number of persons occupying each dwelling
Npc = Average fraction of the year dwelling are occupied
Si = Phosphorus load per capita year
Rsp = Septic system retention coefficient

7.2.2.4. Total Phosphorus Input (Jt)

The Total Phosphorus Input is the sum of all phosphorus inputs to the lake. These include upstream phosphorus input, atmospheric phosphorus deposition, phosphorus surface run off, and phosphorus inputs due to development:

$$Jt = Ji + Jd + Je + Jr \quad \text{where,}$$

Ji = Upstream Phosphorus Input
Jd = Atmospheric Phosphorus Input
Je = Surface Run Off Phosphorus Input
Jr = Development Phosphorus Input

7.2.2.5. Lake Phosphorus Retention Factor (Rp)

The Lake Phosphorus Retention Factor is the fraction of phosphorus entering the lake that is lost by settling to the sediments:

$$Rp = v / (v + q_s) \quad \text{where,}$$

v = Phosphorus Retention Coefficient[1]
q_s = Areal Hydraulic Load

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[1] 12.4 for lakes with an oxic hypolimnion and 7.2 for lakes with an anoxic hypolimnion

7.2.2.6. Lake Phosphorus Retention (Ps)

The amount of phosphorus that is retained in the lake as a result of being lost to the sediments is calculated from the Total Phosphorus Input and the Phosphorus Retention Factor:

$$Ps = Jt \times Rp \quad \text{where,}$$

Jt = Total Phosphorus Input
Rp = Phosphorus Retention Factor

7.2.2.7. Lake Phosphorus Concentration ([P])

The Lake Phosphorus Concentration is calculated as the Total Phosphorus Input minus the amount lost to sedimentation divided by the Total Hydraulic Outflow:

$$[P] = (Jt - Ps) \,/\, Q_o) \quad \text{where,}$$

Jt = Total Phosphorus Input
Ps = Phosphorus Retention
Q_o = Total Hydraulic Outflow

7.2.2.8. Lake Phosphorus Outflow (Jo)

The amount of phosphorus that flows out of the lake is the difference between the total phosphorus input and the amount of phosphorus retained by the lake as a result of settling to the sediments:

$$Jo = Jt - Ps \quad \text{where,}$$

Jt = Total Phosphorus Input
Ps = Lake Phosphorus Retention

7.2.3. Lake Characterization Parameters

The following parameters essentially characterize the lake's hydraulic characteristics and can be important in determining the choice of formulations to use for calculation of phosphorus retention. They all require that the volume of the lake be known.

7.2.3.1. Mean Depth (z)

The Mean Depth of the lake is calculated as the ratio of the surface area and volume of the lake:

$z = Ao / V$ where,

Ao = Lake Surface Area
V = Lake Volume

7.2.3.2. Flushing Rate (FR)

The Flushing Rate is the number of times a volume of water equal to the volume of the lake flows through the lake per year. It is calculated as:

$FR = Q_o / V$ where,

Q_o = Total Hydraulic Outflow
V = Lake Volume

7.2.3.3. Turnover Time (TT)

The Turnover (or residence) Time of a lake is the average amount of time that water remains in the lake. It is the reciprocal of the lake's flushing rate and is calculated as follows:

$TT = V / Q_o$ where,

V = Lake Volume
Q_o = Total Hydraulic Outflow

The longer the residence time, the greater the amount of phosphorus that will be subject to sedimentation and lost to the sediments.

7.2.3.4. Response Time (RT(1/2))

The Response Time of a lake is a measure of the time it would take for the lake to respond to a change in its phosphorus loading. Response time is a function of the lake's flushing rate and is independent of either the lake's phosphorus load or content. Because the rate at which a substance is accumulated or removed from a lake is a logarithmetic function, response time is usually expressed as the time it would take to increase or reduce the concentration of a substance by one-half and can be estimated by the following equation (Dillon and Rigler 1975):

$$RT(1/2) = 0.69 / (FR + 10/z) \quad \text{where,}$$

FR = Flushing Rate of the lake
z = Mean Depth of the lake

It should be noted that this formulation does not consider the case where a significant portion of the phosphorus within the water column of the lake is a result of internal loading (i.e., the resuspension of phosphorus that has been accumulated within the sediments of the lake).

8. Entering Data

Entering the data into the Excel spreadsheets is quite straight forward for most of the input parameters. The only potential difficulty that may be encountered is in the case where more than one upstream input enters the lake. In this instance, it will be necessary to develop a customized formula for the Excel cells to sum all of the upstream water and phosphorus inputs. It is also important to zero out any inputs listed on the spreadsheet that may not be applicable for the lake being modeled.

9. Model Validation

Validation of the model is necessary before it can be used with confidence for prediction and as a basis for making policy decisions. Model validation simply involves comparing the model's prediction with data collected in the field. As a general rule, the model can be considered valid if the model prediction and field measurements of phosphorus concentration do not differ by more than about 20%, a value that is considered to reflect the confidence limits of most field and laboratory measurements[2]. It is important to realize that the model is likely to have been constructed using parameter estimates that are averages of many years, and that the validation data should also be representative of an average year. Mean annual lake phosphorus concentrations can vary considerably from year to year and it is necessary to collect the validation data over a number of years to determine a reasonable average. Although the number of years required is debatable, most believe that it should be somewhere between five and ten years. Hutchinson (2002) provides a number of suggestions for the design of monitoring programs in instances when limited resources are available. He suggests that, *at minimum*, the following data should be collected:

- An annual spring overturn measurement of total phosphorus,
- Biweekly measurements of Secchi Disk depth during the summer,
- An annual determination of a dissolved oxygen profile at the end of the summer and prior to fall turnover.

It would also be wise to collect water samples for determination of chlorophyll *a* concentrations on at least a bimonthly basis.

9.1 Protocol for Collection of Validation Data

The Nova Scotia Department of Environment and Labour (1999) has produced a manual that provides details of the protocols for collecting water samples for validation data.

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[2] This criteria, however, may be difficult to meet for lakes having phosphorus concentrations near to the limit of analytical detection.

Although the manual was specifically developed for a volunteer water quality monitoring program carried out in Kings County of the Annapolis Valley, the protocols described are generic and applicable to any water quality monitoring program. This manual should be consulted in designing the validation data sampling program.

The manual assumes that the analysis of field samples will be done at an accredited laboratory having the capability of processing samples for water quality, and especially for carrying out total phosphorus analyses at a detection limit of 0.001 mg L^{-1}.

10. Model Re-evaluation

If the model does not predict well when compared to the validation data, it must be re-evaluated. Re-evaluation involves assessing each input parameter in terms of its accuracy. It may also require that the processes incorporated into the model be re-evaluated. For example, if the lake is stratified it may be necessary to alter the way in which sedimentation rate is modeled.

11. Sensitivity Analysis

Carrying out a sensitivity analysis can be quite insightful in terms of understanding which factors exert the most influence in determining the level of phosphorus predicted by the model. It is also useful in determining where the greatest effort should be placed in refining the model if it does not meet the validation criteria. As an example, a sensitivity analysis of the Gaspereau River watershed model indicated that the prediction of phosphorus concentration was most sensitive to the phosphorus land run off coefficients and the lake phosphorus retention coefficient.

The general procedure for carrying out a sensitivity analysis is to alter the value of each model input parameter by a constant percentage while holding all other parameters constant, and then determining the percent change in the model's predictions. A factor of ten percent is typically used and, because there is some non-linearity in the model, it is always a good idea to both increase and decrease the input. In some cases, such as inputs related to precipitation, it may be instructive to alter the input parameter by a factor that corresponds to how much the parameter is known to vary on an annual basis.

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Scott Lister	Watershed Planner Nova Scotia Department of Environment and Labour
Jonathan Lowe	Fisheries Representative Nova Scotia Department of Agriculture and Fisheries
Michael MacIntyre	Senior Planner, Community Planning Department Municipality of Kings County
John MacMillan	Fisheries Biologist Recreational Fisheries Nova Scotia Department of Agriculture and Fisheries
Alan McNeill	Aquaculture Coordinator Nova Scotia Department of Agriculture and Fisheries
Vincent Mercier	Environmental Indicator and Reporting Specialist Environment Canada
Randy Milton	Manager, Wildlife Resources Nova Scotia Department of Natural Resources
Jordan Mooers	Hydrogeologist Nova Scotia Department of Transportation and Public Works
Richard Scott	Senior Research Associate Centre for Water Resources Studies, Dalhousie University
Wesley White	Biologist (retired), Science Branch Department of Fisheries and Oceans
David Wigmore	Senior Manager Nova Scotia Department of Environment and Labour

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14. Glossary

Algae - A general term applied to aquatic photosynthetic organisms.

Anaerobic – life without oxygen

Anoxic - having no oxygen

Catchment Area - See watershed.

Chlorophyll *a* - The major photosynthetic pigment present in algae and other plants. Measurement of its concentration in a water body is used as an indication of algal biomass.

Drainage Basin - The land area from which water runs off to drain into a stream, river, lake or estuary.

Epilimnion – The upper, warmer surface layer of a stratified lake.

Export coefficient - A measure of the amount of a substance exported from a system, usually expressed as mass area^{-1} time^{-1}.

Export Coefficient Model - A model for calculating nutrient loads to an aquatic ecosystem based on knowledge of land use and other drainage basin characteristics.

Eutrophic - A measure of a lake's trophic status. Literally means 'well nourished' and applied to aquatic ecosystems exhibiting a high level of productivity (see Table 1).

Flushing Rate - The number of times a volume of water equal to the volume of the lake flows out of the lake. It is calculated as the ratio of the volume of water leaving the lake to the volume of the lake, usually on an annual basis.

Hypolimnion - The lower, colder water later of a stratified lake.

Hypoxia – having low (generally < 2-3 mg L^{-1}) dissolved oxygen

Internal Nutrient Loading - The release of nutrients from sediments into the water column.

Mesotrophic – A measure of a lake's trophic status. Literally means moderately nourished and applied to lakes exhibiting a moderate level of productivity (see Table 1).

Metalimnion – The middle layer of a stratified lake containing an area of rapid temperature change (the thermocline).

Non-point Pollution Source – A nutrient, or other pollutant, source that originates from a diffuse area of the watershed as opposed to a clearly identified single source.

Oligotrophic - A measure of a lake's trophic status. Literally means 'poorly nourished' and applied to lakes exhibiting a low level of productivity (see Table 1).

Oxic - having oxygen

Point Source Pollutant - A pollutant that originates from a single, easily identified location such as a sewage treatment plant.

Residence Time - See Turnover Time

Response Time - The time it would take for the lake to respond to a change in its loading of a substance. Because this is a logarithmetic function, response time is usually expressed as the time for half the change to take place.

Secchi Disk - A circular disk, typically 20 cm in diameter and divided into white and black quadrants, used to measure the transparency of a water body.

Thermocline – The area of a stratified lake in which a strong gradient in temperature exists. It is often further defined as the area of the lake having a change in temperature of at least 1 ºC per metre of depth.

Trophic State - An indication of the relative productivity of an ecosystem. For freshwater systems it is typically evaluated in terms of the chlorophyll *a* concentration (a measure of algal biomass), and the Secchi Disk depth (a measure of water transparency).

Turnover Time - The average amount of time that water remains in a lake. It is calculated as the ratio of the volume of the lake to the volume of water leaving the lake, usually on an annual basis.

Watershed - See Drainage Basin.

Zooplankton - Animals, usually microscopic, that live suspended within the water column.

15. APPENDICES

Appendix I. Sample Excel Worksheet

Lake Name

Input Parameters	Symbol	Value	Units	Budgets		
Morphology				**Hydraulic Budget (m^3)**		
Drainage Basin Area (Excl. of Lake Area)	Ad		ha			
Area Land Use Category 1	Ad1		ha			**% Total**
Area Land Use Category 2	Ad2		ha	Upstream Inflow		
Area Land Use Category 3	Ad3		ha	Precipitation		
Area Land Use Category 4	Ad4		ha	Surface Run Off		
Area Land Use Category 5	Ad5		ha	Evaporation		
Area Land Use Category 6	Ad6		ha	Total Outflow		
Area Land Use Category 7	Ad7		ha			
Area Land Use Category 8	Ad8		ha	**Phosphorus Budget (gm)**		
Area Land Use Category 9	Ad9		ha			
Area Land Use Category 10	Ad10		ha			**% Total**
Lake Surface Area	Ao		ha	Upstream Inflow		
Lake Volume	V		10^6 m^3	Atmosphere		
Hydrology Inputs				Surface Run Off		
Upstream Hydraulic Inputs	Qi		m^3 yr^{-1}	Development		
Annual Unit Precipitation	Pr		m yr^{-1}	Sedimentation		
Annual Unit Lake Evaporation	Ev		m yr^{-1}	Total Outflow		
Annual Unit Hydraulic Run Off	Ru		m yr^{-1}	**Model Validation**		
Phosphorus Inputs						
Upstream P Input	Ju		gm P yr^{-1}	Predicted P (mg m^{-3})		
Annual Unit Atmospheric Phosphorus Deposition	Da		gm P m^{-2} yr^{-1}	Measured P (mg m^{-3})		
Land Use Category 1 P Export Coefficient	E1		gm P m^{-2} yr^{-1}	% Difference		
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}			

Areal Hydraulic Input	q_s		m yr^{--1}			
Total Hydraulic Outflow	Qo		m^3 yr^{--1}			
Total Atmospheric P Input	Jd		gm yr^{-1}			
Total Surface Run Off P Input	Je		gm yr^{-1}			
Total Development P Input	Jr		gm yr^{-1}			
Total P Input	Jt		gm yr^{-1}			
Lake P Retention Factor	Rp		-			
Lake P Retention	Ps		gm yr^{-1}			
Predicted Lake P Concentration	[P]		mg L^{-1}			
Lake P Outflow	Jo		gm yr^{-1}			
Lake Mean Depth	z		m			
Lake Flushing Rate	FR		times yr^{-1}			
Lake Turnover Time	TT		yr			
Lake Response Time	RT(1/2)		yr			

Appendix II. Data Sources

Lake Morphology:

Information Officer
Nova Scotia Department of Agriculture and Fisheries
P.O. Box 700
Pictou, N.S.
B0K 1H0
Tel: (902) 485-5056
(http://www.gov.ns.ca/nsaf/sportfishing/lakesurvey/)

Drainage Basin Topographic Maps:

Nova Scotia Geomatics Centre
160 Willow Street
Amherst, N.S.
B4H 3W5
Tel: 902-667-721
Fax: 902-667-6299
(http://www.gov.ns.ca/snsmr/land/)

Service Nova Scotia and Municipal Relations
5151 Terminal Road
P.O. Box 2205
Halifax, N.S
B3J 3C4
Tel: 902-424-2735
Fax: 902-424-5747
email: lic_hfx@gov.ns.ca

Climate/Meteorology:

Environment Canada - Canadian Climate Normals
(http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html)

Geology:

Nova Scotia Department of Natural Resources
Mineral Resources Branch
1701 Hollis Street
Founders Square, 3rd. Floor
Halifax, N. S.
B3J 3M8
Tel: 902 424-2035
Fax: 902 424-7735
(http://www.gov.ns.ca/natr/meb/pubs/pubshome.htm)

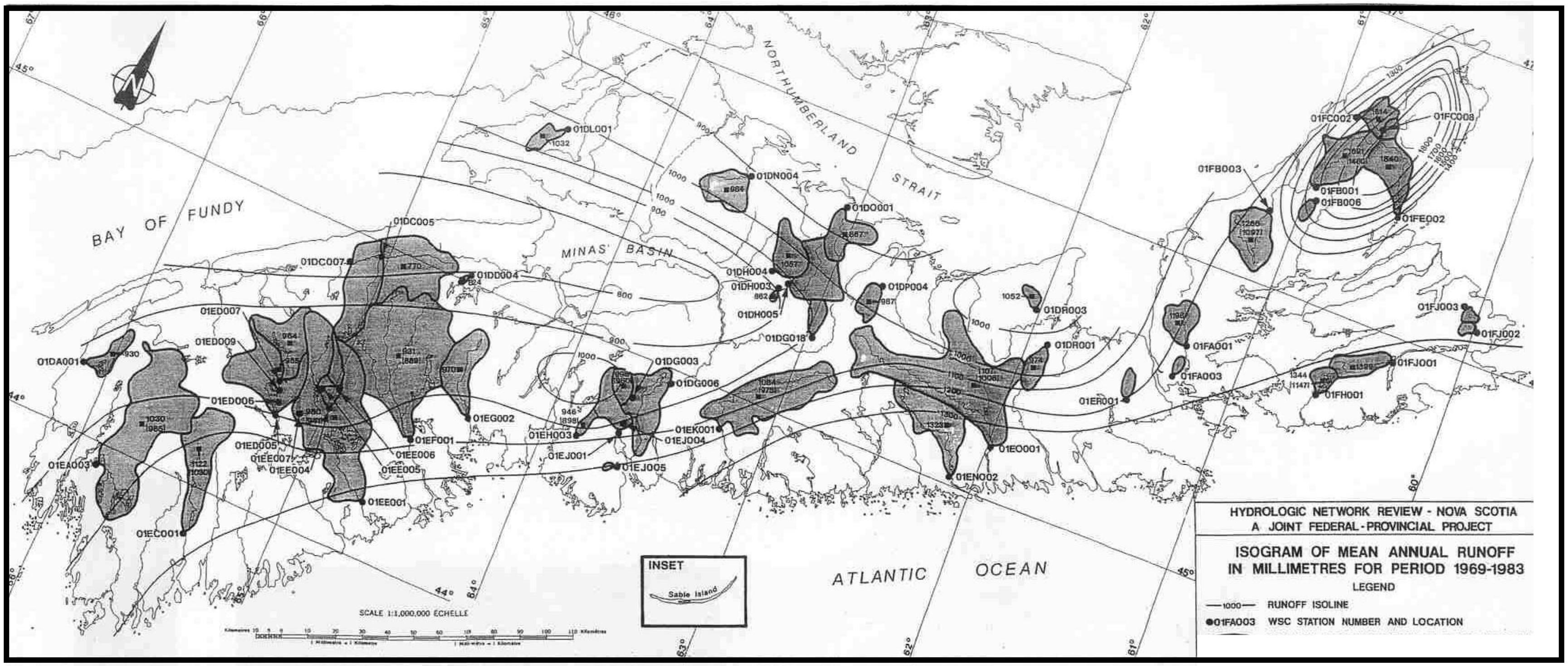
Soil Characteristics:

Nova Scotia Department of Agriculture and Marketing Soils Survey Reports
Agriculture and Agri-Food Canada. 1999. Canadian Soil Information Systems.
National Soil Database. (http://sis.agr.gc.ca/cansis/)

Land Use and Population Statistics:

Local Municipal Planning Offices

Appendix III. Isorunoff Map for Estimating Surface Run Off



Modified from Brimley et al. (1985).

Appendix IV – Literature References for Estimating Export Coefficients

Dillon, P.J. and W.B. Kirchner. 1974. The effects of geology and land use on the export of phosphorus from watersheds. Water Research. 9:135-148.

Lowe, J.S. 2001. Revision of the Kings County lake capacity model: validation and implications. Report prepared for the Municipality of Kings. 21p.

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Scott, R.S., W.C. Hart and G. Patterson. 2000. Phosphorus export from stream catchments in Nova Scotia. Internal Report No. 93-3, DalTech, Dalhousie University, Halifax, Nova Scotia. 102 p.

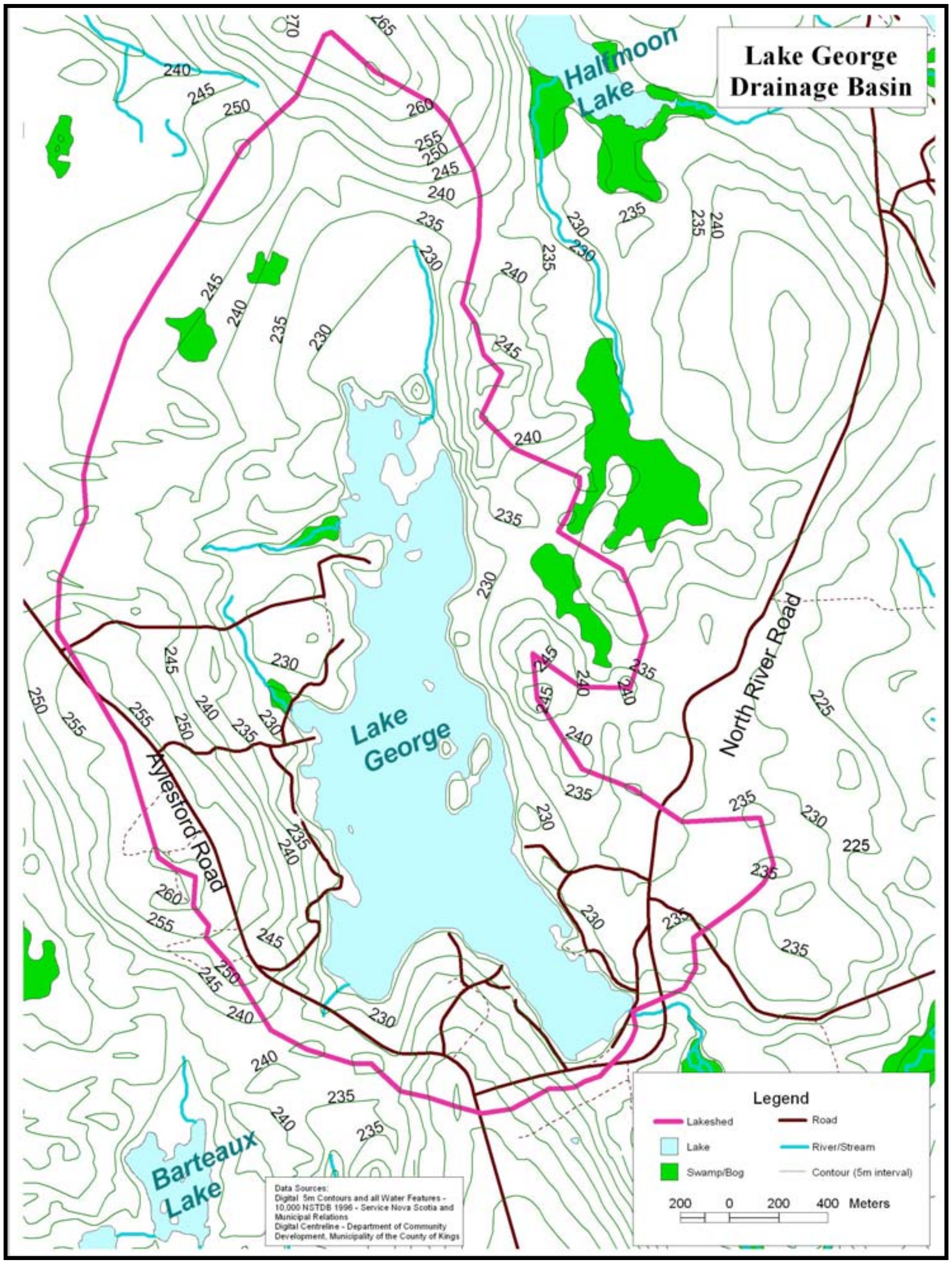
Uttomark, P.D., J.D. Chapin and K.M. Green. 1974. Estimating nutrient loading of lakes from non-point sources. Report No. 660/13-74-020, Ecological Research Series, United States Environmental Protection Agency, Corvallis, Oregon.

Appendix V
Example of Model Application

This appendix contains an example of the application of the model to Lake George, a headwater lake located in the Gaspereau River watershed in Kings County, Nova Scotia. Development of each model input is explained according to the order in which they are presented in the manual and listed in the Excel worksheet.

V.1 Determination of Drainage Basin Area

The area of the drainage basin is determined by outlining the drainage basin on a topographic map (Figure V.1) and determining its area using planimetry (the actual size of the map used for this was at a scale of 1:5,000). The drainage basin surface area was determined to be 747.8 ha.

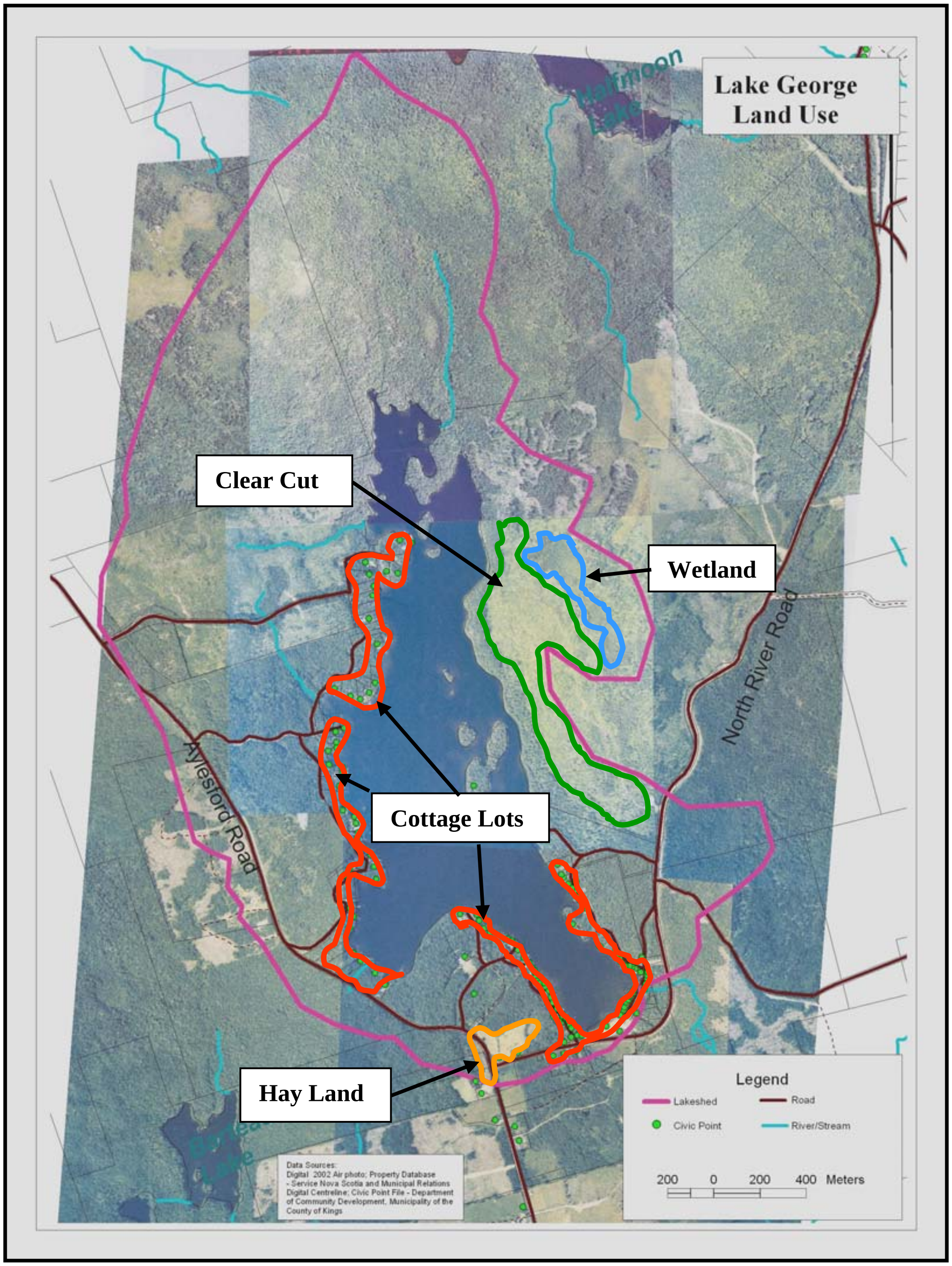


Data Sources:
Digital 5m Contours and all Water Features - 10,000 NSTDB 1996 - Service Nova Scotia and Municipal Relations
Digital Centreline - Department of Community Development, Municipality of the County of Kings

Figure V.1. Map of Lake George showing its drainage basin.

V.2. Determination of the Area of Each Land Use Category

The area of each land use is determined by subdividing the drainage basin into land use categories. For Lake George, in addition to the forestland, four other land use categories were identified (Figure V.2).



Data Sources:
Digital 2002 Air photo; Property Database - Service Nova Scotia and Municipal Relations
Digital Centreline; Civic Point File - Department of Community Development, Municipality of the County of Kings

Figure V.2. Air photo of Lake George drainage basin showing land use categories.

V.3. Determination of Hydrological Inputs/Outputs

The hydrological inputs/outputs include upstream inputs, run off from the land, precipitation onto the lake, and evaporation from the lake.

Since Lake George is a headwater lake, it receives no water inputs from upstream lakes so this value (**Qi**) is set to zero. If it were to receive upstream inputs, this value would be set equal to the Total Hydrologic Outflow of the upstream lake (**Qo**).

The hydraulic input from land run off is determined as the product of the Annual Unit Hydraulic Run Off and the Area of the Drainage Basin. The Hydraulic Unit Run Off (**Ru**) is estimated at 0.80 metres yr^{-1} from the isorunoff map contained in Appendix III.

The Annual Unit Precipitation (**Pr**) onto the lake is estimated as 1.21 metres yr^{-1} from weather records for Kentville, Nova Scotia obtained from the Canadian Climate Normals (see Appendix II for source). The Canadian Climate Normals is also used to estimate Annual Unit Lake Evaporation (**Eu**) of 0.18 metres yr^{-1}.

The following is a partial listing of the database obtained from the Canadian Climate Normals website.

Canadian Climate Normals 1971-2000

Created 2002-06-21; Modified 2003-07-24; Reviewed 2003-07-24.

URL: http://climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html

The Green Lane, Environment Canada's World Wide Web Site

NOTE!! *Data used in the calculation of these Normals may be subject to further quality assurance checks. This may result in minor changes to some values presented here.*

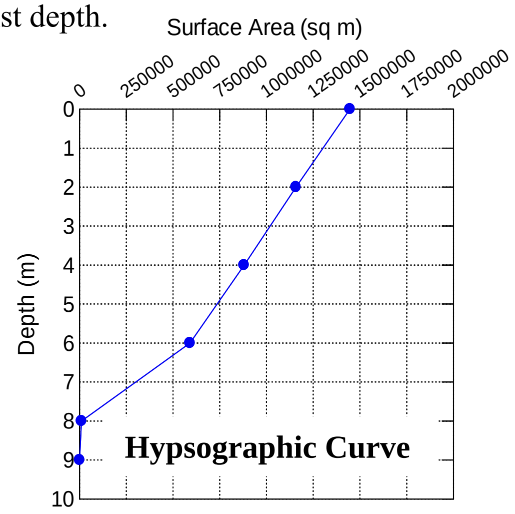
KENTVILLE CDA NOVA SCOTIA Latitude: 45º 4' N; Longitude 64º 28' W; Elevation 48.80 m.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Rainfall (mm)	60.2	45.0	63.9	70.5	92.7	81.4	87.6	85.5	87.3	93.3	103.7	77.0	948.0
Snowfall (cm)	70.9	59.2	45.9	17.3	3.7	0.0	0.0	0.0	0.0	1.9	11.9	55.0	265.9
Precipitation (mm)	126.7	101.5	110.6	90.2	97.4	81.4	87.6	85.5	87.3	95.5	117.4	129.9	1210.9
Lake Evaporation (mm)					3.1	3.6	3.9	3.4	2.5	1.5			18.0

V.4. Determination of Lake Surface Area and Volume

The surface area of the lake (**Ao**), as well as the surface areas at selected depth contours, is determined from a bathymetric map (Figure V.3) using planimetric or image analysis procedures. The results for Lake George are shown in the table below. (It should be noted that if the lake contains islands, as does Lake George, the area of the islands must be subtracted.) This information is used to construct a hypsographic curve in which the area of each depth contour is plotted against depth.

Surface Area at Each Two Metre Depth Contour	
Depth (m)	**Surface Area (m^2)**
0	1,447,015
2	1,157,891
4	880,354
6	590,589
8	10,259
9	0



The volume of the lake (**V**)is equal to the area under the hypsographic curve. This can be determined by counting the number of squares under the curve (each square is equal to 250,000 m^3) or by using the following formula, which assumes each layer of the lake is shaped like a truncated pyramid:

$$\text{Volume} = h \times (A_U + A_L)/2 \quad \text{where,}$$

h = depth between contours

A_U = Surface area of upper contour

A_L = Surface area of lower contour

For Lake George, the volumes are as follows:

$$\text{Volume } 0 - 2 \text{ m} = 2 \times (1447015 + 1157891)/2 = 2{,}604{,}906$$
$$\text{Volume } 2 - 4 \text{ m} = 2 \times (157891 + 880354)/2 = 2{,}038{,}245$$
$$\text{Volume } 4 - 6 \text{ m} = 2 \times (880354 + 590589)/2 = 1{,}470{,}943$$
$$\text{Volume } 6 - 8 \text{ m} = 2 \times (590589 + 10259)/2 = 600{,}848$$
$$\text{Volume } 8 - 9 \text{ m} = 1 \times (10259 + 0)/2 = 5130$$

Total Volume = 6,720,072 m^3

Another method for calculating the volume of a lake is to use the formula for a truncated cone, which assumes each layer of the lake is shaped like a truncated cone (symbols are the same as for the truncated pyramid formula):

$$\text{Volume} = (h/3) \times (A_U + A_L + \sqrt{(A_U \times A_L)})$$

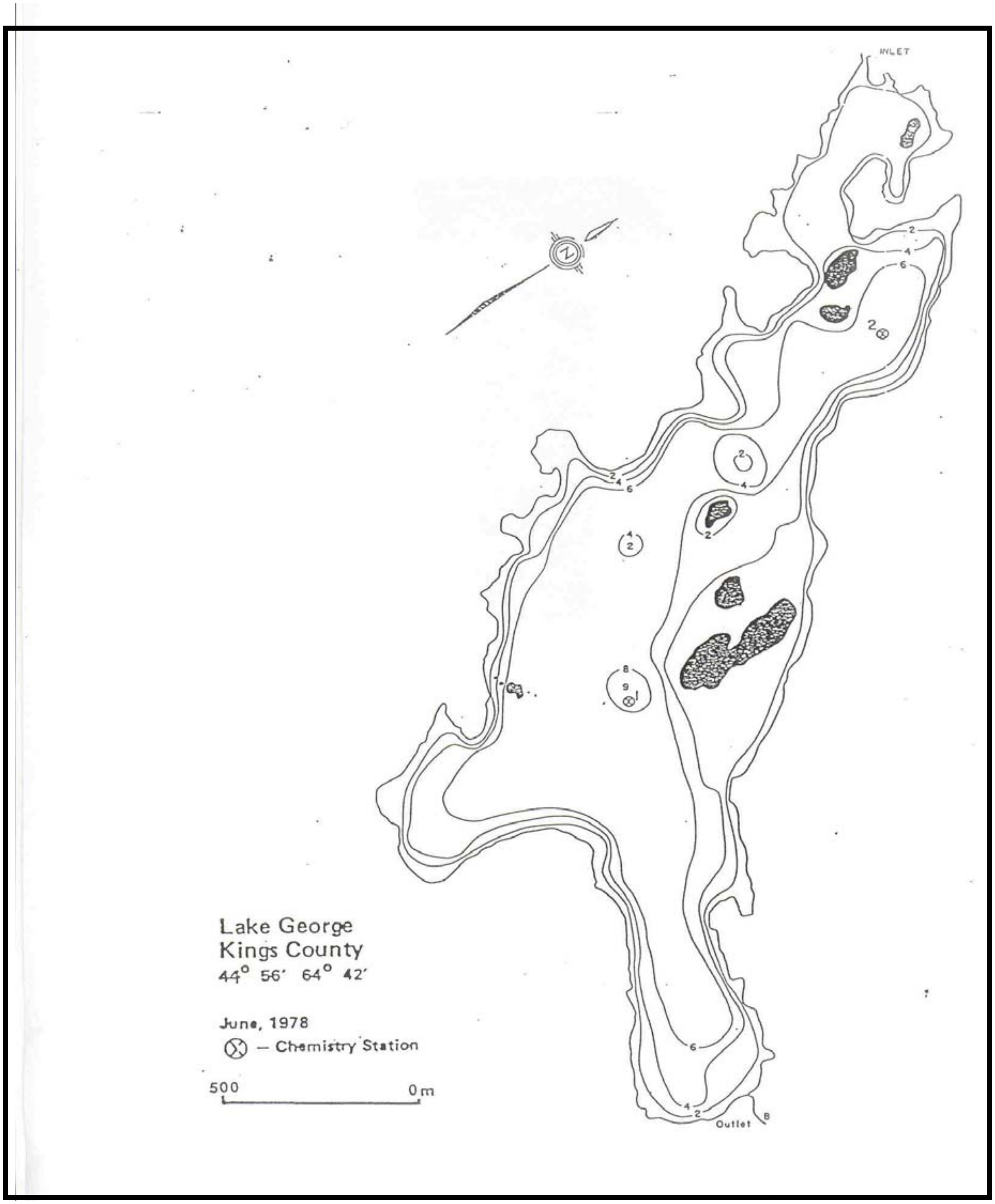


Figure V.3. Bathymetric map of Lake George obtained from the Nova Scotia Department of Agriculture and Fisheries.

V.5. Estimate of Atmospheric Phosphorus Deposition Coefficient

Atmospheric phosphorus unit deposition (**Da**) was assumed to be 0.020 mg gm m^{-2} yr^{-1}, the average of the values reported for Nova Scotia (see Section 7.1.3.2).

V.6. Estimates of Phosphorus Surface Run Off Coefficients

Estimates of phosphorus surface run off coefficients were made based on the geology, soil types and land use characteristics of the drainage basin. Information on bedrock geology was obtained from Donohoe and Grantham (1989)[3] and Finck et al. (1994)[4] and soil characteristics were obtained from Cann et al. (1965)[5]

The bedrock geology is primarily intrusive granite coved by a shallow layer of glacial drift. The major soil type in the drainage basin belongs to the Gibraltar series which consists of coarse till. There is little evidence that either geology or soil type vary significantly within the drainage basin of Lake George.

Land use categories include forest (640.4 ha), clear cut forest land (52.3 ha), wetland (8.3 ha), agriculture (mainly hay land – 3.2 ha), and cottage lots (43.6 ha). The area of each was estimated using an image analysis program..

The following phosphorus export coefficients were estimated from the export coefficients tabulated in Section 7.1.3.3 of the User's Manual.

- Igneous Forested - 0.0069 gm m^{-2} yr^{-1} (from Scott et al. (2000) summary)
- Managed Forest -0.0625 gm m^{-2} yr^{-1} (from Maine Department of Environmental Protection (2000) summary)
- Wetlands – 0.0000 gm m^{-2} yr^{-1} (see discussion in Section 2.1.4 of Supplementary Technical Report)
- Agriculture (mainly hay land) – 0.0081 gm m^{-2} yr^{-1} (mean value for grazing/pasture from Reckhow et al. (1980) in Table 7.4)
- Cottage Lots – 0.0300 gm m^{-2} yr^{-1} (from Maine Department of Environmental Protection (2000) summary)

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[3] Donohoe, H.V. and R.G. Grantham. 1989. Geological highway map of Nova Scotia. Department of Mines and Energy.

[4] Finck, P.W., R.M. Graves, F.J. Bonner and H.B. Bent. 1994. Glacial and till clast geology of Gaspereau Lake, Nova Scotia – South Mountain Batholith Project. Map 94-14. Nova Scotia Department of Natural Resources.

[5] Cann, D.B., J.L. MacDougall and J.D. Hilchey. 1965. Soil survey of Kings County, Nova Scotia. Canadian Department of Agriculture and Nova Scotia Department of Agriculture and Marketing.

V.7. Determination of Development Input

Development input of phosphorus is determined according to the following equation:

$$P_d = \Sigma PS_i + (N_d \times N_u \times N_{pc} \times S_i \times (1 - R_{sp})) \quad \text{where,}$$

PSi = Total phosphorus input from Point Source i
Nd = Number of dwellings in the drainage basin
Nu = Average number of persons occupying each dwelling
Npc = Average fraction of the year dwelling are occupied
Si = Phosphorus load per capita year
Rsp = Septic system retention coefficient

Development on Lake George is due to residential use, most of which is summer cottages. The number of cottages and permanent residences located within 300 metres of the shoreline of the lake was determined from statistics compiled by the Municipality of Kings County. Information on the frequency of occupancy and number of persons using each residence was obtained through a mail-out survey.

The number of dwellings (**Nd**) was determined to be 110. Of these, 104 are seasonal and 6 are permanent. Results of the survey indicated that the average number of persons occupying each dwelling was 2.73 for the seasonal dwellings and 3.20 for the permanent dwellings. The average fraction of the year each dwelling was occupied was 0.19 for the seasonal dwellings and 0.82 for the permanent dwellings. Based on this information, the average number of occupants (**Nu**) and the average fraction of the year occupied for seasonal and permanent dwellings (**Npc**) combined were calculated to be 2.73 and 0.22.

The phosphorus load per capita (**Si**) was considered to be 800 gm P yr^{-1}, and the septic system retention coefficient **(Rsp)** was assumed to be 0.5.

There are no point source inputs to Lake George, so **PSi** is set to zero on the worksheet.

V. 8. Determination of Phosphorus Retention Coefficient

The Phosphorus Retention Coefficient (**v**) is an empirically derived constant (see Section 7.2.2.5). Since there is some evidence, based on monitoring of surface and bottom water temperatures, that Lake George experiences stratification, and possibly anoxic conditions, the value of v is chosen to be 7.2 according to the relationships developed by Kichner and Dillon (1975).

V.9. Model Prediction of Phosphorus Concentration

The following table is an illustration of the Excel spreadsheet containing all of the data entries for Lake George. The model prediction of phosphorus concentration is 0.0082 mg L^{-1}. The phosphorus budget indicates that 19.88 % of the total phosphorus input is due to atmospheric deposition, 61.97 % is due to surface run off, and 18.15 % is due to development[6]. Of the total phosphorus outputs, 58.00 % is lost to the sediments and 42.00 % is lost via the outflow.

Lake George (Initial Model)						
Input Parameters	**Symbol**	**Value**	**Units**	**Budgets**		
Morphology				**Hydraulic Budget (m^{-3})**		
Drainage Basin Area (Excl. of Lake Area)	Ad	747.8	ha			
Area Land Use Category 1 (Forest)	Ad1	640.4	ha			**% Total**
Area Land Use Category 2 (Clear Cut)	Ad2	52.3	ha	Upstream Inflow	0	0
Area Land Use Category 3 (Wetland)	Ad3	8.3	ha	Precipitation	1750991	22.64
Area Land Use Category 4 (Hay Land)	Ad4	3.2	ha	Surface Run Off	6066090	77.36
Area Land Use Category 5 (Cottage Lots)	Ad5	43.6	ha	Evaporation	-260478	3.37
Area Land Use Category 6	Ad6	0.0	ha	Total Outflow	7556603	96.63
Area Land Use Category 7	Ad7	0.0	ha	Total Check		100.00
Area Land Use Category 8	Ad8	0.0	ha			
Area Land Use Category 9	Ad9	0.0	ha	**Phosphorus Budget (gm yr^{-1})**		
Area Land Use Category 10	Ad10	0.0	ha			
Lake Surface Area	Ao	144.7	ha			**% Total**
Lake Volume	V	6.72	10^6 m^3	Upstream Inflow	0	0
Hydrology				Atmosphere	28942	19.88
Upstream Hydraulic Inputs	Qi	0	m^3 yr^{-1}	Surface Run Off	90214	61.97
Annual Unit Precipitation	Pr	1.21	m yr^{-1}	Development	26426	18.15
Annual Unit Lake Evaporation	Ev	0.18	m yr^{-1}	Sedimentation	-84438	58.00
Annual Unit Hydraulic Run Off	Ru	0.80	m yr^{-1}	Total Outflow	61144	42.00
Phosphorus Inputs				Total Check		100.00
Upstream P Input	Ju	0	gm P yr^{-1}			
Annual Unit Atmospheric P Deposition	Da	0.0200	gm P m^{-2} yr^{-1}			
Land Use Category 1 P Export Coefficient	E1	0.0069	gm P m^{-2} yr^{-1}	**Model Validation**		
Land Use Category 2 P Export Coefficient	E2	0.0625	gm P m^{-2} yr^{-1}			
Land Use Category 3 P Export Coefficient	E3	0.0000	gm P m^{-2} yr^{-1}			
Land Use Category 4 P Export Coefficient	E4	0.0081	gm P m^{-2} yr^{-1}	Predicted P (mg L^{-1})		0.0082
Land Use Category 5 P Export Coefficient	E5	0.0300	gm P m^{-2} yr^{-1}	Measured P (mg L^{-1})		0.0105
Land Use Category 6 P Export Coefficient	E6	0.0000	gm P m^{-2} yr^{-1}	% Difference		-21.9
Land Use Category 7 P Export Coefficient	E7	0.0000	gm P m^{-2} yr^{-1}			
Land Use Category 8 P Export Coefficient	E8	0.0000	gm P m^{-2} yr^{-1}			
Land Use Category 9 P Export Coefficient	E9	0.0000	gm P m^{-2} yr^{-1}			
Land Use Category 10 P Export Coefficient	E10	0.0000	gm P m^{-2} yr^{-1}			
Number of Dwellings	Nd	110	#			
Average number of Persons per Dwelling	Nu	2.73	#			
Average Fraction of Yr Dwellings Occupied	Npc	0.22	yr^{-1}			

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[6] This includes only the input from septic systems. It could also, and probably should, include the increase in run off of phosphorus from dwelling lots above that which would occur if the lots were left as forest land.

Phosphorus Load per Capita per Year	Si	800	gm P cap^{-1} yr^{-1}			
Septic System Retention Coefficient	S_r	0.5	n/a			
Point Source Input 1	PS_1	0	gm yr^{-1}			
Point Source Input 2	PS_2	0	gm yr^{-1}			
Point Source Input 3	PS_3	0	gm yr^{-1}			
Point Source Input 4	PS_4	0	gm yr^{-1}			
Point Source Input 5	PS_5	0	gm yr^{-1}			
Phosphorus Retention Coefficient	v	7.2	n/a			
Model Outputs						
Total Precipitation Hydraulic Input	Ppt_i	1750991	m^3 yr^{-1}			
Total Evaporation Hydraulic Loss	E_o	260478	m^3 yr^{-1}			
Total Hydraulic Surface Run Off	Q_l	5982400	m^3 yr^{-1}			
Total Hydraulic Input	Q_t	773391	m^3 yr^{-1}			
Areal Hydraulic Load	q_s	5.16	m yr^{-1}			
Total Hydraulic Outflow	Q_o	7472913	m^3 yr^{-1}			
Upstream P Input	Jd	0	gm yr^{-1}			
Total Atmospheric P Input	Jd	28942	gm yr^{-1}			
Total Surface Run Off P Input	Je	90214	gm yr^{-1}			
Total Development P Input	Jr	26426	gm yr^{-1}			
Total P Input	Jt	145582	gm yr^{-1}			
Lake P Retention Factor	Rp	0.58	n/a			
Lake Phosphorus Retention	Ps	84438	gm yr^{-1}			
Lake Phosphorus Concentration	[P]	**0.0082**	mg L^{-1}			
Lake Phosphorus Outflow	Jo	81144	gm yr^{-1}			
Lake Mean Depth	z	4.6	m			
Lake Flushing Rate	FR	1.11	times yr^{-1}			
Lake Turnover Time	TT	0.90	yr			
Lake Response Time	RT(1/2)	0.21	yr			

V.10. Model Validation

Model validation involves comparing the model's predicted phosphorus concentration with phosphorus concentrations obtained from field measurements. Figure V.4 shows the seasonal and yearly variation in phosphorus concentration for Lake George based on measurements made as part of a volunteer based water quality monitoring program coordinated by the Municipality of Kings County. The mean value of all of the measurements is 0.0105 mg L^{-1}.

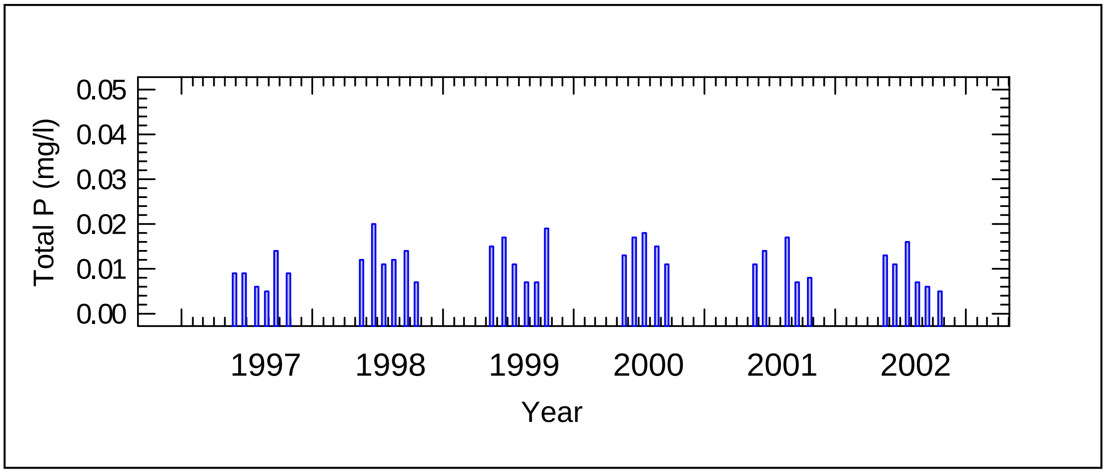

Figure V.4. Phosphorous concentration validation data for Lake George.

The model under predicts the lake's phosphorus concentration by 21.9 %, which is above the 20% difference generally considered acceptable for model validation (see Section 9 of the User's Manual). As a result, it was decided that the model should be re-evaluated.

V.11. Model Re-evaluation

In re-evaluation of the model, it was discovered that Lake George has a summer camp located on its north shore. The camp accommodates 34 persons per day for a period of 14 days, which is equivalent to 476 user days per year or 1.30 capita per year. Assuming a septic input of 800 gm P per capita per year and a septic retention coefficient of 0.5, this would result in an input of 520 gm P per year. The area of land used for the camp should also be considered, and it was assumed that it occupied an area of five ha and had a phosphorus export coefficient of 0.0300 gm m^{-2} yr^{-1} (equal to that of the cottage lots).

Further re-evaluation indicated that Lake George also contains a public beach. Data on the per capita use of the public beach is not available, but if it is conservatively assumed that phosphorus inputs from this source are equal to about four times that of the summer camp, this addition results in a difference of 20.0%, which is on the borderline of the of the 20% guideline.

Other factors that could also be re-evaluated include inputs from roadways along the lake's shoreline and the assumption that there is no phosphorus export from the wetland present in the drainage basin.

The validated model is illustrated below (the input values that were changed or added in the re-evaluation process are in bold print).

Lake George (Validated Model)

Input Parameters	Symbol	Value	Units	Budgets		
Morphology				**Hydraulic Budget (m^{-3})**		
Drainage Basin Area (Excl. of Lake Area)	Ad	747.8	ha			
Area Land Use Category 1 (Forest)	Ad1	**635.4**	ha			**% Total**
Area Land Use Category 2 (Clear Cut)	Ad2	52.3	ha	Upstream Inflow	0	0
Area Land Use Category 3 (Wetland)	Ad3	8.3	ha	Precipitation	1750991	22.64
Area Land Use Category 4 (Hay Land)	Ad4	3.2	ha	Land Run Off	5982400	77.36
Area Land Use Category 5 (Cottage Lots)	Ad5	43.6	ha	Evaporation	-260478	3.37
Area Land Use Category 6 **(Campground)**	Ad6	**5.0**	ha	Total Outflow	7472913	96.63
Area Land Use Category 7	Ad7	0.0	ha	Total Check		100.00
Area Land Use Category 8	Ad8	0.0	ha			
Area Land Use Category 9	Ad9	0.0	ha	**Phosphorus Budget (gm yr^{-1})**		
Area Land Use Category 10	Ad10	0.0	ha			
Lake Surface Area	Ao	144.7	ha			**% Total**
Lake Volume	V	6.72	10^6 m^3	Upstream Inflow	0	0
Hydrology				Atmosphere	28942	19.38
Upstream Hydraulic Inputs	Qi	0	m^3 yr^{-1}	Surface Run Off	91369	61.18
Annual Unit Precipitation	Pu	1.21	m yr^{-1}	Development	29026	19.44
Annual Unit Lake Evaporation	Eu	0.18	m yr^{-1}	Sedimentation	-86615	58.00
Annual Unit Hydraulic Run Off	Ru	0.80	m yr^{-1}	Total Outflow	62722	42.00
Phosphorus Inputs				Total Check		100.00
Upstream P Input	Ju	0	gm P yr^{-1}			
Annual Unit Atmospheric P Deposition	Da	0.0200	gm P m^{-2} yr^{-1}			

Land Use Category 1 P Export Coefficient	E1	0.0069	gm P m^{-2} yr^{-1}
Land Use Category 2 P Export Coefficient	E2	0.0625	gm P m^{-2} yr^{-1}
Land Use Category 3 P Export Coefficient	E3	0.0000	gm P m^{-2} yr^{-1}
Land Use Category 4 P Export Coefficient	E4	0.0081	gm P m^{-2} yr^{-1}
Land Use Category 5 P Export Coefficient	E5	0.0300	gm P m^{-2} yr^{-1}
Land Use Category 6 P Export Coefficient	E6	**0.0300**	gm P m^{-2} yr^{-1}
Land Use Category 7 P Export Coefficient	E7	0.0000	gm P m^{-2} yr^{-1}
Land Use Category 8 P Export Coefficient	E8	0.0000	gm P m^{-2} yr^{-1}
Land Use Category 9 P Export Coefficient	E9	0.0000	gm P m^{-2} yr^{-1}
Land Use Category 10 P Export Coefficient	E10	0.0000	gm P m^{-2} yr^{-1}
Number of Dwellings	Nd	110	#
Average number of Persons per Dwelling	Nu	2.73	n/a
Average Fraction of Yr Dwellings Occupied	Npc	0.22	yr^{-1}
Phosphorus Load per Capita per Year	Si	800	gm P cap^{-1} yr^{-1}
Septic System Retention Coefficient	Rsp	0.5	n/a
P Input from camp	PS1	**520**	gm yr
P input from public beach	PS2	**2080**	gm yr
Point Source Input 3	PS3	0	gm yr
Point Source Input 4	PS4	0	gm yr
Point Source Input 5	PS5	0	gm yr
Phosphorus Retention Coefficient	v	7.2	n/a
Model Outputs			
Total Precipitation Hydraulic Input	Ppt_i	1750991	m^{3} yr^{-1}
Total Evaporation Hydraulic Loss	Eo	260478	m^{3} yr^{-1}
Total Hydraulic Surface Run Off	Ql	5982400	m^{3} yr^{-1}
Total Hydraulic Input	Qt	7733391	m^{3} yr^{-1}
Areal Hydraulic Load	q_s	5.16	m yr^{-1}
Total Hydraulic Outflow	Qo	7472913	m^{3} yr^{-1}
Total Atmospheric P Input	Jd	28942	gm yr^{-1}
Total Surface Run Off P Input	Je	91369	gm yr^{-1}
Total Development P Input	Jr	29026	gm yr^{-1}
Total P Input	Jt	149337	gm yr^{-1}
Lake P Retention Factor	Rp	0.58	n/a
Lake Phosphorus Retention	Ps	62722	gm yr^{-1}
Lake Phosphorus Concentration	[P]	**0.0083**	mg L^{-1}
Lake Phosphorus Outflow	Jo	86615	gm yr^{-1}
Lake Mean Depth	z	4.6	m
Lake Flushing Rate	FR	1.11	times yr^{-1}
Lake Turnover Time	TT	0.9	yr
Lake Response Time	RT(1/2)	0.21	yr

Model Validation		
Measured P (mg L^{-1})		0.0105
Predicted P (mg L^{-1})		0.0084
% Difference		-20.0

V.12. Examples of Model Application

Having verified the model it can now be used to assess the impact of a particular activity with respect to how it will influence the lake's phosphorus concentration. Three examples are presented. (You may want to make these changes on the Excel spreadsheet to verify the results for yourself.)

1. What would be the effect of doubling the amount of clear cut forest?

To evaluate this land use change, it is necessary to adjust the areas of the natural forest and clear cut forest in the spreadsheet. Increasing the area of the clear cut from 52.3 to 104.6 ha and decreasing the area of the natural forest from 635.4 to 583.1 ha results in a change in phosphorus concentration from 0.0084 to 0.0100 mg L^{-1}, an increase of 19.3 %.

2. What would be the effect of doubling the number of dwellings?

Doubling the number of cottages to 220, as well as the area of the cottage lots from 43.6 to 87.2 ha (which also requires decreasing the area of forestland by 43.6 ha), results in changing the phosphorus concentration from 0.0084 to 0.0106 mg L^{-1}, an increase of 26.2 %.

3. What was the lake's phosphorus concentration prior to human activity in the watershed?

This question can be answered by eliminating all of the land uses from the model that result from human activity. This includes agriculture, cottage development, camp, and public beach inputs and setting the area of the forestland to that of the drainage basin minus the wetland area. The results is a lake phosphorus concentration of 0.0045 mg L^{-1}, a value that could be used as reference point for what the lake's phosphorus concentration was prior to human activity in the watershed.

APPENDIX VI

Supplementary Technical Report

Assumptions and Limitations of the Model

VI.1. Introduction

Over the last several decades, the use of mathematical models for predictive purposes has become well established in many areas of ecology. This is especially true in aquatic ecology, and particularly with regard to their use for the prediction of water quality. A large number of water quality models, varying greatly in sophistication and level of complexity currently exist (see e.g., Jorgenson 1995; Chapra 1997).

The major advantage to the use of mathematical models for predictive purposes is that they represent simplifications of natural systems that are difficult or impossible to duplicate experimentally, and provide a means whereby 'experiments' can be performed by altering components of the model and observing the resulting changes. They also provide an important means of evaluating how well we understand a system by comparing model predictions to what occurs in nature. If the model replicates what occurs in nature, we can have some confidence in believing that it contains all the important elements that control a particular process. If, however, the model behaves differently from what we observe in nature, this is an indication that the model lacks important qualitative elements, or is not correct in its quantitative formulations. If the model does appear to work well in terms of its predictive ability, we then have a tool that we can use to make management decisions.

The phosphorus run off coefficient modeling approach is one of the simplest approaches available to evaluate potential changes in phosphorus concentration resulting from changes in land use activities. This simplification has both its advantages and disadvantages. Its main advantage is that it is relatively easy to apply, does not require a great deal of costly field work for estimation of parameters and, most importantly, it provides for a relatively standardized procedure for making the 'best guess' when a decision has to made based on the potential impact of a particular development scenario being proposed for a watershed.

Because the model is simple, its main disadvantage is that it has a number of inherent simplifications and assumptions, and these must be fully appreciated and understood in order to avoid application of the model to situations in which it has not been shown to work successfully. The major purpose of this supplementary document is to discuss these limitations and assumptions, to the extent they have been discussed and recorded in the literature, so that users of the manual will be able to determine the degree to which the model is applicable to the systems they propose to model. A secondary objective of this document is to present some approaches that have been suggested, and in some cases applied, to overcome some of these assumptions and limitations and should prove particularly useful as a reference in those cases when it proves difficult to validate a model. There is also a discussion of the potential for use of the model as an aid to the development of a Phosphorus Water Quality Objective.

VI.2. Model Assumptions

VI.2.1. Phosphorus Transport

VI.2.1.1 Drainage Basin Size and Juxtaposition of Land Use Types

A major assumption of the model is that the amount of phosphorus transported by surface run off to the lake is independent of the distance over which transport occurs (Shuman et al. 1975). This means, for example, that an agricultural land use located in an area of the drainage basin far removed from the lake, or tributaries that enter the lake, will transport as much phosphorus to the lake as an agricultural area located in close proximity to the shoreline of the lake.

Related to this is the influence of drainage basin size on phosphorus transport. The model assumes that the transport of phosphorus is a linear function of drainage basin area. Prairie and Kalff (1986) have evaluated this assumption using literature data tabulated on phosphorus export from 210 drainage basins having a diversity of land uses that included forested and agricultural lands. The latter included pasture, row crops, non-row crops and mixed agriculture. Their results indicated that drainage basin size does not appear to have an affect on phosphorus export for forested, mixed agricultural and non-row crops, but does for pastures and row crops.

They suggest that the differences in observed export may be related to the form of phosphorus that is exported from the different land use areas, and that particulate phosphorus is, for a number of reasons, more likely to be retained within the drainage basin than dissolved phosphorus. In their study, the range and mean percent of particulate phosphorus exported from agricultural land was 44-98 and 84.5 percent, respectively. For forest lands, less than 50 percent of the phosphorus exported was in the particulate form.

The authors provided the following equations to estimate the relationship between phosphorus export and drainage basin area for pasture and row crop agricultural land uses:

Pasture $\log \text{TP export} = 1.562 + 0.589 \times \log \text{Drainage Basin Area}$

Row Crops $\log \text{TP export} = 1.880 + 0.589 \times \log \text{Drainage Basin Area}$

They suggest these equations be utilized by determining a 'standardization factor' based on drainage basin area. Thus, if an estimate of the amount of phosphorus exported for a particular land use is to be estimated based on export coefficients obtained from a study carried out in another area, the export should be corrected to account for any difference in drainage basin size. They provide the following example:

> "...if the TP export of two row crop catchments (5 and 15 km^2) are to be validly compared, the export of the larger basin must be pro-rated by a factor of 1.6

> (the expected TP export from 5 km^2 divided by the expected TP export from 15 km^2) so as to correct for the spatial scale effect observed from this agricultural practice. … The [standardization] factor is simply the ratio of the expected TP exports [predicted from the above equations] for the two catchments."

VI.2.1.2 Phosphorus Retention in Stream and Rivers

The model makes no allowance for the assimilation of phosphorus within upstream rivers or streams entering a lake, or for tributaries contained within a lake's drainage basin. This is a potentially serious limitation if the model is used to determine the permissible level of development within the watershed of a lake that has effluents entering lakes located downstream. If a downstream lake exceeds a phosphorus objective, no upstream development would be allowed.

The retention of phosphorus in streams and rivers can result from settling of particulate phosphorus, sorption of dissolved phosphorus to stream sediments, chemical precipitation of phosphorus, and uptake of phosphorus by benthic algae and macrophytes (Wagner et al. 1996). Behrendt and Opitz (2000) carried out a number of studies in which it was found that as much as 20 to 40 % of the phosphorus load was retained within streams before reaching the receiving water body.

VI.2.1.3. Proximity of Dwellings to Lake

When assessing the impacts of development, most phosphorus loading models have only considered dwellings located within 300 m of the lake's shoreline or a tributary entering the lake, and that phosphorus export to the lake is not influenced by the distance of the dwelling from the lake. The 300 m distance is arbitrary and has never been substantiated.

Hutchinson (2002) has proposed that this be modified to at least include a factor that takes into consideration the distance of the dwelling from the shoreline of the tributary. He proposes that the 300 m limit be maintained, but because all soils have some ability to retain phosphorus, the amount of phosphorus export to the lake or tributary be reduced as follows:

- Development between 100 and 200 m be reduced by one third
- Development between 200 and 300 m be reduced by two thirds
- Development beyond 300 m considered to have no input

VI.2.1.4. Wetlands

There are conflicting reports of the amount of phosphorus contributed by wetlands. At one extreme, some report that wetlands act neither as sources or sinks of phosphorus and that, on an annual basis, do not have a net export of phosphorus (Uttomark et al. 1974; Lee et al. 1980). Scott et al. (2002) on the other hand, suggest that wetlands export high amounts of organic rich phosphates. Rast and Lee (1980), however, suggest that much of the phosphorus exported from wetlands may not be in a form available to algae. The results of other studies indicate that wetlands have variable export or retention of phosphorus depending on their flushing rates and the sorptive capacity of the soils contained in the wetland, which decreases with time as wetlands age (Faulkner and Richardson 1989). Knight et al. (1987) advocate that retention is minimal if the residence time of water in the wetland is less than 10 to 15 days. Soil sorptive capacity is much more variable and requires empirical data to estimate.

Dillon and Molot (1997) made estimates of phosphorus loadings for wetlands located in south-central Ontario and presented the following relationship:

$$P_W = A_d \times (3.05 + (0.54 \times \%\ \text{wetland}) \quad \text{where,}$$

P_W = Wetland Phosphorus Load (kg yr^{-1})
A_d = Drainage Basin Area (km^2)
% Wetland = Percentage Wetland in the Drainage Basin

VI.2.1.5. Groundwater Inputs

The model does not address either the loss of phosphorus to groundwater, or the potential for phosphorus input by way of groundwater flows into a lake. It is often assumed that groundwater is relatively depleted of phosphorus because of the immobility of phosphorus in soils. Although this may be true generally, a recent review of phosphorus loss in agricultural drainage (Sims et al. 1998) indicates that considerable phosphorus can leach into groundwater systems under conditions of deep sandy soils and soils with high phosphorus concentrations resulting from over-fertilization or excessive use of organic fertilizers. There is also the possibility of groundwater transport to surface run off in agricultural fields that are tile drained. This should be considered in model applications where a significant proportion of the lake's drainage basin contains agricultural land use, especially if the crops grown receive high levels of fertilization.

VI.2.2. Lake Morphology

Aside from the surface area and, indirectly, volume of the lake, the model does not take into account differences in lake morphology or the position of water inputs to the lake.

A lake having a complex shoreline with bays and arms may have considerable spatial variation in such things as residence times, which in turn could result in considerable variation in phosphorus retention. Long, narrow water bodies, of the type commonly associated with river impoundments for example, may have a horizontal gradient in hydrological characteristics resulting in a greater amount of phosphorus retention in the upper portion where influents enter.

Some lakes also contain more than one basin and these may behave differently from each other. In this case, it may become necessary to treat each basin as a separate lake, especially if there are major differences in the number and characteristics of any tributaries that may enter each basin.

VI.3 Model Limitations

The model does not appear to work well for lakes that are very shallow. Shallow lakes are often characterized by high flushing rates and a limited ability to retain phosphorus. Any phosphorus that does settle appears to be easily resuspended as a result of the lake's water column being mixed to depths at or near the sediment surface (Welch and Cooke 1995). As a result, the model tends to overestimate the retention of phosphorus in shallow lakes (Hutchinson 2002). The presence of macrophytes, which are often well developed in shallow lakes, is also thought to influence the cycling of phosphorus since they can act as pumps bringing nutrients that have been deposited into the sediments back up into the water column.

Colored lakes are those lakes characterized by high levels of naturally occurring organic acids. The organic acids are largely in the form of humic and fulvic acids that arise from run off originating in wetlands and forested landscapes dominated by coniferous vegetation. Application of nutrient loading models to colored lakes has not been very successful as model predictions of phosphorus concentration are generally much lower than measured lake phosphorus concentrations (Kerekes 1981). In addition, the relationship between phosphorus concentration, phytoplankton production, phytoplankton biomass, chlorophyll *a* concentration and Secchi Disk depth appears to be different for colored lakes (Jackson and Hecky 1980; Chow-Fraser and Duthie 1987; Nurnberg 1996).

At present, it does not appear that phosphorus loading models, as they are presently developed, can be as easily applied to reservoirs as they can to natural lakes (Kerekes 1982; Kennedy 1998). The major reasons for this are as follows:

- The depth and volume of reservoirs typically undergo changes over a relatively short term depending on the need for the water they contain. As a result, the flushing rate and, in turn, the sedimentation rate of phosphorus, varies greatly over the same time period

- Reservoirs used for power generation have their outflows located at the bottom which depletes the hypolimnion and the phosphorus that has settled into it
- Reservoirs are often constructed in drowned river valleys and tend to be morphologically more like rivers than lakes
- The watersheds of reservoirs are generally much larger than those of lakes and tend to have more surface run off relative to the volume of the reservoir
- Because of their larger watersheds, reservoirs tend to have higher sediment loads and a greater proportion of their phosphorus input in particulate form.

Kennedy (1998) makes the following recommendations for anyone attempting to develop phosphorus loading models for reservoirs:

- Because reservoirs tend to have short hydraulic residence times, it may be necessary to formulate nutrient and water balances on a seasonal, as opposed to annual, basis
- If the sediment load is high, the phosphorus sedimentation factor should be adjusted
- Because of the river-like morphology of reservoirs, and the tendency for phosphorus to settle near inlets, it may be necessary to model reservoirs as a series of longitudinal segments. (Kerekes (1982) provides an example of how this approach can be applied.)

VI.4. Application of Model to Establishing Phosphorus Water Quality Objectives

The trophic response of a lake to inputs of phosphorus depends on many factors and it is unlikely that a single phosphorus water quality objective can be established that would be applicable to all Nova Scotia lakes. This makes it necessary to either develop objectives on an individual lake basis, or develop objectives for lakes that behave similarly in terms of their trophic response to phosphorus. The former is unlikely to be practical because of the effort and cost that would be involved. The latter approach requires the development of some sort of lake classification system based on how a lake responds to additions of phosphorus. This approach, often referred to as the 'ecoregional' or 'reference condition' approach, is currently being taken by many federal and state agencies in the United States (USEPA 2000) and has been suggested as a potential approach for setting phosphorus objectives in Canada. (Environment Canada 2003).

Determining exactly which factors should be considered in classifying lakes for this purpose is still a subject of debate. In general, they are those factors that determine the degree to which a lake will respond to an increase in phosphorus concentration, and particularly those factors that determine the biomass of algae under conditions when nutrients are not limiting. These include those factors that determine the potential level of algal production, especially the relationship of lake mixing depth to euphotic zone depth (both of which are closely related to the lake's morphology), and those factors that determine the loss of algal biomass. The later include grazing by zooplankton and flushing from the lake.

The establishment of phosphorus water quality objectives also requires a somewhat subjective assessment of how much of a change in water quality is considered acceptable. The two most commonly used characteristics used to assess water quality with respect to trophic status are water clarity and, in a stratified lake, the degree to which dissolved oxygen levels become depleted in the hypolimnion. If these two criteria are to be used in determining the amount of acceptable change in the water quality of a lake, then quantitative relationships between these factors and the biomass of algae, and between phosphorus concentration and algal biomass, must be developed. The latter will differ depending on the particular characteristics of the lake and is further argument of the need for a lake classification system.

In establishing phosphorus objectives, it is also important to consider the range in levels of phosphorus that are characteristic of natural lakes not impacted by human activities. This also requires that an extensive database be developed, using both existing information and by acquiring new information for those lake types that have not been well studied. This approach also requires that data be available on phosphorus concentration for lakes not impacted by human activity. Hutchinson (2002) presents a means whereby a phosphorus water quality objective can be set for a lake that has already been subjected to development. The approach involves using a validated phosphorus model based on export coefficients, and simply removing the development contribution of phosphorus to determine the pre-development lake phosphorus concentration. He stresses, however, that the model must be well developed and validated, if the results are to be of any significance.

VI.5. References

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