Apparent sources of phosphorus affecting Cusheon Lake, Salt Spring Island, B.C.

2007 October

By: John B. Sprague, Ph.D.
Sprague Associates Ltd.
474 Old Scott Road, Salt Spring Island, B.C.

A background report for
The Cusheon Watershed Management Plan
and Steering Committee
Salt Spring Island, B.C.

Table of contents

List of figures

List of tables

Acknowledgements

This report was prepared on behalf of the Cusheon Watershed Management Plan Steering Committee, by J.B. Sprague, with advice from people on the committee.

Members of the steering committee, local residents unless otherwise noted, have been: Eric Booth (Trustee, Islands Trust), Michael Butler, Judy Ellis, Deborah Epps (Ministry of Environment, Nanaimo, B.C.), Bob Francis (PARC), Mark Head (Planner, Islands Trust), Wayne Hewitt (chair and co-chair), Gary Holman (Director, S.S.I., Capital Regional District), Dr. Carol N. Kelly, Kimberly Lineger (Trustee, Islands Trust, former chair), Frank Moore (Beddis Waterworks), Maureen Moore (co-chair, Beddis and Cusheon Lake Area Residents Association), Wiebke and Wilfried Ortlepp (Cusheon Lake Farm), Kathy Reimer (Island Stream and Salmon Enhancement Society), John B. Sprague, Don and Kit Stevens, Robert Twaites, Judy Tyson, Tom Volquardson (Cusheon Lake Stewardship Committee) and Dr. Bob Weeden (Salt Spring Conservancy).

Chemical data were supplied by Ms. Epps and Ms Reimer. Watershed maps and areas of sub-basins were made by Brett Korteling, GIS Coordinator for Islands Trust, while other working maps were provided by Mark Head, former planner for Islands Trust, and created by Barb Dashwood of Islands Trust, Victoria. Information on water consumption was provided by Trevor Hutton of North Salt Spring Waterworks District and Don Stevens of the Beddis Waterworks District.

Welcome technical advice was offered by Dr. Neil F. Hutchinson of Gartner Lee Ltd., Markham, Ont. and Wayne Hewitt of the committee, with specific advice on modelling provided by Dr. Carol N. Kelly. Thanks are extended to Dr. Rick Nordin (University of Victoria) for general and particular technical advice and for finding data on phosphorus in rainfall. Similar thanks go to Dr. Roxanne Vingarzan, atmospheric scientist with Environment Canada (Vancouver) who searched for information on chemistry of rainfall.

Early copying cost and other tangible support was provided by the Ganges office of Islands Trust. Additional copying costs were supported by the Cusheon Lake Stewardship Committee. The electronic version of this report was produced by Tina Kempling of Imagine That Graphics.

It is hoped that this report will be available on the web sites of Islands Trust, Victoria, and/or the B.C. Ministry of Environment, http://wlapwww.gov.bc.ca/wat/wq/wqhome.html. Technical enquiries could be addressed to the author at 474 Old Scott Road, Salt Spring Island, B.C., V8K 2L7, or sssprague@shaw.ca.

OVERALL SUMMARY

(1) This report attempts to identify the probable sources of nutrient loading which have been causing algal blooms in Cusheon Lake. Estimates are derived from models and available data. Estimates are also year-long averages for a "typical" year, in order to describe the major relationships. Conditions in any particular year or season will differ from averages of the model.

(2) The amount of phosphorus is the overall factor that controls the strength of algal blooms in Cusheon Lake. The lake has been *mesotrophic* (somewhat enriched) from the 1970s to the present, judging from its phosphorus concentrations. Concentrations have been variable from year to year, with occasional excursions into *eutrophic* (enriched) conditions and also briefly into *oligotrophic* (low nutrient) status. Average phosphorus concentration has been 16.6 μg/L (parts per billion or ppb) in the most recent decade (1996 to 2006).

(3) The deep water of Cusheon Lake is isolated all summer by natural stratification. Decay of algae and other material deoxygenates this deep water. In turn, lack of oxygen results in regeneration of slightly more than 25 kg of phosphorus from the sediment into the bottom water, every year. This recycled nutrient adds on to the yearly external load, when lake waters become mixed in the autumn. The load regenerated from the sediment appears to have been increasing over the years, from about 7 kg in 1974-75. This makes it more urgent to reduce the external inputs to the lake. Delays will apparently mean that greater and greater reductions will be required for the external inputs, to balance the increasing internal contributions, in order to achieve a desirable status for the lake.

(4) A "cottage-country" predictive model was used to estimate phosphorus loads to the three lakes in the Cusheon basin. Estimates were based on land runoff and on contributions from about 100 households. The cottage-country model had been developed by Drs. Dillon, Rigler and Hutchinson for Ontario lakes.

(5) The "probable" scenario from the cottage-country model estimated that Cusheon Lake received 92.6 kilograms per year from external sources. Adding to that, the internal regeneration of 25 kg from the bottom sediments raises the amount which is mixed into the water to a total of 118 kg. The component sources can be listed as follows.

46 kg	(39%)	-- inflow from upstream lakes, mostly from land runoff in the sub-basins
17 kg	(15%)	-- land runoff in the Cusheon sub-basin
25 kg	(21%)	-- regeneration from the bottom sediment
19 kg	(16%)	-- direct human input from homes around the lake, plus shoreline clearing
8 kg	(7%)	-- direct human input (septic fields) from trailer homes upstream of lake
3 kg	(2%)	-- precipitation and aerial fallout

The steps in obtaining these values are given below.

(6) The sizes of drainage areas ("sub-basins" including lake surfaces) are: Roberts L. 119.9 hectares (ha); Blackburn L. 510.8 ha; Cusheon L. 220.0 ha; and downstream Cusheon Creek 214.5 ha. These were estimated by Islands Trust specialists using computer technology.

(7) The first step in modelling the Cusheon system was to estimate water balance, by incorporating average rainfall, runoff, evaporation, and withdrawals for human use. Eleven sets of existing data yielded an estimate that 48% of the rain and snow that fell on a basin ran off in creeks. The long-term average precipitation near the Cusheon basin has been measured as almost one metre per year (0.98 m/year). Evaporation from lake surfaces has recently been calculated as 0.713 metres per year. Water withdrawals were estimated from licences and from records of the water districts for household consumption.

These data led to the following flow estimates: outflow from Roberts Lake equals 520 thousand cubic metres per year; outflow of Blackburn Lake is 2,900 thousand m^3/yr; and outflow of Cusheon L. into the creek is 3,830 thousand m^3/yr. The final predicted outflow for Cusheon Lake represents a yearly average of 121 litres per second, showing excellent agreement with the actual outflow previously measured by Environment Canada (less than 2% difference after adjustment for slightly different precipitation during the periods of measurement).

(8) The regeneration of phosphorus (P) from bottom sediment was estimated from the buildup of P in the in the deep waters during summer isolation (lack of mixing), using existing data.

(9) The deposit of P from rain, snow and dust fallout is estimated as 0.11 kg per year on each hectare of lake surface. This was estimated from scanty data for the region.

(10) The direct contribution from houses around Cusheon Lake was estimated from standard values developed elsewhere for escape of P from septic fields, and for decline in amount with various distances of travel through soil.

(11) The rate of phosphorus runoff from land in the Cusheon basin was estimated by using the two upper lakes, Roberts and Blackburn, and their sub-basins. These lakes have no households near their shorelines, so the significant inputs of phosphorus are limited to land runoff, transfer from upstream lake, internal regeneration from bottom sediments, and aerial fallout and rainfall. The last three of those inputs can be estimated directly. The remaining unknown input is the runoff of P from the land; it can be estimated by trying various runoff rates of P in the model, until the model predicts the actual (observed) concentration in the lake. Land runoffs of 0.099 and 0.079 kilograms of phosphorus per hectare of land per year, were estimated for Roberts and Blackburn Lake respectively. The estimates for both lakes have some uncertainty because there are relatively few measurements of phosphorus concentrations in the lakes.

(12) An average of the two estimates for land runoff is 0.089 kilograms of phosphorus from each hectare in a year. That value was adopted for runoff of P for the land draining directly to Cusheon Lake. The estimate is close to an empirical value of 0.106 kg/ha•yr determined by one year of monitoring in Blackburn Creek. It is also close to 0.1 kg/ha•yr which is a standard value for phosphorus runoff from forested land in eastern Canada.

(13) Having estimated the land runoff of P to Roberts and Blackburn Lakes, the downstream flow of phosphorus from those lakes to Cusheon Lake was estimated by the model as 46 kg per year.

(14) The only remaining undefined source of P for Cusheon Lake was the contribution from household septic systems. The standard values for escape of P from septic fields and decline with travel through soil, were used in modelling to obtain a realistic scenario.

(a) A "worst-case" scenario for Cusheon L. assumed zero control of nutrients by all septic systems (i.e., the escape from a septic field was equal to the input to that septic system). Standard reductions were applied for travel through the soil between the septic field and the lakeshore, as determined by research elsewhere: 33% reduction for 100 metres of travel and 67% reduction for 200 metres. For this scenario, the model predicted 30 ppb of phosphorus in Cusheon Lake, almost twice as high as the recent observed average. It was concluded that the septic fields perform better than that.

(b) A "probable" scenario adopted the standard 74% retention of phosphorus by a septic system and its field, plus the above-mentioned decreases for distance from the lakeshore. The model predicted 16.8 ppb in the lake, almost the same as the recent observed average of 16.6 ppb. In view of the remarkable agreement, this scenario was accepted.

(15) The estimated total loading can be applied to a widely-known, more general *Vollenweider* model. That model predicts a low mesotrophic condition for all three lakes, Roberts, Blackburn, and Cusheon. That shows approximate agreement with the current average phosphorus concentrations of 16.3 to 16.6 in the three lakes.

(16) If the total loading of phosphorus to Cusheon L. were reduced by 18 kg per year (15%), the lake would probably attain an acceptable status in the lower mesotrophic zone. The prediction of 13.5 ppb of phosphorus as springtime average would be similar to the historic situation before settlement by Europeans. There would probably be fairly satisfactory conditions of minor algal blooms, and few problems with toxic cyanobacteria. This reduction is recommended. A level of 13.5 ppb would meet B.C.'s upper criterion for protecting fish (15 ppb of phosphorus). For such reduced loading, the Vollenweider model predicts a status just at the level of "permissible loading", which is in general agreement but slightly more optimistic.

(17) Achieving a phosphorus reduction greater than 18 kg seems unlikely since it would mean that the status of the lake would be better than the pristine pre-settlement condition. Reducing phosphorus concentration to 10 ppb, which would achieve oligotrophic status and meet the provincial goal for a "drinking-water lake", would require 38 kg less loading to the water, which is considered unrealistic.

(18) The recommended reduction of 18 kg of phosphorus could come from any single source, or a combination of sources. The large input from land drainage could be reduced by strict programs of revegetation along riparian areas of all creeks and lakes. Near-elimination of the direct human input from septic fields (25.5 kg) could be done by complete collection of sewage from all residences (or connecting to a specially-built sewer) with central waste treatment.

Eliminating regeneration from sediments would also be a solution. However, the conventional cure of aerating bottom water is not feasible in this shallow lake, and use of a chemical precipitant might not be favoured.

A good overall management program which achieved moderate improvements in each of the inputs appears to be the most efficient way of attaining the recommended reduction.

1 INTRODUCTION

This report provides background information and analysis for the *Cusheon Watershed Management Plan* (CWMPSC 2007), produced by the Cusheon Watershed Management Plan Steering Committee (hereafter called the *management plan* and *steering committee*). The present report attempts to describe the enrichment situation in Cusheon Lake, based on the existing data.

The overall objective of this report is to identify the major sources of phosphorus loading to Cusheon Lake. Phosphorus is the key nutrient. The idea is to help focus management efforts on the most important problems, or those most amenable to remedy.
The report has five steps.

(1) Estimating background physical characteristics of the watershed (size of the sub-basins and water balance for the whole basin).

(2) Estimating how much phosphorus runs off the land in the Cusheon watershed.

(3) Estimating how much phosphorus is regenerated into the water each year from the sediments of Cusheon Lake.

(4) Estimating how much phosphorus reaches Cusheon Lake from local septic systems. This final piece of information allows the construction of a phosphorus budget for Cusheon Lake, showing the input amounts from the various sources.

(5) Estimating the reduction in phosphorus input required to reach a satisfactory status for the lake, and some possible methods for reduction.

Cusheon Lake has the largest yearly water inflow of any lake on Salt Spring Island (Sprague 2007c). The lake supplies drinking water for the Beddis Water District, and is used for swimming, fishing, and other recreation. Recently, there has been concern about algal blooms in the lake, and in particular, there have been blooms of cyanobacteria (“blue-green algae”) which can produce toxin.

Starting in 1974, considerable effort has been expended by the Ministry of the Environment and others, collecting physico-chemical data on Cusheon Lake, including the nutrients that govern algal blooms. The results have been summarized and analyzed (Holms 1999, McPherson 2004). However, neither government nor university scientists have described where the nutrients are (probably) coming from. The present report attempts to identify the sources, and is focused on total phosphorus, the key nutrient. In an attempt to guide future clean-up efforts, this report sometimes pushes information to its useful limit and uses judgemental interpretation.

The modelling approach used in this report is based on year-long average conditions for such things as rainfall, and furthermore it uses "average" years. This is useful for overall predictions, but of course, conditions in any given year or any given season are likely to differ considerably from the average or “typical” year.

The management plan gives basic information on the Cusheon watershed and its relation to Salt Spring Island. Some such information is provided in section 4 of this report. Despite enrichment, Cusheon Lake has reasonable fish populations, and is valued for recreation and potable water.

2.0 WATER QUALITY STATUS

Summary

- *Phosphorus concentrations in Cusheon Lake indicate that it has been moderately mesotrophic (somewhat enriched) from the 1970s to date. The average springtime concentration in the most recent decade is 16.6 ppb, below the level of 20 which is generally taken as the start of eutrophy (enriched), but well above 10 ppb which would identify an oligotrophic lake (low-nutrient).*

- *Measurements of chlorophyll and clarity of the water also indicate mesotrophic to eutrophic conditions in the lake.*

The quality of lake water affects its use for drinking and also its suitability for fish and other aquatic organisms. The quality also reflects overall ecological conditions in the watershed. Cusheon Lake has had much chemical monitoring over the years, largely by the environmental ministry of the province (Goddard 1976, Holms 1999, MWLAP 2003, McPherson 2004). Other work has been done by the Cusheon Stewardship Committee, the University of Victoria, and Reimer (2003). Further details of this work are given in Appendix A.

The basic characteristics of Cusheon Lake water are typical of the region and satisfactory. Over the years, hardness of the water has averaged 30 to 45 ppm, depending on season, with an overall average of about 34 ppm, which classifies it as *soft* (less than 60 ppm). The acid/base reaction has been normal, i.e. slightly alkaline, typically ranging from 7 to 8.4 and averaging about 7.2 (MWLAP 2003, McPherson 2004).

2.1 Degree of enrichment

Nutrient enrichment of the lake is the main concern, because of undesirable algal blooms including cyanobacteria (see management plan, CWMPSC 2007). The trophic status of lakes can be judged by some useful rules of thumb, shown in Table 1. The criteria in the table may be compared with available data for Cusheon Lake. (For ease of comprehension, concentrations in Table 1 and elsewhere in this report are stated as parts per million (ppm) or parts per billion (ppb), although the technically correct units would be milligrams per litre (mg/L) and micrograms per litre (μg/L)). P is sometimes used as an abbreviation for phosphorus.

The criteria in Table 1 should not be regarded as sharp dividing-lines, but as guideposts on a gradient of conditions. For example the second one, for total phosphorus, classifies lakes according to traditional limits of 10 and 20 ppb. But lakes can vary in characteristics which affect such criteria, and some can exceed 20 ppb without showing heavy algal blooms or other features of eutrophy. Some experts such as Dr. R.N. Nordin of the University of Victoria (personal communication) regard 30 ppb of phosphorus as a more suitable limit marking the start of eutrophy in some lakes.

Table 1. Commonly-used criteria for judging enrichment of lakes.

Variable	Oligotrophic (low-productivity lake)	Mesotrophic	Eutrophic (enriched)
Secchi disc reading, depth in m. (Dobson et al. 1974)	6 or more	Between 3 and 6	Less than 3
Total phosphorus in ice-free period, ppb. (OMOE 1984)	10 or less	Between 10 and 20	20 or more
Total P in lakes, ppb, for drinking water, recreation (spring overturn or growing season average) (B.C. MELP 2000, Nordin 2001)	Maximum 10		
Total phosphorus for aquatic life in lakes, ppb. (B.C. MELP 2000, Nordin 2001)	From 5 to 15		
Algal biomass as chlorophyll a, annual maximum, ppb. (Michalski and Conroy 1972)	5 or less	Between 5 and 10	10 to 15
Chlorophyll a, maxima in streams, ppb. (B.C. MELP 2000)	50 for recreation and 100 for aquatic life. (No criterion proposed for lakes.)		

Phosphorus

Phosphorus is the most important nutrient for algae in practically all lakes in Canada and elsewhere, and Cusheon Lake is no exception. Phosphorus is called the ***limiting nutrient*** because it is in shortest supply. When phosphorus is limiting, it means that there is more than enough of the other nutrients, and so they do not have any role in governing the extent of algal blooms. In Cusheon Lake, nitrogen is occasionally in shorter supply than phosphorus (McPherson 2004). Such a lack of nitrogen can encourage the growth of cyanobacteria, since many of those organisms can fix their own nitrogen from dissolved gaseous nitrogen. However, phosphorus is limiting for almost all of the year, so this report is based on phosphorus.

Total phosphorus is the most useful measurement, rather than any particular sub-category such as phosphate. A variety of combined forms of phosphorus exist, but many of them can change back and forth rapidly to provide nutrient for algae, so the total amount is customarily used for evaluation.

The most useful monitoring of phosphorus in Cusheon Lake is given in the sequence of measurements shown in Figure 1. There are two sets of measurements in the figure. One set is for samples taken at any depth in the springtime when the lake is mixed (February to April), and many experts consider that is the most dependable assessment during the year. The other set is for measurements at the surface (down to a depth of 3.1 m) for any time of year. This is a recommended criterion in British Columbia (see rationale in Appendix A).

The two sets of measurements show similar trends and variation as can be seen in Figure 1. It appears convenient to divide the data into three time-periods, each about a decade, and phosphorus concentrations for the time-periods are averaged in Table 2.

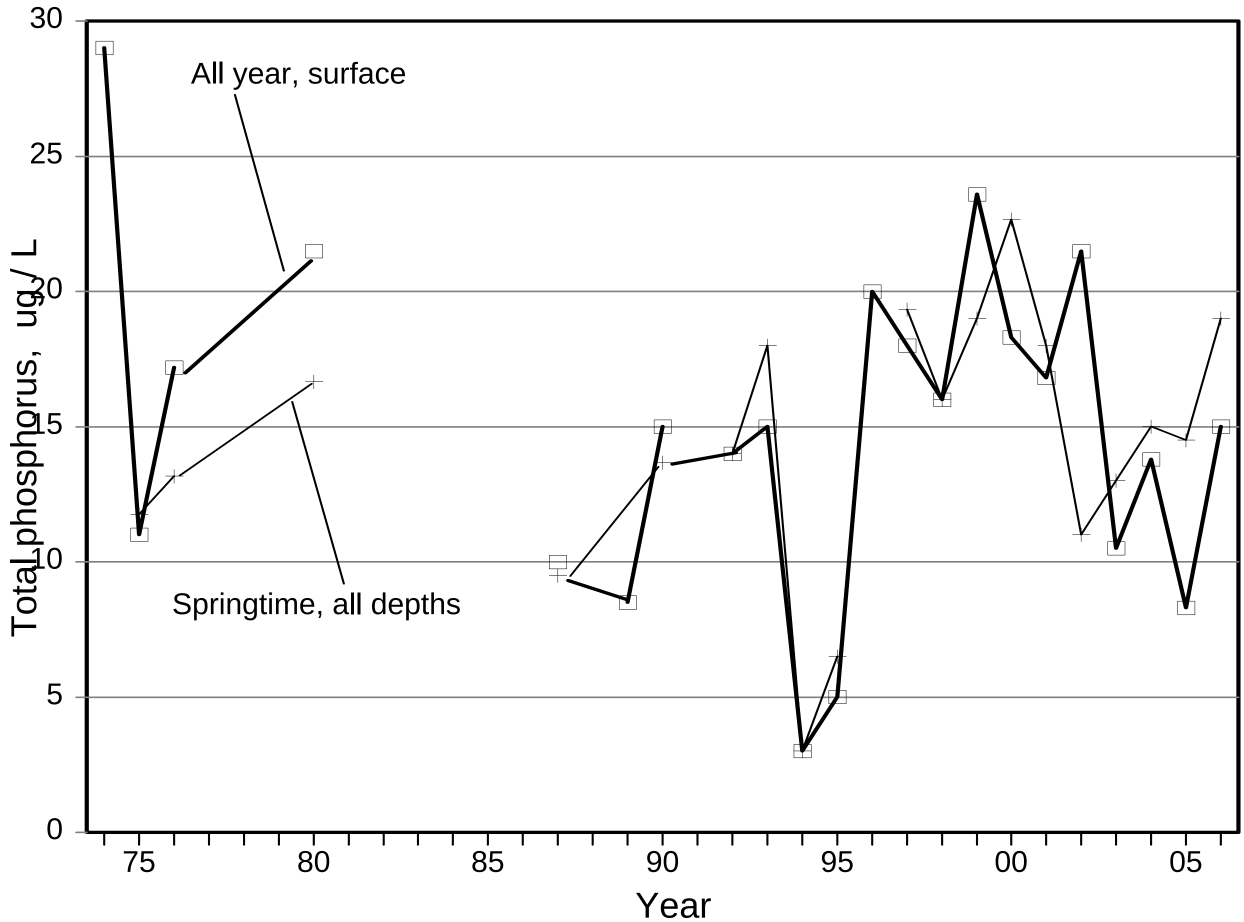


Figure 1. **Total phosphorus in Cusheon Lake.** One set of samples was taken at spring overturn when the lake is mixed top to bottom. The other set was taken from surface waters at any time of year, but mostly in the growing season. Data from MWLAP (2003), Reimer (2003) and Epps (2006).

The two types of data (spring mixing and all-season surface water) produce similar averages in the two later time-periods (Table 2), and that is evident in Figure 1. The springtime values might be somewhat more reliable, judging by the smaller variation (less spread for standard deviations, calculations not shown here).

Table 2. Average concentrations of phosphorus in Cusheon Lake during three periods of time. Calculated from data of MWLAP (2003) Epps (2006) and Reimer (2003). See details in Appendix A.

	MWLAP 1974 - 1980	MWLAP 1987 - 1995	MWLAP, Reimer 1996 – 2006
Spring mixing (February to April), average of the yearly mean values	13.9	10.8	16.8
Number of individual measurements included in the average	19	14	26
Number of days represented by the average	6	6	10
Surface water (zero to 3.1 m) in all seasons, average of the yearly mean values	19.7	10.1	16.5
Number of individual measurements included in the average	45	10	49
Number of days represented by the average	25	7	33

The recent past can be represented by the decade of data for 1996 to 2006, which has more measurements and more days sampled than the previous time-periods. At first, phosphorus was mostly above 15 ppb (Figure 1), a level which the province considers the limit for protecting aquatic life (Table 1). Three measurements from 1999 to 2002 were above 20 ppb, indicating eutrophy. Following that, concentrations were generally lower. Yearly averages for this most recent decade range from 8.3 to 23.6 ppb (Appendix A).

For the most recent decade, the decade-long averages for the two sets of measurements are close. Taking the values to two decimal places, the springtime average is 16.75 and the all-seasons average is 16.53. Both criteria are valid for judging the lake. They are so close that it does not really matter which is selected. Therefore an average of the two is used here to characterize the lake in the recent decade. That average is 16.6 ppb. This confirms an overall mesotrophic status.

In earlier history from 1974 to 1980, the lake showed extreme variation from very low mesotrophy up to the 1974 value which is well up into eutrophy, according to the phosphorus levels (Figure 1). The extreme variation is probably related to the type of flow through the lake during the wet season. Cusheon Lake has a relatively small volume, but a large annual inflow, resulting in a 95% replacement time for the lake water in less than a year. The nutrient status of the lake in a given year will be partly shaped by the characteristics of the winter flow that flushed out the lake.

The years 1987 to 1995 represent an intermediate period with very low average concentrations just above 10 ppb, the borderline for oligotrophy. There are two excursions to very low oligotrophic status (Figure 1) in 1994 and 1995. These are thought to have resulted from major "flush-outs" of the lake. A verbal report from that time indicates that the outlet creek ran green from algae (K. Reimer, personal communication). The flushed-out algal cells probably removed a lot of phosphorus, temporarily lowering phosphorus concentration in the lake. It is less likely that those low values resulted from other anomalies or sampling errors.

Algal blooms

Algal blooms would be expected as the result of those recent phosphorus averages which were in the 15 - 20 ppb range with excursions above 20 ppb (Figure 1). A major bloom of cyanobacteria in 1999 corresponded to the highest all-season peak of phosphorus concentration during the decade, a value in the mid-twenties of ppb. No measurements of chlorophyll levels are available for that year.

Other criteria lead to similar conclusions on the trophic status. McPherson (2004) reports peak measurements of chlorophyll *a*, of about 6, 14 and 34 ppb in the recent years 2000 to 2002. Those values indicate mesotrophic or strongly eutrophic conditions compared to the classical criterion of 5 - 10 ppb for mesotrophy (Table 1). (The B.C. criteria for chlorophyll *a* in drinking-water lakes are based on seasonal averages which are less meaningful when considering algal blooms.)

Visibility through the water, as measured by depth of a Secchi disk, averaged 3.5 m over the years, (McPherson 2004). In recent years 2000 to 2003, the warm-season Secchi depths appear to have averaged about 3 m with most values from 2.5 to 5 m. Those measurements are indicative of mesotrophy or mild eutrophy according to criteria in Table 1. (The only Secchi-disk criterion adopted by British Columbia is 1.2 m or greater for purposes of recreation (B.C. MELP 2000) and Cusheon Lake meets that limit.

3 PURPOSE AND GENERAL STRATEGY

The purpose of this report is to identify the main sources of phosphorus reaching Cusheon Lake, so that the information can be used for a basin management plan. The management plan can then focus on means of controlling the most serious sources, or the ones that are easiest to deal with.

We can divide most of the phosphorus sources into **"land runoff"** and **"direct human inputs"**. The amount of phosphorus in land runoff has not been described definitively for this part of British Columbia, but it is influenced by soil type, vegetation and erosion. Direct human inputs can include septic field seepage. One goal of this report is to estimate the amounts coming from the two sources.

Luckily, there is a workable approach as indicated by the following three steps.

- The two upper lakes in the basin have little direct human input, i.e. there are no houses directly on the lakes or very near the lakes. Therefore, if, by trial and error, we can find factors for land runoff of phosphorus that predict the observed concentrations of phosphorus in the two upper lakes, then those factors are estimates of the hitherto uncertain value for land runoff.

- The newly-determined runoff factor can be applied to the third lake of the chain (Cusheon).

- That leaves human input as the only other unknown external input to Cusheon Lake, and its magnitude can then be estimated by relatively simple modelling. The technique would be to enter standard values for septic input into the model. If this did not predict the P concentration actually observed in the lake, then other input values could be tried until the model predicted the observed concentration.

The mathematical modelling attempts to simulate the movements of nutrient through the watershed. The models are based on pre-existing knowledge gained from other lakes. Modelling is always somewhat speculative, and must be checked against any available hard observations.

The models used here are derived from the work of world-renowned Canadian freshwater scientists. A general model developed by Vollenweider (1975) can predict the enrichment status of a lake (its *trophic status*) on the basis of only the dimensions of the lake, the amount of water flowing through, and the yearly loading of phosphorus (see section 5). Scientists used the concepts to develop a more specific *"cottage-country model"* (Dillon and Rigler 1975; Dillon et al. 1986; Hutchinson et al. 1991; Hutchinson 2002). This model estimated how many cottages could be added to the shore of any given lake in Ontario, without causing the lake to ”turn green”.

The predictions make use of mathematical formulae based on known relationships for soil types, geology, rainfall, lake dimensions, water flow-through, and human developments on shore. The Dillon-Rigler-Hutchinson "cottage-country" model is used as the primary tool in this report, recognizing that the numerical factors from Ontario might not exactly fit the Pacific coastal situation. The beauty of the cottage-country model is that various scenarios can be created for nutrient loading, to see which of them predict the conditions actually observed in the Cusheon basin. The Vollenweider model is used here for confirmation; it has been successfully applied to lakes anywhere in the world.

The first things needed in the modelling process are rather basic pieces of information: (1) the size of the drainage basin that feeds each lake, and (2) the amounts of water flowing down the system each year. Those items are estimated immediately below in section 4.

4 DRAINAGE BASINS AND RUNOFF

Summary.

• Expert estimates were obtained for the sizes of the sub-basins draining to the three lakes. The estimated sizes including the lakes are: Roberts L. 119.9 hectares (ha), Blackburn L. 510.8 ha, Cusheon L. 220.0 ha, and downstream Cusheon Creek 214.5 ha, for a total watershed area of 1065.2 ha.

• Average yearly rain and snowfall on the Cusheon basin is documented as 0.98 metres. An average of eleven sets of data indicate that 48% of this will run off into creeks and lakes. Evaporation from lake surfaces is taken as 0.713 metres per year from recent calculations for Salt Spring.

• The flows out of the lakes, in thousands of cubic metres, were estimated as 520 for Roberts, 2,918 for Blackburn, and 3,827 for Cusheon. The Cusheon outflow converts to a yearly average of 121 litres/second, agreeing closely with the measured average of 116 L/sec, and agreeing almost exactly when adjustment is made for relative rainfall.

• The estimates of flow (given immediately above) take into account the presumed amounts of water removed for human use. Withdrawal was estimated as 722 litres per day for an average household of 2.2 people, and amounts for irrigation were taken as exactly the amounts licensed.

4.1 Size of drainage basins

The boundaries and areas of the Cusheon watershed and its sub-basins, were determined by a computerized interpretation on a contour map by Brett Korteling, the GIS Coordinator for Islands Trust in Victoria. Those boundaries and areas are used in this report (Figure 2).

The areas of the lake surfaces are those published by the B.C. government, from surveys done over the years by various provincial ministries, as listed in detail by Sprague (2007c).

There is one minor anomalous drainage. A small area directly south (i.e. "downstream") of Cusheon Lake, is normally drained into Cusheon Creek by a ditch ("Ortlepp culvert"). However in the early autumn runoff when the lake is not full, this drainage flows into the lake near its outflow. The proportions of flow that go to each place cannot be estimated easily. The anomaly is trivial, so it has been neglected, and the small amount of runoff and the area drained, are credited to Cusheon Creek.

Table 3. **Sizes of the Cusheon watershed basin and its sub-basins.** [1]
Determined by Brett Korteling of Islands Trust, using computerized interpretation of a contour map.

	Area in hectares		
	Land without lake	Lake	Total with lake(s)
Roberts Lake	116.5	3.44	119.9
Blackburn Lake	507.7	3.08	510.8
subtotal, 2 sub-basins	624.2	6.52	630.7
Cusheon Lake	193.1	26.9	220.0
subtotal, 3 sub-basins	817.3	33.4	850.7
Cusheon Creek	214.5	0	214.5
Basin total	1031.9	33.4	1065.2

[1] The land areas are those that would be measured on a flat map. Brett Korteling, of Islands Trust, also used a computer program to estimate the land areas with allowance for the extra amounts resulting from slopes of the land. Those land areas (without lakes) were, in hectares: Roberts sub-basin 121.0, Blackburn sub-basin 521.4, Cusheon Lake sub-basin 196.8 and Cusheon Creek 222.5, for a total land area of 1061.6 hectares. These larger areas were not used because the amount of water reaching the land and running off was a major use of the information, and the interception of rain and snowfall is proportional to the flat or “map” areas.

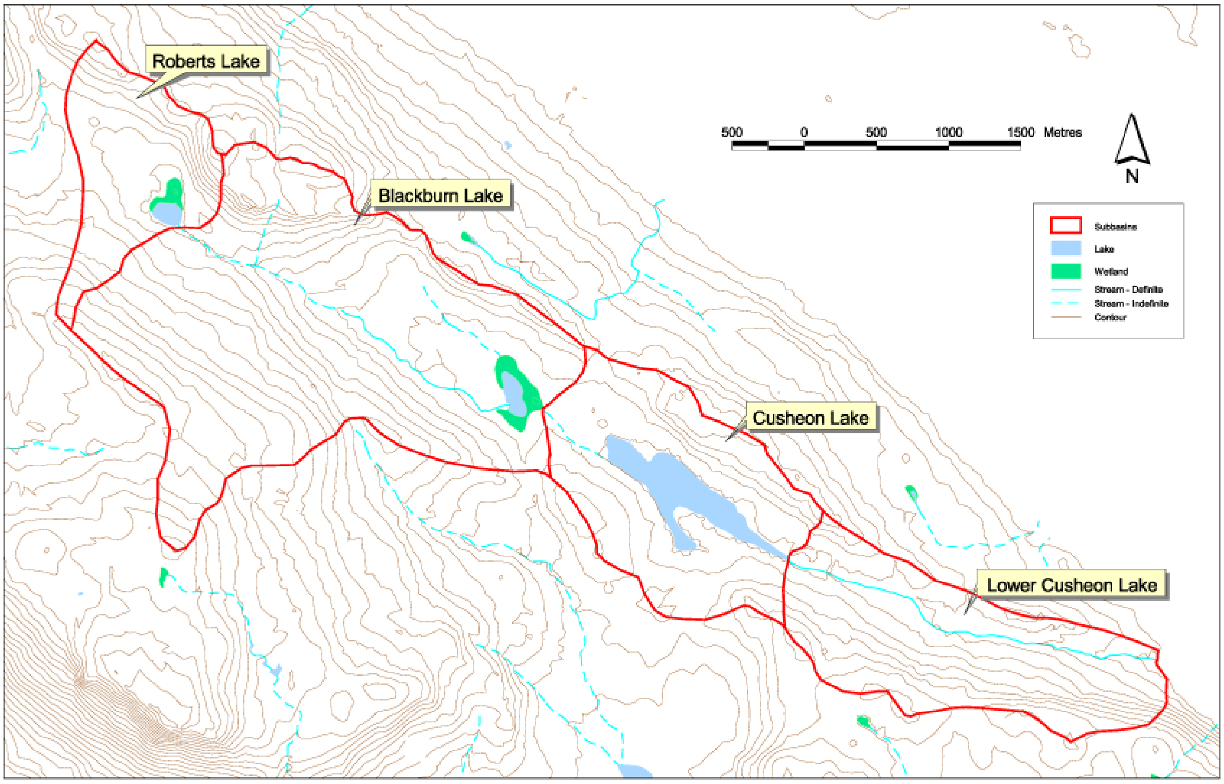


Figure 2. Boundaries established for the Cusheon drainage basin and its sub-basins. Roberts Lake is the upstream part of the watershed. The label "Lower Cusheon Lake" indicates Cusheon Creek which drains Cusheon Lake. Boundaries determined by Brett Korteling of Islands Trust.

4.2 Precipitation and runoff

The second step in modelling the Cusheon watershed is to estimate the amounts of water which pass through. Previously, this has not been well documented. There were good records for rainfall (including snow), there was one good estimate of average annual streamflow at the outlet of Cusheon Lake, and there was a recent calculation of the rate of evaporation of water from lakes.

Things that were not known or not well-known, were the proportion of rainfall that runs off the land, and the amounts of water withdrawn for use by humans. (There are precise amounts specified in licences for withdrawal, but the actual amounts withdrawn are not recorded except for the Beddis water system.)

The procedures used for estimating runoff and water flows through the Cusheon basin are outlined immediately below. The details of all these measurements and how the estimates were calculated, are provided in Sprague (2007c).

Rain and snowfall

This is well documented. The average obtained by Aston (2006) was used -- 0.98 metres per year. The average is based on meticulous daily observations over three decades. The measurements are from Douglas Road, on the south-easterly side of Ganges village, 2.5 km northerly from Blackburn Lake which is nearly central in the Cusheon watershed. Precipitation in the Cusheon watershed is discussed in Sprague (2007b) and for other parts of Salt Spring Island, in Sprague (2007c). This does not take into account any possible future changes resulting from global warming.

Runoff proportion

A standard value of 0.484 was estimated for the proportion of rain and snowfall that runs off the land into creeks and lakes, in other words about 48%. This was based on eleven sets of data from various parts of Salt Spring Island, described in detail in Sprague (2007c). The quality of the background data varied, but the average appeared to be quite dependable. (The average remained 0.48 when the highest and lowest of the eleven estimates were left out of the calculation, and also when the two highest and two lowest were left out.) Applying this runoff proportion to the Cusheon situation, if it was an average year and 0.98 metres of rain and snow fell, then $0.98 \times 0.484 = 0.474$ metres of water would be expected to run off the land into the creeks. The rest of it would sink into the soil, evaporate directly, or transpire via trees and other vegetation.

Evaporation from lakes

There have been relevant measurements made in nearby Saanich, of evaporation from a water surface in relation to season and temperature. Those measurements have recently been used by Watson (2006) to estimate the average evaporation from St. Mary Lake. His average is 0.713 metres per year. This estimate for conditions on Salt Spring is accepted, and is applied to the three lakes in the Cusheon system. Watson's estimate is slightly higher than earlier estimates of 0.673 and 0.658 by Hamilton (1995, 1998), based on earlier and shorter periods of records. Hamilton explains the theoretical basis of the calculations.

Licensed and unlicensed withdrawals of water

The actual amount withdrawn for human use by the Beddis Water District was used, and is based on dependable records of the actual amounts. The other "water licences" in the Cusheon basin are published (Barnett et al. 1993). An updated listing was obtained from the British Columbia government web-site and may be seen in the management plan (CWMPSC 2007). These uses are for household consumption and agricultural irrigation. For these other licences, however, there is no real knowledge whether the actual amounts withdrawn are more than or less than the licensed amounts.

Accordingly, some assumptions and estimates were made.

(1) The amounts licensed for irrigation were assumed to be used.

(2) The amounts licensed for households appeared to be larger than would actually be used. Therefore, estimates of withdrawal were based on actual use per household, as documented recently by the North Salt Spring Water District, which provides the largest body of data. That usage is 722 litres per day for an average household. A household was defined as 2.2 people, from data of the Canadian census of Salt Spring Island. The North Salt Spring value agrees reasonably with overall Canadian usage for household purposes (343 L per person x 2.2 = 755 L/day) and with the Beddis consumption of 753 L/day per household served.

(3) Some larger household licences were issued in multiples of the standard amount. In these cases, the estimated use was assigned using the same multiple, applied to 722 litres/day.

(4) Certain licences were for withdrawals from springs. They were also issued in multiples of household units, so that multiple was again applied to the base of 722 litres/year, to obtain the estimates used here.

Calculations

Knowing the sizes of the sub-basins (section 4.1), the runoff into each lake was calculated as the proportion of rainfall on that sub-basin. For the lower two lakes, the flow from upstream in the chain was added in. The withdrawals and evaporation were subtracted at the appropriate stages. The calculations are shown in Table 4 and explained in the text that follows the table.

Table 4. **Estimated flows of surface water in the Cusheon watershed.** This is based on 29-yr average rain and snowfall of 0.980 m (Aston 2006), a rainfall runoff factor of 0.484, evaporation of 0.713 m from the lakes during each year(Watson 2006). and includes withdrawals of water by humans.

	cubic metres per year
<u>Roberts sub-basin</u>	
Land runoff: (1165 ha x 10,000) x (0.980 m of rain x 0.48385) =	552,412
Directly onto lake = (3.44 x 10,000 x 0.980) =	33,712
Minus evaporation: lake area 34,400 x 0.713 m =	24,527
Minus irrigation licence: 37,005 =	37,005
Minus 6 licences for springs, equiv. to 16 households: 16 x 0.722 x 365.25 =	4,219
Estimated outflow:	520,372
<u>Blackburn sub-basin</u>	
Upstream, from Roberts Lake:	520,372
Sub-basin land runoff: (507.7 ha x 10,000) x (0.980 m of rain x 0.48385) =	2,407,376
Directly onto lake = (3.08 x 10,000 x 0.980) =	30,184
Minus evaporation: lake area 30,800 x 0.713 m =	21,960
Minus 2 irrigation licences: 7120.2 + 3700.5 =	10,821
Minus 2 licences for households: 2 x 0.722 x 365.25 =	527
Minus licence for trailer court, equiv. to 27 households: 27 x 0.722 x 365.25 =	7,120
Estimated outflow:	2,917,504
<u>Cusheon sub-basin</u>	
Upstream, from Blackburn Lake:	2,917,504
Sub-basin land runoff: (193.1 ha x 10,000) x (0.980 m of rain x 0.48385) =	915,628
Directly onto lake = (26.9 x 10,000 x 0.980) =	263,620
Minus evaporation: lake area 269,000 x 0.713 m =	191,797
Minus Beddis waterworks, withdrawal in 2003 =	33,550
Minus irrigation licence: 26,323 =	26,323
Minus individual licences equiv. to 41 households: 41 x 0.722 x 365.25 =	10,812
Minus unlicensed, estimated equiv. to 20 households: 20 x 0.722 x 365.25 =	5,274
Minus licence for resort, equiv. to 9 households: 9 x 0.722 x 365.25 =	2,373
Estimated annual Cusheon outflow:	3,826,622
Estimated annual Cusheon outflow converted to litres/second =	121.3 L/sec.

This value is only 1.5% higher than the measured mean annual outflow, after adjustment for rain and snowfall in differing time-periods (see following text).

After all the calculations were made, the predicted outflow from Cusheon Lake was equivalent to a yearly average of 121 litres per second (Table 4). That corresponded almost exactly (less than 2% difference) with the actual yearly average published by Barnett et al. (1993) based on the measurements of Water Survey Canada (2006), after adjusting for slightly different rainfall in the two time-periods represented (see explanation in next paragraph). It is not known whether this agreement indicates remarkable accuracy of the predictions or lucky accident, but the water balance of Table 4 was accepted for use in subsequent modelling.

The adjustment for differing rainfall was made in the following manner. The observed mean annual outflow reported by Barnett et al. (1993 was 116.0 litres per second (L/sec), That had been measured for 1970-1992 by Water Survey Canada. However, that 23-year period had average rain and snowfall that was 2.6% lower than the rainfall data for 1977-2005, which was used for the prediction in Table 4. The difference in rainfall is shown by available data for Victoria. If the value for precipitation in Table 4 is adjusted downwards by 2.6% (from 0.980 to 0.955 metres of precipitation per year), the predicted outflow of Cusheon Lake is 117.8 L/sec. That is 1.5% higher than the average measured value of Water Survey Canada. Such a small discrepancy must be considered excellent agreement.

5 PHOSPHORUS RUNOFF TO THE UPPER LAKES

Summary.

- *Recent measurements estimate a total phosphorus content (P) of 16.5 parts per billion in Roberts Lake, and this was adopted for further calculations and modelling.*

- *An initial trial of modelling for Roberts Lake used a runoff value of 0.2 kg of P from each hectare of land per year, which is the value for "forest and pasture" in the Ontario cottage-country model. This predicted more than 32 ppb in Roberts Lake, far too high, so the runoff value was rejected.*

- *When the Ontario "forest" runoff value of 0.1 kg was used in the model, it predicted a concentration in the lake of 16.6 ppb, only slightly higher than the observed concentration. A runoff value of 0.09909 kg per hectare exactly predicted the observed concentration in Roberts Lake, and this runoff value was accepted.*

- *For Blackburn Lake, a runoff value of 0.07876 kg of P per hectare predicted the average concentration that was observed in the lake, 16.3 ppb. The runoff value was accepted for the Blackburn sub-basin.*

- *The runoff values of 0.99 and 0.79 kg/hectare are not identical, but similar. Their average, 0.089 kg/hectare, was adopted for modelling the downstream sub-basin of Cusheon Lake.*

The objective is to use each of the upper two lakes to estimate phosphorus runoff from the land. Each lake is modelled, using various values of P runoff by trial and error. The value that predicts the actual concentrations in the lake is adopted. The two estimates of P runoff are averaged to provide a final estimate of P runoff in the upper basin.

Roberts Lake in particular is a relatively simple picture for study, since it has no houses directly on its shores, and is not complicated by an upstream lake. Land runoff is its main source of phosphorus, and the same is true for Blackburn Lake which has the largest sub-basin in the Cusheon system. Fallout of phosphorus in rain, snow and dust is the only other apparent source and this contribution is estimated immediately below.

5.1 Phosphorus fallout

The phosphorus contained in rain, snowfall and dust, which is deposited on land and water surfaces, is estimated as 0.11 kg/ha • yr. Four estimates from the region have been averaged to provide this value which is adopted for use on Salt Spring Island (see Appendix E).

5.2 Modelling Roberts Lake

The Dillon-Rigler-Hutchinson model (or “cottage country model”) was used to predict lake concentration of phosphorus, starting with trial-and-error values for runoff of phosphorus from the land. Most of the variables that enter into the calculations of this model are measurements or factors that are fixed or quite well-defined (Table 5 and Appendix C). Sizes of the lakes, areas of the sub-basins, phosphorus in precipitation and flows of water can be treated as known quantities and are described above in section 4 or in Sprague (2007c). The main thing that must be selected (“guessed”) and entered on a trial basis, is an initial value for phosphorus runoff from the land.

Also required is an observed average value of phosphorus concentration in Roberts Lake, in order to decide if the prediction of the model is valid. Unfortunately, there were only two historic measurements in the provincial data-base (MWLAP 2003), and they do not appear to be realistic. Values of 3 ppb P were reported in June 1987 and August 1996, presumably in surface waters. These values are too low to be credible as an assessment of mixed-lake values, and they were not accepted. For example, Maxwell Lake, the most protected and pristine lake on Salt Spring, had historic values of about 9 ppb of phosphorus. Nordin et al. (1982) reported surface values from 7 to 16 ppb in Maxwell Lake, with 9 ppb as a "probable underestimate" of the concentration at spring overturn.

Recently, six measurements were made in Roberts Lake as part of a survey of phosphorus runoff in the upper Cusheon watershed. The measurements varied from 15.0 to 20.5 ppb and averaged 16.5 ppb (rounded from 16.54 ppb). All the samples were taken in 2004-2006 after autumn overturn in October, and during the winter until late March, while the lake would be mixed. The individual values are given in Sprague (2007e).

Accordingly, 16.5 ppb of total phosphorus was adopted as the best current estimate of phosphorus content of Roberts Lake.

5.2.1 Trial scenarios

Forest and pasture. The Roberts sub-basin is a mixture of "young forest", some "mature forest", and some agricultural use (Appendix C and *Land Classification* map of the management plan (CWMPSC 2007)). There has been selective logging in the past few years, of the immediate area just “upstream” from the lake (northerly and north-westerly). These uses guided the initial choice of a "forest and pasture" scenario with its phosphorus runoff of 0.20 kilograms of phosphorus per hectare each year (kg P/ha • yr) in the Ontario model (Dillon et al. 1986).

The initial run of the model used this factor of 0.20 kg P/ha • yr, and ran through calculations explained in Appendix C and shown in Table C1 of that appendix. The calculations are the same as those in Table 5, except for the land runoff factor. A prediction of 32.5 ppb of phosphorus in the lake was far too high, being double the observed concentration. Accordingly, the "forest and pasture" runoff of 0.20 kg P/ha • yr was rejected as being too high.

Forest. A second run used the Ontario factor of 0.10 kg P/ha • yr, for forested land (Appendix C). The predicted concentration in Roberts Lake was 16.6 ppb, only slightly higher than the observed concentration of 16.5 ppb. A slightly lower value for runoff seemed warranted.

Final scenario. As mentioned, much of the information that goes into the model is fixed, as shown by the final scenario in Table 5. The top 8 lines in the table are for measurable items of size of the lake and basin and amount of water flow (further comments in Appendix C). The formula for retention *(Rp)* of phosphorus (P) in the lake is based on research in Ontario lakes and might or might not be a good fit for Pacific coast lakes. The value used here for Rp is for lakes that have deoxygenated bottom waters in the summer. There are no direct measurements to show that deoxygenation occurs in Roberts Lake, but it is presumed to be the situation since Roberts is roughly similar in depth and phosphorus concentration, to Blackburn and Cusheon Lakes which have deoxygenation of bottom waters.

Table 5. Enrichment calculations for Roberts Lake with 0.09909 kg / hectare runoff of phosphorus from the land. This represents a scenario with a lake concentration of 16.5 ppb of phosphorus. The calculations use the Dillon-Rigler-Hutchinson "cottage-country" model for Ontario lakes.

V = Volume of lake =	140,000	cubic metres
Q = outlet discharge per year =	520,372	cubic metres
Ao = area of lake = 3.4 hectares =	34,400	square metres
Ad = area of watershed including lake = 119.9 hectares =	1,199,000	square metres
Ad2 = area of watershed without lake = 116.5 hectares =	1,164,600	square metres
r = runoff = Q/Ad = 520,372 / 1,199,000 =	0.43401	metres / year
qs = areal water load on lake = Q/Ao = 520,372 / 34,400=	15.127	metres / year
Tw = turnover time = V / Q = 140,000 / 520,372 =	0.2690	years
Rp = retention coefficient of P in lake = 7.2 / (7.2 + qs) =	0.32248	
JA = input of P by direct human activity = 2 x 2.2 x 0.6 x 0.26 x 0.33 kg =	0.227	kg / year
JN = input of P from sub-basin land = 116.5 x 0.09909 kg =	11.540	kg / year
JPr = input of P from precipitation to lake surface = 3.34 x 0.11 kg =	0.378	kg / year
Total input	**12.14**	**kg / year**
Loading = (JA + JN + JPr) / Ao = (Total input) / 34,400 =	0.3531	gm / m2 • yr

Predicted P concentration in ice-free season = [Loading (1 – Rp)] / [0.956 x qs]
= [(0.3531) x (1 – 0.32274)] / [0.956 x 15.127] = 16.540 ug/L
= 16.5 ppb, rounded off.

Three lines near the bottom of Table 5 estimate P inputs from (a) land runoff, (b) rainfall/fallout and from (c.) the very tiny input from distant septic fields (labelled as “input ... by direct human activity”). Total input is the sum of those three items.

That total input, in turn, is expressed as loading per unit area of the lake. The loading is used to predict P concentration in the lake by a final formula based on the Ontario research. Various trial values for P runoff from the land, slightly lower than the “forest” value of 0.1 kg/ha, were entered into the model, and 0.09909 kg P/ha • yr was adopted because It exactly predicted the observed 16.5 ppb in the lake.

5.3 Modelling Blackburn Lake

Blackburn Lake drains the largest part of the Cusheon watershed (Table 3). Blackburn does not have reports of major algal blooms, even at the times when there have been problem blooms in Cusheon Lake. This is probably because of the very fast turnover time of Blackburn Lake (Sprague 2007c).

The model for phosphorus flow uses the same basic technique as for Roberts Lake. Phosphorus was measured on four occasions in 1981 when the lake would have been mixed (MWLAP 2003). Combined with a sample in the spring of 2005, the average phosphorus concentration was 16.3 ppb, considered a best estimate and adopted for modelling of Blackburn Lake. Some historical measurements were not accepted, and the details of selection are given in Sprague (2007e).

Nutrient runoff from sub-basin. According to the Islands Trust map of *Landscape Classifications* (see management plan, CWMPSC 2007), the sub-basin is largely young forest, with a small amount of mature forest, and areas near the lake that are "rural", "agricultural" (pasture) and "developed" (a golf course and Salt Spring Centre which is a school and conference centre). The golf course has minimized its impact by using only organic fertilizer (recycled from rendered animal meal) and using it in a cautious manner. In case of a rainfall, that fertilizer would not rinse off into creeks as readily as fertilizer manufactured from chemicals. In addition, small waterways on the golf course have been allowed to retain varying degrees of natural vegetation to stabilize the banks.

A great deal of the young forest on the hillside to the southwest of Blackburn Lake, towards Mt. Maxwell, was clear-cut in 2001. However, problems of runoff and erosion have apparently been remedied because the area is well grown up with shrubs and other ground cover. The erosion would be more similar to a forested area. An intermittent creek draining the area has low concentrations of phosphorus (Sprague 2007e). Nordin et al. (1983), in their study of St. Mary Lake, comment that the effects of logging on phosphorus runoff might not be as large as indicated in the Ontario cottage country model. They state, concerning the aftermath of cutting: "If revegetation is prevented, the P export is substantially increased. Otherwise there is not a big increase with logging."

Accordingly, the land use in the Blackburn sub-basin seems reasonably comparable to that for Roberts Lake, as far as phosphorus runoff is concerned.

Other inputs. Direct human input appears to be limited to two households, both further than 100 m from the lake. The phosphorus outflow from Roberts Lake must be included as an input to Blackburn. Regeneration of phosphorus from the bottom sediments is a factor in Blackburn Lake because the bottom water goes anaerobic in May (MWLAP 2003). The volume of the hypolimnion is relatively small, but it experiences an increase of 80 ppb from the sediments. That results in an estimated loading of 1.44 kg of phosphorus being recycled into the lake (McKean 1981, details in Appendix C). This contribution of phosphorus from the bottom sediments is handled in the model by using the appropriate factor for calculating the retention coefficient for phosphorus in the lake *(Rp)*.

Conclusions from the model. The inputs to the model (Table 6) parallel those for Roberts Lake, but with the additional item of phosphorus carried down from Roberts Lake. It was expected that the best estimate of unit runoff from the land around Blackburn Lake would be in the vicinity of 0.099 kg/hectare which was obtained for Roberts Lake. However, that value predicted too high a concentration of phosphorus in the lake. By trial and error, a runoff value of 0.07876 kg/ha • yr predicted the observed concentration of 16.3 ppb of phosphorus in the lake. The total input to the lake was estimated as 49 kg, for a loading of 15.9 kg/ha of lake surface. That is a very high loading but the lake deals with it because of the large inflow to a relatively small lake (95% replacement of water in about one month (Sprague 2007c)).

Table 6. Enrichment calculations for Blackburn Lake with 0.07876 kg/hectare runoff of phosphorus from the land. The observed concentration of phosphorus in the mixed lake was 16.3 ppb. The calculations use the Dillon-Rigler-Hutchinson "cottage-country" model for Ontario.

V = Volume of lake =	92,400	cubic metres
Q = outlet discharge per year =	2,917,504	cubic metres
Ao = area of lake = 3.08 ha =	30,800	square metres
Ad = area of total upstream watershed including lakes = 630.7 ha =	6,307,000	square metres
Ad2 = area of watershed without lake = 507.7 ha =	5,077,000	square metres
r = runoff = Q/Ad = 2,917,504 / 6,307,200 =	0.46258	metres / year
qs = areal water load on lake = Q/Ao = 2,917,504 / 30,800 =	94.724	metres / year
Tw = turnover time = V / Q = 92,400 / 2,917,504 =	0.0317	years
Rp = retention coefft of P in lake = 7.2 / (7.2 + qs) = 7.2 / (7.2 + 94.724) =	0.07064	
JA = input of P by direct human activity = 2 x 2.2 x 0.6 x 0.26 x 0.67 kg =	0.460	kg / year
JN = input of P from watershed = 507.7 ha x 0.07876 kg =	39.985	kg / year
+ upstream = Roberts [input x (1 - Rp)] = 12.14 x (1 - 0.32248) =	8.225	kg / year
JPr = input of P from precipitation = 3.08 x 0.11 kg =	0.339	kg / year
Total input =	**49.009**	**kg / year**
Loading = (JA + JN + JPr) / Ao = (Total input) / 30,800 =	1.591	gm / m^2 • yr

Predicted P concentration, in ice-free season

= [Loading (1 - Rp)] / [0.956 $\times$ qs] = [(1.591) (1 - 0.07064)] / [0.956 x 94.724]

= 0.016330 gm / m^3 = **16.3 ppb, rounded off.**

5.4 Conclusions from modelling phosphorus runoff

The Dillon-Rigler-Hutchinson model seems to be suitable for the upper two lakes, and the models for Roberts and Blackburn Lakes are accepted here.[2]

Modelling the Roberts and Blackburn sub-basins produced factors for land runoff of 0.09909 and 0.07876 kg P / ha • yr. An intermediate (average) value of 0.089 kg P / ha • yr was adopted for runoff in the Cusheon Lake sub-basin.

The estimate of 0.089 is close to the empirical estimate for a typical year, of 0.106 kg P / ha • yr obtained by year-long monitoring of Blackburn Creek (Sprague 2007b). It is also close to the classical value of 0.1 kg P / ha • yr for forested land in Ontario (Dillon et al. 1986). One might have expected the Roberts/Blackburn estimate to be higher than the Ontario value, since there has been deforestation of some land in the Cusheon watershed. However, the value of 0.089 is retained as the most defensible estimate, from currently available information.

Truscott (1981) cites seven values for phosphorus runoff from forested land. The values range from 0.02 to about 0.6 kg P / ha • yr, but they averaged 0.21 kg P / ha • yr. That average is about twice as high as the value estimated for the Cusheon basin, and about twice as high as the Ontario value for forest. Perhaps that is because most of the values cited by Truscott were for the U.S.A. where richer soils might prevail. More probably, the one high value of 0.6 kg P / ha • yr might have represented an unusual situation; without that value, the average of six measurements reported by Truscott would be 0.14 kg P / ha • yr, closer to the value used here.

---

[2] In their study of St. Mary Lake on Salt Spring Island, Nordin et al. (1983) concluded that the best predictions for that lake were provided by the model of Reckhow and Simpson (1980), which parallels the Dillon-Rigler model. The Reckhow-Simpson model was tried here, for the data on Roberts and Blackburn Lakes. Starting with the same average concentration in Roberts Lake, and using the appropriate values for its physical characteristics, the Reckhow-Simpson model estimated that the runoff of phosphorus from the land would be 19% higher than the value obtained from the Dillon-Rigler-Hutchinson model. Starting with the observed concentration in Blackburn Lake, the Reckhow-Simpson model estimated that sub-basin runoff should be 33% higher than the value estimated by the Dillon-Rigler model, a difference that is appreciable.

If the Reckhow-Simpson model had been adopted throughout, it would have resulted in greater estimated inputs from the land to Cusheon Lake, with consequently lower apparent contributions from septic fields. The Dillon-Rigler-Hutchinson model is judged to be valid for the Cusheon watershed because various independent estimates of variables for Cusheon Lake were in remarkably good agreement with the values from the model. For example, the contribution of recycled phosphorus from the sediment that was estimated by the model was quite close to that estimated on the basis of empirical values measured in the deep water by MWLAP (2003), discussed in section 6.

6. PHOSPHORUS FROM CUSHEON LAKE SEDIMENT

Summary

- *Natural stratification of Cusheon Lake isolates the bottom water all summer. Decay of material in the enriched water causes deoxygenation of the bottom water, and the condition continues all summer.*

- *Lack of oxygen in the deep water causes phosphorus to recycle from the sediment into the water, each year. The amount regenerated in Cusheon L. is estimated as 25 kg.*

- *The recycled phosphorus acts as if it were a new "load" each year, to the water in the lake. After mixing of the lake in the autumn, it becomes available to help stimulate algal growth in the surface layers.*

- *If the deep water were oxic, phosphorus would disappear into the sediment and stay there, i.e., a "sink" for removing phosphorus from the water. Remedial action might be possible, to partially achieve that desirable condition.*

Before modelling Cusheon Lake, it is useful to make an independent estimate of how much P regenerates from the lake sediments each year. The attempt is made here. The estimate is not required for modelling because the model makes its own allowance for the regenerated phosphorus. However, a direct estimate of P regeneration can be compared with the prediction by the model, to judge the apparent “truthfulness” of the model.

6.1 The mechanics of lake stratification

During the winter, Cusheon Lake usually remains mixed, as shown in the upper panel of Figure 3 (for March, 1980). Cool temperatures of 4° to 5° C prevailed from top to bottom because of mixing. Dissolved oxygen was about 10 ppm.

Things change in springtime. Cusheon Lake is deep enough to *stratify* in the warm season, a normal process in Canadian lakes. Surface water is warmed by the springtime sun, so it becomes less dense and floats as a warm layer which goes down to 3 or 4 metres in Cusheon Lake (Goddard 1976, MWLAP 2003). Water within this upper layer (the ***epilimnion)*** can be mixed by wind and waves, and retains reasonably high oxygen concentrations, from exposure to the air.

Also in the springtime, the dense cool water becomes isolated at the bottom of the lake. That deep water (the ***hypolimnion***) stays isolated by gravity, and does not mix with the rest of the lake during the warm season. In Cusheon Lake the depth of the hypolimnion varies a little with the season (Figure 3 and MWLAP 2003), but a depth of 6 m may be taken as the top of the hypolimnion. The maximum depth of the lake may be taken as 9.1 m (Goddard 1976).

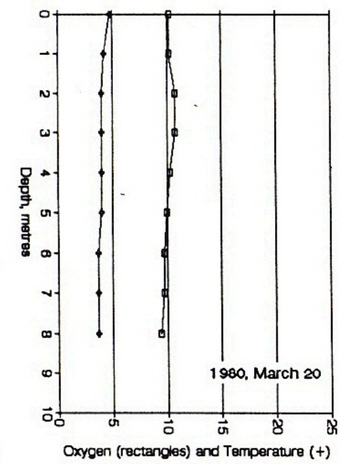
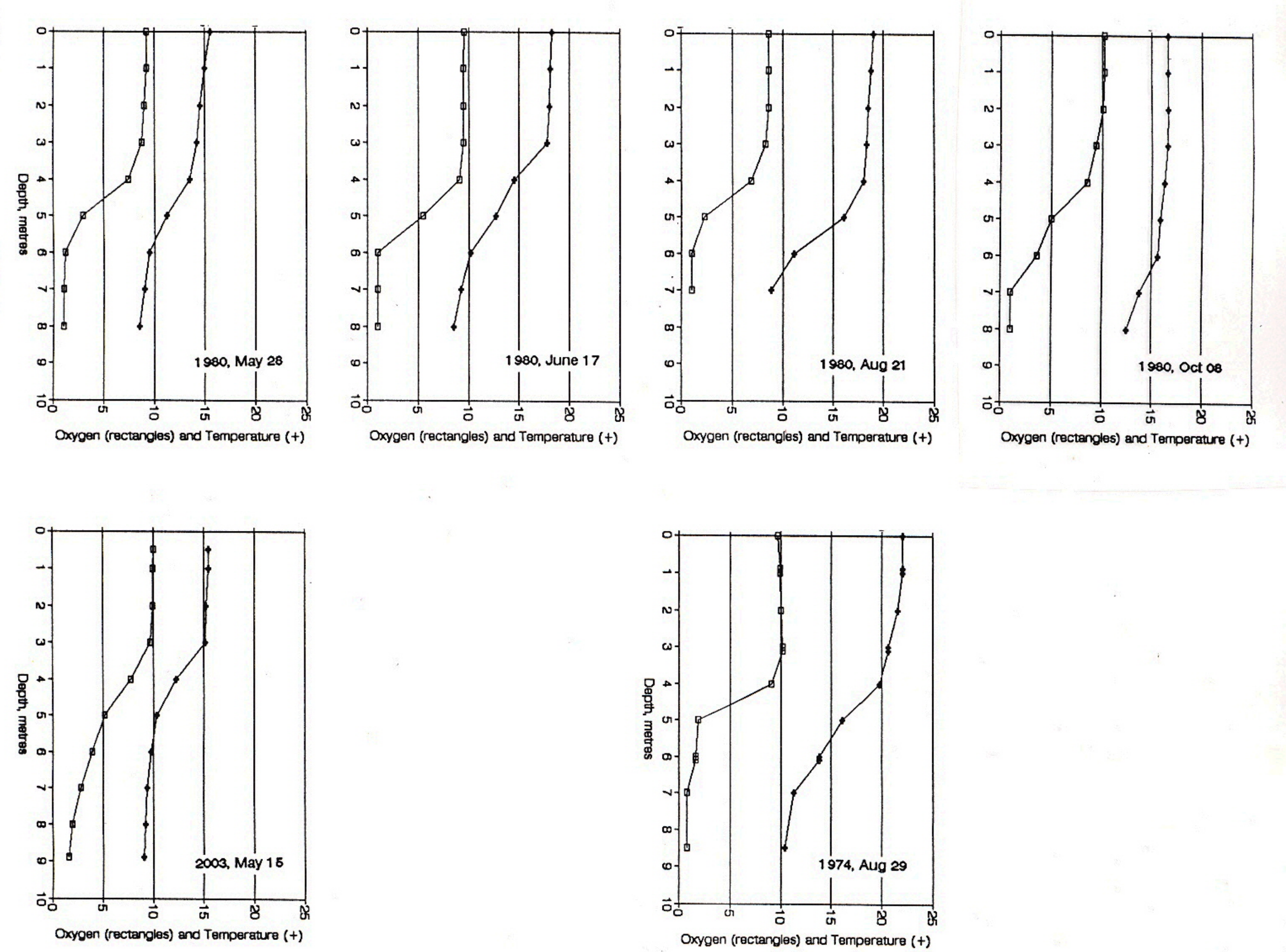


Figure 3. Profiles of dissolved oxygen and temperature in Cusheon Lake. Temperature, in degrees Celsius, is the right-hand profile in each of the panels (but reversed in the top panel). Oxygen as milligrams per litre (parts per million) is the left-hand profile in each panel except for the top panel. The top panel indicates the winter profile. Middle panels run from the beginning to end of the warm season in 1980. The two lower panels compare profiles for May and August in other years. Data are those of MWLAP (2003).



Between the surface and deep layers is an intermediate layer ***(the thermocline)*** where the temperature changes rapidly from warm at the top (usually about 20 °C in summer), to cool in the deep layer (typically about 10°C in Cusheon Lake).

The four panels in the middle of Figure 3 show summer stratification for Cusheon Lake in 1980. By late May, stratification had established itself with warming to 15° at the surface and a cool 9° at the bottom (right-hand line, panel for May 1980). The discontinuity from 4 to 6 m depth shows the rapid change of temperature in the thermocline. The deep bottom water was already sealed off from the surface.

Oxygen in the deep water was already low in May of 1980, very noticeable as the left-hand line in Figure 3 . The discontinuity of oxygen is evident in the thermocline, coinciding with the gradient of temperature. Hypolimnetic oxygen was less than 1 ppm, unsuitable for fish and other standard aquatic organisms. Such severe depletion early in the season indicates that the water was relatively rich in algal cells and other organic matter, and that the decay bacteria went to work quickly, depleting the oxygen with their respiration.

By June of 1980 (second panel from left) conditions were somewhat more extreme. Surface water had warmed to about 18°, while the hypolimnion remained a cool 9°. Similar conditions continued in August of 1980, with slightly more deoxygenation, particularly evident at depth 5 m (third panel in middle group). The surface water had only about 8.5 ppm of oxygen, somewhat lowered from the saturation value which would be about 9.3 ppm.

The layering of Canadian lakes ends in the autumn. Surface water cools down, becomes similar in temperature and density to the thermocline, and a windy day will mix the two layers. Much of the upper part of the lake is mixed. Sometime in early- or mid-October in coastal areas, the surface waters are cooled to the same temperatures (and density) as the deep waters. Then the first autumn windstorm can completely mix the lake ***(fall overturn)***.

In Cusheon Lake, stratification weakened by early October 1980 (Figure 3). Evidently there had been some mixing, because bottom water was warmer than it had been and there was some replenishment of oxygen down to about 6 m. However there was still almost no oxygen at depths of 7 and 8 m. Soon after that, the lake probably mixed and achieved winter conditions like those shown for March of 1980 (top panel).

In Figure 3, the lower left-hand panel for May 2003 shows oxygen and temperature profiles that are quite similar to those for the same month of 1980. Oxygen conditions do not seem to have changed much over the 23 years, agreeing with the similar degrees of eutrophication indicated by phosphorus content (Figure 1). The slightly less severe deoxygenation in 2003 compared to 1980 probably resulted from sampling earlier in the month, when stratification was more recent.

Similarly, August of 1974 (lower right-hand panel) shows profiles much the same as those of the same month in 1980. Surface waters were somewhat warmer during the sampling of 1974.

6.2 Sediment phosphorus

Stratification has serious implications for enriched lakes. Presence or absence of oxygen in the deep water causes differences in fundamental chemistry, including a change in behaviour of phosphorus. If the deep water has dissolved oxygen, phosphorus tends to be insoluble and move from the water into the sediment, where it stays bound up and is effectively removed from the lake's metabolism. That is what happens under low-nutrient (oligotrophic) conditions in a lake that would probably have very clear waters. The sediment would be a *sink* for the nutrient, removing it from the lake water, and helping to maintain the oligotrophic character.

If oxygen disappears from the deep water, there is a fundamental chemical change from oxic reactions to “reducing” reactions, which affect many chemical functions. One change is that phosphorus compounds tend to become soluble and move from sediments into the water. This happens all summer, so deep water can build up high concentrations of P. The deep-water phosphorus is available to algae and other organisms, but is little used because the dark anoxic surroundings are unfriendly to normal plants and animals.

In the autumn, the lake mixes and the phosphorus in the bottom water gets distributed throughout the lake. The nutrient is ready to support an algal bloom as soon as other conditions of light and temperature become suitable. The bloom might happen in the spring, but in B.C.'s coastal lakes, blooms often occur in winter.

Deep-water deoxygenation brings other problems. The hypolimnion is no longer suitable for cool-water fish; they must stay in the surface water which might be warmer than their optimum.

Thus, the natural phenomenon of summer stratification is responsible for the recycling of phosphorus from sediments of Cusheon Lake. Greater enrichment of a lake causes more algae, more subsequent bacterial decomposition, resulting in faster removal of oxygen from bottom waters, earlier “reducing” conditions, and earlier movement of P from the sediments. Very clear lakes with low nutrients have low populations of algae, and correspondingly low rates of decomposition by bacteria. Such clear lakes stratify in the same way, but they may retain dissolved oxygen in the bottom waters, and with oxic conditions, last year’s phosphorus stays locked in the bottom sediments.

6.3 Regeneration in Cusheon Lake

One way to estimate how much phosphorus regenerates from the sediments did not appear to be available for Cusheon Lake. This method would measure the increase in concentration of P in the surface water, from just before the autumnal mixing to just after the mixing. The load from bottom waters could be estimated from the increase in concentration. Nordin et al. (1983) did such an estimate for St. Mary Lake. However, for Cusheon Lake none of the years had clear data for a comparison of “just-before” and “just-after” mixing.

Another approach was used -- measuring the build-up of P in the deep water over the summer. A similar estimate had been provided for Blackburn Lake by McKean (1981). In this approach, deep measurements for Cusheon Lake were selected from the data-base of MWLAP (2003). The fragmentary series shown in Table 7 indicates that phosphorus emerging from the Cusheon sediments is indeed a major factor.

In Table 7, no single year shows a complete series of measurements for all depths and all months. Nevertheless, analysis of the data provided an estimate that 25 kg of phosphorus per year were regenerated from the sediments into the water, and added to the loading of the lake. That estimated internal loading was used to check validity of the modelled assessments of Cusheon Lake.

The somewhat complex details of the estimate are in Appendix D. Briefly, the build-up in phosphorus at the bottom during a summer was plotted on a graph. Each year was plotted separately on the same graph. A representative slope was obtained for the increase in P as the season progressed. That slope was applied to the trend in the deepest values for 2001, the most recent year with data. A slight extrapolation was done to the probable concentration in early October, when the lake would mix. Next, for early October 2001, a gradient in concentrations was allowed, from the highest concentration near the bottom sediment, to the much lower concentration of about 47 ppb which prevailed at the top of the hypolimnion (see Appendix D). The concentrations due to regeneration were derived by subtracting the initial springtime concentration.

The amounts (volumes) of water were estimated as individual volumes for horizontal 10-centimetre "slices", from top to bottom of the hypolimnion. The total weight of regenerated phosphorus was arrived at by multiplying the volume in each slice by its concentration due to regeneration, then summing those amounts.

Table 7. Total phosphorus in the layers of Cusheon Lake during the warm season. Data from MWLAP for years up to 1980. Data from Cusheon Lake Stewardship Committee and MWLAP for 2001. In the epilimnion, values have been averaged for depths zero to three metres.

Year and depth, m		Total phosphorus, micrograms/litre (ppb)				
		June	July	August	Sept.	October
1974	0 - 3	19		16.5		
	6 - 6.1	22		42		
	8.5	-		229		
	9.1	76		-		
1975	0 - 3	12				
	6 - 6.1	--				
	8.2	29				
1976	0 - 3			14.5		
	6 - 6.1			59		
	--			-		
1980	0 - 3	15		18		30
	4	--		39		27
	5	--		46		23
	6 - 6.1	--		115		40
	7	75		435		368
	7.2 – 7.4	--		--		755
2001	0 - 3	10	11		18	
	6 - 6.1	--	--		--	
	8	--	--		930	
	8.4	--	380		--	
	9.5	206	--		--	

Checking the validity of the cottage-country model

As stated above, the Dillon-Rigler-Hutchinson model makes its own estimate of how much phosphorus comes out of the sediment in a lake with anaerobic bottom waters. The empirical estimate using MWLAP data, described above, provides a method of checking the probable validity of the estimate by the model.

The Dillon-Rigler-Hutchinson model can be run for Cusheon Lake, for both anoxic bottom water (the correct model for present conditions) and for hypothetical aerobic (oxic) conditions in the deep water. The aerobic model uses a different retention coefficient (12.4) in line 9 of the model (Table 9). With that coefficient, the model assumes that litle or no phosphorus is regenerated from the sediment.

In order to make the theoretical oxic model predict the same concentration of P in the lake (16.8 ppb) as the correct anoxic model, it is necessary to force the model by adding in some kilograms of P, to represent the P that comes from the bottom sediments, that is missing in the calculations of the model.

The anaerobic run of the model is shown in Table 9, with a total external input to the lake of 92.55 kg. In the aerobic (oxic) run of the model, trial and error was used to determine how many kilograms of P had to be added to the input of the model, to force it to predict the concentration of 16.8 ppb. It turned out that the total input of P had to be 115.01 kg of P instead of 92.55 kg which is shown in the correct anaerobic model (Table 9). The difference is 22.46 kg. This represents the required addition to the oxic model to make up for the missing contribution from the sediments. The value of 22.46 is quite close to the value of 25.46 estimated directly in this section of the report, considering all the variables involved, including the transfer of a model from Ontario to British Columbia. Accordingly, this is regarded as reasonable confirmation of the general validity of the Dillon-Rigler-Hutchinson model for application to this lake in coastal British Columbia.

7 NUTRIENT FLOW TO CUSHEON LAKE

Summary.

- *The "cottage-country" model was applied to Cusheon Lake and its sub-basin, assuming 65 + 26 housing units near the lake. The land runoff of phosphorus was assumed to be 0.089 kg per hectare, each year, which is the average of estimated runoffs for the two upstream lake sub-basins.*

- *A worst-case scenario assumed that all septic systems were completely ineffective in holding back phosphorus. The model estimated the phosphorus concentration in Cusheon Lake as 30 ppb. That is much higher than the recent average of 16.6 ppb, so it is likely that the septic fields perform better than zero effectiveness.*

- *A "probable" scenario assumed normal 74% retention of phosphorus by all the septic systems (including their drainage fields), and further standard improvements with distance from the lake. This scenario predicted 16.8 ppb in the lake, almost the same as the observed recent average of 16.6. This is considered the likely scenario at present.*

- *Under the "probable" scenario, the estimated total external loading of phosphorus into the lake was 92.6 kg/yr. Adding the 25 kg (25.46) of internal regeneration from the sediment gives an effective yearly load of 118 kg to the lake water. Almost 39% of that was estimated to come from the upstream lakes, and almost 15% from runoff in the Cusheon sub-basin. Direct input from human residences and shoreline would contribute 23%, regeneration from the bottom sediment almost 22%, and input from precipitation would be about 2.5%.*

- *If the total effective yearly phosphorus loading were reduced by 18 kg/yr (15%), the lake would probably reach a satisfactory state with regard to algal blooms. Phosphorus concentration would probably drop to the historic level before European settlement (in the vicinity of 13.5 ppb) and meet the upper limit of provincial criteria for maintaining fish populations (15 ppb).*

The following sections show how the Dillon-Rigler-Hutchinson model was applied to Cusheon Lake, using the procedures of Dillon et al. (1986).

It must be emphasized again, that the results and conclusions are theoretical ones based on a mathematical model which was designed for the summer-cottage area of southern Ontario. Nevertheless, the model appears to be valid for the Cusheon basin (preceding section 6.3). Existing hard data were integrated into the model, and the predictions agreed almost exactly with observed conditions. Whether that represents blind luck or truthful simulation of the watershed, the estimates seem useful for orienting future activities to improve Cusheon Lake.

Three scenarios were compared. The first one assumed that septic systems near the lake were completely ineffective, so that all phosphorus from human waste escaped from the septic fields. (Normal decrease was applied for large distances from the lake.) A second scenario assumed normal efficiency of septic systems. A third scenario started with a desirable level of phosphorus in the lake, then predicted the loading allowed to achieve that level. That third loading might be a suitable goal for the subsequent management plan.

In all scenarios, the land runoff rate of 0.089 kg P / ha • yr was adopted as the relevant value for the Cusheon sub-basin, by the reasoning outlined in section 5. The contribution of phosphorus to Cusheon Lake from its bottom sediments was estimated as 25 kg P / yr (section 6), although that value is not needed for the modelling. (The model makes its own calculation of phosphorus from the sediments in an anoxic lake.)

7.1 "Worst-case" scenario

This scenario assumed that for each household near the lake, there was zero retention of phosphorus in the septic system and in the soil immediately around its field. For households that were some distance from the lakeshore, there were appropriate standard reductions for distance. This extreme scenario should be considered even if it is unlikely . There has been much speculation in the stewardship committee that some septic systems along the northerly side of Cusheon Lake are not well-designed or effective because of the limited land available. There has been further speculation with some confirming evidence, that disposal from a mobile home subdivision is not satisfactory.

For this scenario, the predicted phosphorus concentration in the lake was 30 ppb, almost twice as high as the observed average concentration in recent years. This is too high to accept the scenario, but the calculations are shown in Table 8.

As seen before in Tables 5 and 6 for the upper lakes, the first eight lines of Table 8 are physical characteristics of Cusheon Lake, its sub-basin, and the inputs of water. These characteristics are known with reasonable accuracy, and have major effects on the calculations. The discharge of the outlet stream *(Q)*, is taken as 121.3 L/second, the value estimated in section 4. Values for *AdT* and *AdS*, the areas of basins, were also described in section 4, as was the water runoff *(r)*.

In mid-table are the estimated inputs of phosphorus to the lake. The direct human input *(JA)* from household septic systems is based on the number of household units, with 2.2 person-years per unit (census data), and phosphorus excretion of 0.6 kg per person (Hutchinson 2002). As stated above, all this contribution is assumed to escape the septic field, but is then reduced by distance from the lakeshore. Residences more than 100 m from the lake have their input lowered by one-third (by applying a factor of 0.67), those 200 m away are reduced by applying a factor of 0.33, and households 300 m away are considered to have no septic input to the lake. These are standard reductions with distance as determined by research in eastern Canada (Hutchinson 2002). Some of the trailer-homes are assumed to have zero reduction with distance, because they are located close to inflowing Blackburn Creek, others are further removed. An additional direct human input of 1.36 kg is allowed for effects of shoreline clearing at the residences (Hutchinson 2002).

The input from land runoff *(JN)* uses 0.089 kg of P per year from each of almost two hundred hectares of the sub-basin (symbol for units is kg / ha • yr). The loading from upstream lakes is calculated as that carried out of Blackburn Lake, after allowing for Blackburn's retention coefficient (Table 6). The input from precipitation *(JPr)* is 0.11 kg/ha on the lake surface, as used for the upper lakes.

Table 8. Enrichment calculations for Cusheon Lake with "worst-case" septic input.
This scenario uses phosphorus runoff of 0.089 kg per hectare of land in the basin.
The calculations use the Dillon-Rigler-Hutchinson "cottage-country" model from Ontario.

V = Volume of lake =		1,214,000	cubic metres
Q = outlet discharge =	121.3 litres / sec. =	3,826,622	cubic m. / year
Ao = area of lake =		269,000	square metres
AdT = area of total upstream watershed including lakes =		8,507,000	square metres
AdS = area of Cusheon sub-basin without lake =		1,931,000	square metres
r = runoff, from table of flows (approx = Q/AdT) =		0.44982	metres / year
qs = areal water load on lake = Q/Ao =	3826622 / 269000 =	14.225	metres / year
Tw = turnover time = V / Q =	1214000 / 3826622 =	0.3173	years
Rp = retention coefficient of P in lake =	7.2 / (7.2 + qs) =	0.33605	
JA = input of P by direct human activity =			
40 households within 100 m of lake =	40 x 2.2 x 0.6 kg =	52.800	kg / year
10 households > 100 m from lake =	10 x 2.2 x 0.6 x 0.67 kg =	8.844	kg / year
15 households > 200 m from lake =	15 x 2.2 x 0.6 x 0.33 kg =	6.534	kg / year
16 units in trailer court, within 100 m =	16 x 2.2 x 0.6 kg =	21.120	kg / year
10 units in trailer court > 100 m =	10 x 2.2 x 0.6 x 0.67 kg =	8.844	kg / year
Shoreline clearing at 40 residences =	40 x 0.034 kg =	1.360	kg / year
JN = P input from sub-basin = AdS x 0.0891 kg =	193.1 x .0889233 kg =	17.171	kg / year
+ upstream = Blackburn [input x (1 - Rp)] =	46.009 x (1 - 0.07064) =	45.547	kg / year
JPr = input of P from precipitation =	0.11 x 26.9 kg =	2.959	kg / year
	Total input =	**165.1791**	**kg / year**
Loading = (JA + JN + JPr) / Ao = (Total input) / 269000 =		0.6140	$gm / m^2 . yr$

Predicted P concentration, in ice-free season

$$= [\text{ Loading } (1 - Rp)] / [0.956 * qs] = \frac{[(0.6140)*(1-0.33605)]}{[0.956 * 14.225]} = 0.029979 \text{ gm / m}^3$$

= **30 ppb, rounded off**.

Near the bottom of Table 8, the total input of phosphorus is expressed in terms of loading per square metre of lake surface. That, in turn, is entered into a formula which predicts a concentration of 30 ppb in the lake. Since the recent observed average has been 16.6 ppb, the loading assumed in this worst-case scenario is obviously too great. The septic systems are apparently performing better than the assumption of complete leakage of phosphorus.

7.2 "Probable" scenario

During research in Ontario on the cottage-country model, there was some uncertainty about phosphorus leakage from septic fields. An early assumption that all phosphorus eventually reached the lake was apparently incorrect, and resulted in several over-estimates for Ontario lakes. Recent work (Hutchinson 2002) indicates that about 74% retention is more realistic, although this depends greatly on the quality of the soil. The figure of 74% was for "ground moraine, glacio-lacustrin delta, and outwash plain" soils.

The percentage of 74% has been adopted for the "Metchosin" soils around Cusheon, an assumption which is probably of the correct order. The resulting estimate of direct human input has been used in this second “probable” scenario. The reduction factors for distance from the lake are the same standard ones that were used in the worst-case scenario. Table 9 gives the calculations, which are the same as Table 8 except for the lower human input.

The "probable" scenario of Table 9 predicts a phosphorus concentration of 16.8 ppb. That is very close to the observed average in recent years, an agreement which was not expected and must be regarded as highly unusual in modelling of this kind. Perhaps the agreement is fortuitous, but is accepted as a description of the present situation. All inputs to the model were decided before the start of calculations, and were not adjusted.

The overall agreement of predicted and observed values is subject to some caveats. It must be remembered that the predicted concentration agrees with an *average* observed concentration in the lake in recent years. It does not necessarily agree with any particular year because of the considerable year-to-year variation in phosphorus (Figure 1).[3] This model, developed in Ontario, might be a less-than-perfect simulation of conditions in the Cusheon watershed. And of course, the components of the model might not reflect the correct proportions, even though the overall prediction agrees with reality. Nevertheless, the overall harmony of the estimate makes it seem likely that the relative contributions are approximately correct.

In any case, Table 9 shows a dramatically lower estimate of the direct human input than was shown for the "worst-case" scenario. The septic input is lower by almost 73 kg/yr. The performance of septic fields can obviously make a big difference for the lake. The total external loading of the lake is now estimated as 92.6 kg. With the internal regeneration from the sediment added (25.5 kg), the total effective loading to the water of the lake in a year is 118 kg.

The relative importance of the main sources can be stated as percentages of the 118 kg. Input from the upstream lakes and drainage basin now makes up 38.6% of the total load. Input from the land of the Cusheon sub-basin is 14.5%, for a total of 53.1% resulting from land runoff. This includes the component which drains to the lake through culverts under the roads (Sprague 2007d). Direct human input from Cusheon Lake septic fields and shoreline clearing is 16.2%, and from the nearby modular homes is 6.6%, for a direct human input of 22.8%. Internal regeneration represents 21.6% of the total, and input from precipitation and fallout is a modest 2.5% of the total.[4]

---

[3] Hutchinson et al. (1991) comment on the variability of phosphorus in lakes. They state that "variation on the order of 20% can be expected even in intensive sampling programs for TP [total phosphorus] in lake water." They cite the work of Kwiatkowski (1985) who measured phosphorus at one site in Lake Ontario for a year and found a coefficient of variation of 14 to 17%. That would indicate, for example, that if the mean value were 20 ppb, individual measurements could commonly extend over the range 14 to 26 ppb.

[4] Residents of the Cusheon area have suspected other sources of nutrients such as ditch runoff (see section 8.1.4). By and large, these are included in the overall inputs estimated here, and they have been shown as a significant small factor in the overall picture (Sprague 2007d).

Table 9. **Enrichment calculations for Cusheon Lake with "probable" septic performance.**
This scenario uses phosphorus runoff of 0.089 kg per hectare of land in the basin.
The calculations use the Dillon-Rigler-Hutchinson "cottage-country" model from Ontario.

V = Volume of lake =		1,214,000	cubic metres
Q = outlet discharge =	121.36 litres / sec. =	3,826,622	cubic m. / year
Ao = area of lake =		269,000	square metres
AdT = area of total upstream watershed including lakes =		8,507,000	square metres
AdS = area of Cusheon sub-basin without lake =		1,931,000	square metres
r = runoff, from table of flows (approx = Q/AdT) =		0.44982	metres / year
qs = areal water load on lake = Q/Ao =	3826622 / 269000 =	14.225	metres / year
Tw = turnover time = V / Q =	1214000 / 3826622 =	0.3173	years
Rp = retention coefficient of P in lake =	7.2 / (7.2 + qs) =	0.33605	
JA = input of P by direct human activity =			
40 households within 100 m of lake =	40 x 2.2 x 0.6 x 0.26 kg =	13.728	kg / year
10 households > 100 m from lake =	10x2.2.2x0.6x0.26x0.67 kg =	2.299	kg / year
15 households > 200 m from lake =	15x2.2x0.6x0.26x0.33 kg =	1.699	kg / year
16 units, trailer court, within 100 m =	6 x 2.2 x 0.6 x 0.26 kg =	5.491	kg / year
10 units in trailer court > 100 m =	10 x2.2x0.6x0.26x0.67 kg =	2.299	kg / year
Shoreline clearing at 40 residences =	40 x 0.034 kg =	1.360	kg / year
JN = P input from sub-basin = AdS x 0.089 kg =	193.1 x .0889233 kg =	17.171	kg / year
+ upstream = Blackburn [input x (1 - Rp)] =	2 x (1 - 0.07064) =	45.547	kg / year
JPr = input of P from precipitation =	0.11 x 26.9 kg =	2.959	kg / year
	Total input =	**92.5540**	**kg / year**
Loading = (JA + JN + JPr) / Ao =	(Total input) / 269000 =	0.3441	gm / m^2 . yr

Predicted P concentration, in ice-free season

$$= [\text{ Loading } (1 - Rp)] \;/\; [0.956 * qs] = \frac{[(0.3441) * (1-0.33605)]}{[0.956 * 14.225]}$$

= 0.016798 gm / m^3 **= 16.8 ppb,** **rounded off.**

7.3 Desirable loading

The type of modelling in Tables 8 and 9 can be used to estimate the phosphorus loading that would achieve a concentration that is desirable. The historic phosphorus concentration in Cusheon Lake, before it was developed by Europeans, is thought to have been in the range 11 to 17 ppb, according to analysis of algal fossils in old sediments. The geometric mean (mid-point) of that range is about 13.5 ppb and that is adopted here as a recommended realistic goal for phosphorus (P). It is in the low mesotrophic zone, and could be expected to result in mild algal blooms, fairly acceptable to residents

Observations elsewhere show another important benefit of reducing P to such a moderate level. Any blooms are more likely to be green algae than the less desirable cyanobacteria. (The usual reason is that with very high P concentrations, the limiting nutrient can become nitrogen instead of P. That favours cyanobacteria because some of them can fix their own nitrogen from the gas dissolved in the water. Lowering the P level means that nitrogen is unlikely to be limiting, and normal green algae are more likely to prevail.)

The value of total loading in the Dillon-Rigler-Hutchinson model shown in Table 9, was adjusted by trial and error until it predicted a concentration of 13.5 ppb of phosphorus.

To achieve that, the total input of phosphorus (external and internal) would have to be lowered by 18 kg, from its present estimated input of 118 kg to 100 kg. That is a reduction of approximately 15%. It would not matter how the reduction was made. It could be attained by modest reductions in several of the individual sources, or in a single source. With any reduction in external inputs, there would probably be a slight improvement in oxygen content of deep waters, and a secondary benefit that regeneration of phosphorus from the sediments would be slightly reduced.

Achieving 13.5 ppb of phosphorus would meet another British Columbia guideline. There is a criterion with limits of 5 to 15 ppb of phosphorus for protecting fish and other aquatic life. Such a lake would almost certainly be suitable for salmonids. The lake would probably suffer a little less from deoxygenation of deeper zones, so fish could make use of somewhat deeper and cooler waters.

In British Columbia, the phosphorus criterion for "drinking-water lakes" is 10 ppb (Nordin 2001), the rule of thumb for the upper limit of oligotrophic lakes. In other words, the province has set a criterion that would provide a clear lake with no observable algal blooms and generally low productivity. Attaining 10 ppb would not seem feasible since it would apparently be lower than the natural concentration of the lake.

7.4 Predicted status of lake

Summary.

- *Another way of assessing lake enrichment involves plotting the phosphorus loading on a "Vollenweider graph". This is a more general and robust model which successfully predicts the status of lakes from many parts of the world.*

- *When Roberts Lake is plotted on the Vollenweider graph, for the estimated value of 0.099 kg for land runoff of phosphorus, it falls in the lower part of an intermediate or mesotrophic zone. Thus it is between the oligotrophic and eutrophic condition, or between "permissible loading" and "excessive loading". Blackburn Lake also plots in a very similar position in the lower mesotrophic zone.*

- *For Cusheon Lake, the "probable" scenario also plots on the Vollenweider graph in the lower part of the mesotrophic zone. The "worst-case" scenario would plot just into the eutrophic zone, just above the level of "excessive loading". For the "desirable" scenario with a hypothetical reduction of 18 kg of P input, the lake would plot at a desirable position on the border of the oligotrophic and mesotrophic zones, just about at the limit of "permissible loading".*

- *All these positions plotted on the Vollenweider graph give general confirmation of the interpretations given earlier in the report, which were based on phosphorus concentration in the lake.*

A superior way of assessing phosphorus enrichment of a lake is to plot the loading on the famous "Vollenweider graph", named after its originator, a limnologist who worked for Environment Canada (Vollenweider 1975, 1976). This is a general model, widely applicable to various kinds of lakes around the world. The Dillon-Rigler-Hutchinson model was developed as a special case of the Vollenweider model.

All that is needed to plot the three lakes on the Vollenweider graph is the total phosphorus loading per year, and the physical characteristics of the lake. The loading is expressed as grams of phosphorus entering the lake every year, per square metre of lake surface. Those values are shown near the bottom of Tables 5, 6, 8 and 9 in this report. For the physical characteristics of the lake, the mean depth (Sprague 2007c) is divided by the hydraulic residence time. The latter is simply the volume of the lake divided by the outflow, which can be obtained from Table 4. These physical characteristics determine the position of the lake on the horizontal axis of the graph. In Figure 4, the vertical line for each lake indicates its position on the horizontal axis.

"Green" lakes will plot in the upper *eutrophic* part of Figure 4. Unpolluted, low-nutrient, clear-water lakes will place themselves in the bottom *oligotrophic* part of the graph. Between the "excessive" and "permissible" boundaries, there is an intermediate *mesotrophic* zone.

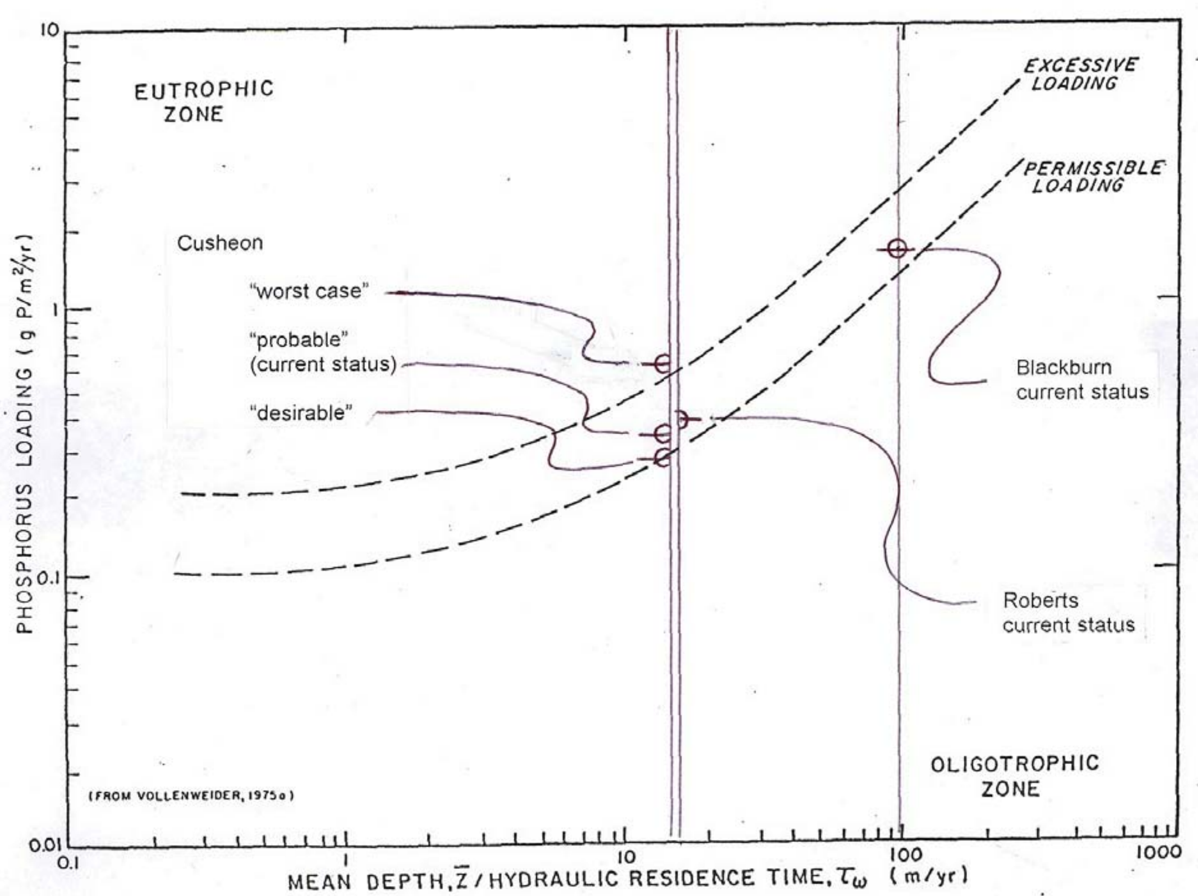


Figure 4. Enrichment status of lakes, judged by the "modified Vollenweider graph". The labels point to the existing status of Roberts and Blackburn Lakes, and existing and hypothetical status for Cusheon Lake under various scenarios described in the text. The modified relationship is that determined by Vollenweider (1976) and the graph is taken from Rast and Lee (1978).

7.4.1 The upper lakes

The status of Roberts Lake is shown on the vertical line which goes up from 16.4 on the horizontal axis. (The position is very close to the position of Cusheon Lake). For the estimated current loading of 0.353 g/m^2.yr (= 3.53 kg/ha), Roberts Lake plots in the lower part of the mesotrophic zone, above the curved line marking “permissible loading”, but well below the line of “excessive loading”. This agrees in general with earlier interpretations for Robert Lake, based on its observed average concentration of 16.5 ppb of phosphorus. That is between the standard criteria of 10 and 20 ppb which are usually taken to mark the limits of oligotrophy and eutrophy.

Blackburn Lake is positioned well to the right on Figure 4, because of its rapid turnover time, i.e., a large amount of water flowing through a small lake every year. The loading is 1.59 g/m^2.yr (Table 6). Accordingly, Blackburn plots in a very similar vertical position to Roberts Lake, in the lower part of the mesotrophic zone. That is also in reasonable agreement with its observed concentration of 16.3 ppb.

7.4.2 Cusheon Lake

Cusheon Lake's physical characteristics place it on the line drawn vertically from 13.6 on the horizontal scale (Figure 4, mean depth is 4.33 m, turnover time is 0.318 years as given in Tables 8 and 9).

The "worst-case" septic loading produced an estimated phosphorus loading of 0.614 g/m^2.yr, associated with a predicted concentration of 30 ppb (Section 7.1, Table 8). On the Vollenweider graph, this plots just above the “excessive” level, juts into the eutrophic zone (Figure 4). Clearly, that would not be a satisfactory level.

The "probable" scenario produced a loading of 0.344 g/m^2.yr (Table 9). That plots in the lower mesotrophic zone of Figure 4, showing approximate agreement with the average phosphorus concentrations observed in recent years (16.6 ppb, Table 2). This is very similar to the positions of the two upstream lakes. Such a mesotrophic condition would be expected to create occasional algal blooms in most lakes.

The next scenario estimated that the P concentration in the lake would be lowered to 13.5 ppb, if 18 kg of phosphorus were removed from the "probable" external input (Section 7.3). That resulted in a lake loading of 0.2765 g/m^2.yr. Under that loading, the lake would plot on the curve for “permissible loading” in Figure 4, on the boundary between oligotrophic and mesotrophic conditions. That gives support to the prediction that such loading might prove to be reasonably satisfactory as a goal for Cusheon Lake.

The Vollenweider model can be taken as a widely valid tool. It appears that the cottage-country modelling by the Dillon-Rigler-Hutchinson method gives estimates of phosphorus concentrations in these three lakes that are in general agreement with the Vollenweider model. The cottage-country modelling is a useful predictive tool for estimating the relative loadings from different sources.

8 REMEDIES

Summary.

- *There does not appear to be any single source of nutrient that could be eliminated easily, quickly, cheaply, and without risk, to achieve the desirable reduced loading to Cusheon Lake.*

- *Moderate improvements in all inputs might succeed. Revegetation in the total watershed would help, especially if focussed on riparian areas. Complete diversion of all household waste to a central system would suffice, but is a costly option. Eliminating regeneration of phosphorus from the bottom sediments would probably be sufficient; the suitability of chemical precipitation and sealing of sediments should be investigated.*

- *There is a good chance of reducing the algal problem in Cusheon Lake to a satisfactory level, given time and application of a good management program.*

An ideal yet realistic target for Cusheon Lake on the Vollenweider graph (Figure 4) would be the *permissible* boundary. The previous sections indicate that it would be achieved by reducing the P loading by 18 kg, with a resultant lowering of the P concentration to 13.5 ppb. This would probably be satisfactory to residents and users of the water, and is recommended as an initial goal. It seems to be achievable, as discussed below. It does not matter how the reduction is achieved; it could be from one source or it could be small improvements in all the sources presently contributing nutrient.

Tactics for improvement

Some of the items on the list of inputs (Table 9) are large enough that they might provide the complete reduction by themselves. However, none of them could be eliminated by a process that had all four desirable characteristics: (1) easy to carry out, (2) quick to achieve, (3) economical, and (4) no concerns about potential side-effects.

Land runoff

Loading of 63 kg of phosphorus results from drainage of the Cusheon sub-basin plus the input from upstream lakes, itself mostly from land runoff (Table 9). Widespread revegetation in the watershed would decrease this loading somewhat. There is not enough information on erosion and runoff in this watershed to estimate the degree of decrease, but it would probably be only a modest part of the needed 18 kg.

The management plan calls for improving land runoff by appropriate revegetation, especially along waterways. Avoiding further clear-cutting would be desirable. Complete reforesting of the basin is not likely considering the existing hayfields, pastures, golf course and garbage transfer operation, as well as the clearings for residences. However, candidate areas for improvement would be any denuded areas, particularly riparian areas of creeks which are subject to erosion and delivery of phosphorus in silt. Solid revegetation of buffer strips along all watercourses can achieve improvements that approach the benefits of complete reforestation. Accomplishing improved vegetation would be a major exercise in public education and effort, but worthwhile.

Direct human input

The probable loading from septic systems is almost 26 kg of phosphorus, so elimination of that source would surpass the goal for reduction. Inspection and upgrading of septic systems could lead to improvements, but would never eliminate migration of nutrients, especially for small sloping lots which are common on Cusheon Lake. Any reduction from upgrading would probably be minor in relation to the recommended 18 kg.

The only ways to drastically reduce the direct human input would be collecting from the individual septic systems for treatment at a central facility. This might be done by frequent pumping of tanks at individual houses, or by a collector pipe around much of the lake, leading to the central treatment facility. Technically, either could be done, but the cost might be appreciable and not welcomed by residents.

Sediment regeneration

This is another source which, if eliminated, would achieve the desired reduction in loading. If the bottom layer of the lake (the hypolimnion) were kept oxic during the entire summer, sediments would serve as a nutrient sink instead of a source.

The apparent history of regeneration from the sediment adds some urgency to a clean-up of Cusheon Lake. It appears that regeneration of phosphorus from the bottom sediments was only about 7 kg in 1974 and 1975, compared to 25 kg in 2001. If the sediment input continues to increase, it will become more and more difficult to turn around the eutrophication of the lake. In other words, the more P that comes out of the sediment, the greater reduction will be necessary in the external inputs (septic fields, land runoff), in order to achieve a satisfactory state. Therefore is it highly desirable that early and vigorous action should be taken on the recommendations in the management plan (CWMPSC 2007).

Actually, the amount of phosphorus regenerated by the sediment would be slightly reduced by any measures which reduced the external inputs of phosphorus to the lake (erosion and surface runoff, septic fields). With reduction of external nutrient, algal blooms would weaken, and the load of organic debris in the water would be slightly less. Then, when the deep water was sealed off for the summer, decay would be less and so would deoxygenation of the deep water, resulting in slightly less regeneration. Therefore, to some extent, reducing the external load would achieve a "double bonus". The size of the double bonus might be small, however.

There are mechanical remedies to prevent regeneration. One method is to *destratify* the lake in summer by bubbling air or pumping water. The idea is to mix the entire lake and prevent a deoxygenated bottom layer. Often, this would not be desirable since the whole lake would assume the same intermediate temperature. That would be unfavourable to salmonid fish which like the cooler, deeper water, and it would be unfavourable to human recreation because surface water would be less warm.

A more common approach is to *aerate the hypolimnion* during the summer. Certain devices release air at the bottom, but usually, water is pumped to a surface apparatus, aerated, and returned to the bottom. Unfortunately Cusheon Lake is considered to be too shallow for the conventional aeration systems.[5]

[5] On Salt Spring Island's St. Mary Lake, an aeration device was operated for this purpose from 1985 to 1993. It appeared to be successful since whole-lake phosphorus concentrations were lowered to favourable levels (average 18 ppb) during the operation. Post-aeration values averaged 27, however, little different from the pre-aeration average of 25 ppb (Ashley and Nordin 1999). Comparison was complicated by large natural changes over the years, and by the slow overturn of the lake which meant that the remedial activity would have to continue for many years. The operation apparently ceased for lack of funding but is currently being revived.

For lakes in other places, the suggestion has been made to pump or siphon off deep water during the summer when it is high in phosphorus, and release it downstream. The idea is to rid the lake of some phosphorus load for the current year, and eventually to deplete the reservoir of phosphorus available from the sediments. This technique is only suitable if the lake has inflow and outflow all year. Cusheon Lake has no summer outflow, so the procedure is not desirable.

Chemical inactivation

Certain chemicals can be added to a lake, to precipitate algae and organic matter to the bottom, and then "seal" the bottom so that phosphorus does not emerge into the water. The usual chemical is *alum*, a mix of aluminium salts, which effectively precipitates material upon first addition, and also achieves major reduction of phosphorus return from the sediments over several more years. Toxic effects on aquatic organisms are seldom evident, but if the lake is used for drinking water, the users are often concerned about effects on water quality. If the acid/base reaction of water deviates far from neutral, the aluminum can become toxic. Iron and calcium salts have been used in similar fashion, but less often. The cost has not been ascertained for this report but might be reasonable.

This technique would reduce phosphorus loading for the year in which it was applied, and into some future years. To be meaningful in the long term, the procedure should be carried out in concert with some major improvement in external input. Otherwise, when the effect of treatment wore off, the other sources of nutrient might once again result in the anoxic hypolimnion, with regeneration and return of the lake to its enriched status.

Other potential remedies

Operation of the drinking-water treatment plant of the Beddis Water District could have an influence on nutrients in the lake. In former years, there were reports that filters at the plant were backwashed into the lake. That backwash would include a concentrated mass of removed algae and any other organic matter from the filter. The net effect would be to increase phosphorus levels in the lake (water was removed, but nutrients returned). Current rebuilding of the treatment plant means that this procedure will not occur. Apparently the backwash will be collected for suitable use elsewhere (land fertilizer?), so the plant will have a neutral effect on lake phosphorus.

Cleanout of ditches near the lake for roadway management, is another situation which has been under negotiation. If there is scraping of soil, that could lead to silty runoff in the wet season. The relative importance of this potential input has not been assessed for this report.

Harvesting of water-weeds is often thought of as a mechanism for removing phosphorus, and indeed some beds of aquatic plants look as if they should contain a rich crop of nutrients. However, the amounts of phosphorus removed with plants have been shown elsewhere to be relatively small, and any slight benefits must be weighed against the major disturbances to shallow areas of lake-bottom. An example is provided by a survey of Lakelse Lake, between Terrace and Kitimat, B.C. A survey of the phosphorus content of the lake showed that 99.5 % of it was in the sediments, 0.3% in the water, but only 0.2% in the tissues of rooted aquatic plants, and less than 0.1% in phytoplankton (Warrington 1986).

8.1 Conclusion

The modelling exercise in the present report shows that there is indeed, scope for major improvement of Cusheon Lake, with a real chance of controlling the algal problem to a level that is, at least, satisfactory. However, there is no complete solution that is simple, economical, rapid and also risk-free. Time and much continued effort on a management program will be required.

The estimates in this report for the status of Cusheon Lake are approximate, and the estimates of phosphorus inputs are only predictions. Nevertheless, the general agreement among all parts of the modelling suggests that the results are realistic. The relative loads of phosphorus from different sources seem to be approximately correct, and the absolute magnitudes of those loads probably agree with reality. Accordingly, this report provides a starting-point for designing a logical Cusheon management plan. At least, it will help to avoid wasted effort on activities which are based on hunches or trendy issues of the day.

REFERENCES

Ashley, K., and R. Nordin 1999. Lake aeration in British Columbia: applications and experiences. P. 87 - 108 *in* T. Murphy and M. Munawar (eds), Aquatic restoration in Canada, Ecovision World Monograph Series, Bachhuys Publishers, Leiden, The Netherlands.

Barnett, L., B. Blecic, and W. Van Bruggen 1993. Saltspring Island water allocation plan. British Columbia Ministry of Environment, Lands and Parks, Vancouver Island Region, Regional Water Management, Victoria, B.C. Unnumbered report, 34 p. + 7 appendices.

B.C. MELP [British Columbia Ministry of Environment, Lands and Parks] 2000. A compendium of working water quality guidelines for British Columbia. 1998 edition. B.C. MELP, Water Management Branch, Victoria, B.C. Updated to June 28, 2000 from web site www.elp.gov.bc.ca/. 40 p.

Brandes, Oliver M. and Keith Ferguson 2003. Flushing the future? Examining urban water use in Canada. Univ. of Victoria, Victoria, B.C.

CWMPSC [Cusheon Watershed Management Plan Steering Committee] 2007. Cusheon Watershed Management Plan. CWMPSC, Salt Spring Island, B.C. Report, 81 p.

Dillon, P.J., and F.H. Rigler 1975. A simple method for predicting the capacity of a lake for development based on lake trophic study. J. Fish. Res. Board Can. 32: 1519-1531.

Dillon, P.J., K.H. Nicholls, W.A. Scheider, N.D. Yan, D.S. Jeffries, E. DeGrosbois, A. Nicholls, P.J. Scholer, and R.A. Reid 1986. Lakeshore capacity study. Trophic status component. Ontario Ministry of the Environment, Water Resources Branch, Aquatic Ecosystems Section. Report, May 1986. 89 p.

Dobson, H.F.H., M. Gilbertson, and P.G. Sly 1974. A summary and comparison of nutrients and related water quality in lakes Erie, Ontario, Huron, and Superior. J. Fish. Res. Board Can. 31: 731-738.

Ellsworth, N. and C.D. Moodie 1964. Nutrient inputs in rainfall at nine sites in Washington state, 1962 and 1963. State of Washington, Agricultural Experimental Station. Interim Report on Project 1670. 9 p plus unnumbered tables and figures.

Environment Canada 2006. [Climate records, near Cusheon Lake and Sooke Lake.] www.climate.weatherofice.ec.ca/climateData/monthlydata_e. [Accessed 2006.March.06]

Epps, D. 2006. Personal communication (March 2006). Measurements of total and dissolved phosphorus in Cusheon Lake from 2003 to 2006. Deborah Epps, B.C. Ministry of the Environment, Nanaimo, B.C.

Gilliom, R.J. 1980. Estimation of background loadings and concentrations of phosphorus for lakes in the Puget Sound region, Washington. U.S. Dept. of Interior, Geological Survey, Open File Report of 80-328. 37 p. [Cited through Truscott 1981.]

Goddard, J.M. 1976. Cusheon Lake, Saltspring Island. Data report for the water quality monitoring program, June 1974 to June 1975. Water Resources Service, Dept Environment, Victoria, B.C. Unnumbered report.

Hodge, W.S. 1995. Groundwater conditions on Saltspring Island. B.C. Ministry of Environment, Lands and Parks, Water Management Div., Hydrology Branch, Groundwater Section. Unnumbered report, 74 p.

Holms, G.B. 1999. State of water quality of Cusheon Lake 1974 - 1995. Water Quality Section, Water Management Branch, Ministry of Environment, Lands and Parks, Victoria, B.C. Draft report, 43 p.

Hutchinson, N.J. 2002. Limnology, plumbing and planning: evaluation of nutrient-based limits to shoreline development in Precambrian Shield watersheds. P. 647 - 680 in R.L. France (ed.), Handbook of water sensitive planning and design. Lewis Publishers, Boca Raton, Flor., U.S.A.

Hutchinson, N.J., B.P. Neary, and P.J. Dillon 1991. Validation and use of Ontario's trophic status model for establishing lake development guidelines. Lake and Reservoir Management 7: 13 - 23.

Kwiatkowski, R.E. 1985. Importance of temporal variability to the design of large lake water quality networks. J. Great Lakes Res. 11: 462-477.

McKean, C.J.P. 1981. Domestic water supply potential of Blackburn, Bullock's, Ford and Stowell Lakes, Saltspring Island. B.C. Ministry of Environment, Assessment and Planning Div., Victoria, B.C. 75 p. [ISSN 0-7719-8539-8]

McPherson, S. 2004. A water quality assessment of Cusheon Lake (Saltspring Island, British Columbia): a summary of data collected between 1974 and 2003. Unnumbered report, B.C. Ministry of Water, Land and Air Protection, Nanaimo, B.C., 82 p.

Michalski, M.F.P., and N. Conroy 1972. Water quality evaluation for the lake alert study. Biology Section, Water Quality Branch, Ontario Ministry of the Environment, 23 p.

MWLAP [British Columbia Ministry of Water, Land and Air Protection] 2003. Roberts Lake, EMS ID E207160; Blackburn Lake, inflow @ road EMS ID 1130065; 1100123 Cusheon Lake, midlake w. arm. B.C. MWLAP, Nanaimo, B.C. [Electronic spreadsheets of chemical measurements from 1974 to 2003, compiled by Deborah Epps of MWLAP, Nanaimo, B.C.]

Nordin, R.N. 2001. Water quality criteria for nutrients and algae. B.C. Ministry of Water, Land and Air Protection, Water, Air and Climate Change Branch, Victoria, B.C. [Original 1985, updated 2001]

Nordin, R. 2006. Personal communication. [Phosphorus measured in precipitation at the Sooke reservoir] Dr. Rick Nordin, Senior Research Scientist, Environmental Management of Drinking Water, Dept. of Biology, Univ. of Victoria, Victoria, B.C.

Nordin, R.N., C.J.P. McKean, J.H. Wiens 1983. St. Mary Lake water quality: 1979-1981. Prov. of British Columbia, Ministry of Environment, Victoria, B.C. 120 p. [File: 64.080302]

OMOE [Ontario Ministry of the Environment] 1984. Water management. Goals, policies, objectives and implementation procedures of the Ministry of the Environment. OMOE, Toronto, Ontario, Nov. 1978, revised May 1984. 70 p.

Rast, W., and G.F. Lee 1978. Summary analysis of the North American (U.S. Portion) O.E.C.D. Eutrophication project: nutrient loading -- lake response relationships and trophic state indices. United States Environmental Protection Agency, EPA-600/3-78-008, 455 p.

Reckhow, K.H. and J.T. Simpson 1980. A procedure using modeling and error analysis for the prediction of lake phosphorus concentration from land-use information. Can. J. Fish. Aquat. Sci. 37: 1439 - 1448.

Reimer, K. 2003. State of water quality of Cusheon Lake -- 1999, 2000, 2001. Salt Spring Salmon Enhancement Society, Ganges, Salt Spring Island, B.C. Report of water analyses, 6 p.

Sprague, J.B. 2007b. Phosphorus runoff from the upper Cusheon basin, Salt Spring Island, B.C. Sprague Associates Ltd., 474 Old Scott Road, Salt Spring Island, B.C. Background report for the Cusheon Watershed Management Plan and Steering Committee, Salt Spring Island, B.C. 48 p.

Sprague, J.B. 2007c. Nine lakes on Salt Spring Island, B.C.: size, watershed, inflow, precipitation, runoff and evaporation. Sprague Associates Ltd., 474 Old Scott Road, Salt Spring Island, B.C. Background report for the Cusheon Watershed Management Plan and Steering Committee, Salt Spring Island, B.C. 19 p.

Sprague, J.B. 2007d. Phosphorus carried by small culverts into Cusheon basin, Salt Spring Island, B.C. Sprague Associates Ltd., 474 Old Scott Road, Salt Spring Island, B.C. Background report for the Cusheon Watershed Management Plan and Steering Committee, Salt Spring Island, B.C. 14 p.

Sprague, J.B. 2007e. Phosphorus content of certain creeks and lakes in the Cusheon Lake basin, Salt Spring Island, B.C. Sprague Associates Ltd., 474 Old Scott Road, Salt Spring Island, B.C. Background report for the Cusheon Watershed Management Plan and Steering Committee, Salt Spring Island, B.C. 18 p.

Truscott, S.J. 1981. Quantitative models for integrated land use and lake quality planning: applications in the Brannen and St. Mary Lakes watersheds, B.C. Master's thesis, Faculty of Interdisciplinary Studies, Simon Fraser Univ., Burnaby, B.C. 92 p.

Vingarzan, R. 2006. Personal communication. Dr. Roxanne Vingarzan, Atmospheric Processes Scientist, Environment Canada, Vancouver, B.C.

Vingarzan, R., W. Belzer and R. Thomson 2003. Nutrient levels in the atmosphere of the Elk Creek Watershed, Chilliwack, BC (1999-2000). Environment Canada, Aquatic and Atmospheric Sciences Division, Vancouver, B.C. Tech. Rept # EC/GB-02-038. 74 p.

Vollenweider, R.A. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweiz. Zeitschrift Hydrologie 37: 53-84.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist Ital. Idrobiol. 33: 53-83.

Warrington, P. 1986. The distribution of aquatic vegetation in Lakelse Lake and the partitioning of nutrients among sediments, water and plant tissue. Resource Quality Section, Water Management Branch, Ministry of Environment and Parks, Victoria B.C., 34 p.

Water Survey of Canada 2006. Water levels and streamflow statistics. Environment Canada, Water Survey of Canada website: www.wsc.ec.gc.ca/staflo/index_e.dfm?cname=flow_daily.cfm. (Accessed 2006.Nov.28.)

Watson, R.H. 2006. Water supply assessment. Draft report in preparation for the North Salt Spring Waterworks District, Salt Spring Island, B.C. 25 p.

Zeman, L.J. and O. Slaymaker 1978. Mass balance model for calculation of ionic input loads in atmospheric fallout and discharge from a mountainous basin. Hydrological Sciences Bull. 23: 103-117. [Cited through Truscott 1981.]

APPENDIX A. HISTORICAL MEASUREMENTS OF PHOSPHORUS IN CUSHEON LAKE

Phosphorus as the limiting nutrient

The focus for nutrient input is phosphorus because it is in shortest supply in Cusheon Lake. Therefore, the amount of available phosphorus completely governs the growth of algae. Nitrogen is another essential nutrient, and the classical ratio is 15 to 1 for necessary nitrogen-to-phosphorus concentrations. If the ratio is higher, then nitrogen is in excess and phosphorus is limiting. In Cusheon Lake, the ratio is almost always higher than 15:1 in the surface waters (MWLAP 2003, McPherson 2004), and that is the common situation in almost all lakes in Canada and elsewhere. The other trace nutrients (carbon, potassium, magnesium, calcium, etc.) are almost always in sufficient supply, so that they do not affect growth.

We might illustrate the principle of limiting nutrients by an analogy with vitamins and human health. Let us say that a child had excellent nutrition with excess intakes of proteins, carbohydrates, fats, minerals, and all the vitamins except D. That child might have severe bone-growth problems, because vitamin D was the limiting substance in the diet. The situation is similar with algal growth in lakes. It does not matter how much excess nitrogen and other minerals are present, it is the available supply of phosphorus which limits the production of new algal cells.

(An exception to this can take place when nitrogen is the limiting nutrient in a lake. That might occur in a lake which is strongly enriched with phosphorus, so that the normal amounts of nitrogen become limiting. In such a case, certain cyanobacteria (blue-green algae) have the unusual ability to practise nitrogen-fixing, converting gaseous nitrogen (N_2) which is dissolved in the water, into other molecules such as nitrates, which can be used as a nutrient. The cyanobacteria might bloom strongly, using up the available phosphorus so that normal green algae could form blooms.)

Available sets of measurements

The major source of data on total phosphorus in Cusheon Lake is a tabulation by the Ministry of Water, Land and Air Protection (previously, Ministry of Environment and Parks, now Ministry of Environment). The data are summarized in a recent report (McPherson 2004), derived from a spreadsheet of all measurements on the lake (MWLAP 2003). That spreadsheet was provided by Deborah Epps of the Ministry's office in Nanaimo, and was used to establish historical conditions for the present report. The data-set contains 277 measurements of phosphorus dating from 1974 to 2003. The spreadsheets were updated to 2006 by a personal communication from Ms. Epps.

The MWLAP tabulation includes samples taken by the Cusheon Lake Stewardship Committee in recent years, which were analyzed by the ministry. Several series of measurements by Dr. R. Nordin and colleagues at the University of Victoria are also included.

The well-known summary by Holms (1999) is based on the same MWLAP data-set, but covers only the earlier part of the time-period. Holms reports averages of 62 phosphorus measurements from 1974 to 1995, and individual values at spring overturn from 1996 to 1999. No separate consideration is necessary for the data reported by Holms, since they are all included in the recent spreadsheet of MWLAP.

In addition there are 30 measurements of total phosphorus provided by Reimer (2003) for surface samples during the growing seasons of 1996 to 2001.

Selection of comparable information

A great diversity of approaches can be seen in the MWLAP data-set. Over three decades, various investigators sampled at diverse depths and seasonal times A selection was necessary, to obtain values that were comparable and meaningful over the years.

Two kinds of historic measurements can be considered compatible with each other and comparable within their own series, and are used in this report:
(a) average concentration in the lake at the time of spring overturn; and
(b) average concentration in surface water during the year (almost all values were in the growing season).

All available data were used to compile the two sets of averages shown in Table A1. Both sets of averages are useful, and were shown to be not significantly different from each other. A t-test comparing the averages, year by year, showed no significant difference in the two sets of data. There was an 80% probability of getting similar differences by chance alone (data from t-test: t = -0.268459, degrees of freedom = 18, P = 80%).

The set of phosphorus measurements at spring overturn is usually considered the best appraisal of a lake. The water is of similar temperature and density from surface to bottom, and so waters are mixed in the entire lake. Therefore, similar phosphorus concentrations can be expected at any depth. In this report, all measurements at the time of spring overturn in a given year were averaged to yield a single value for the year. Spring overturn is not a sudden event in the lakes of coastal British Columbia, because of the mild winters. Therefore, any measurement in February, March, or April was included in the overturn average.

The second set of historic phosphorus measurements was based on all the surface-water concentrations available for a given year. This set is somewhat flawed by irregular sampling over the years. However, it still provides useful information, especially when considered along with the overturn series. Surface values were defined as any measurement down to 3.1 m of depth, representing the upper layer *(epilimnion)*. That layer mixes within itself during the warm season, and remains isolated from the deeper waters (see section 6).

Assessing surface waters is an approach which follows a recommendation of the B.C. government (Nordin 2001). The recommendation for assessing such a rapidly flushing lake is to measure phosphorus in the epilimnion during the growing season. Most of the available surface measurements in Cusheon Lake (80% of them) were for the warm season, and in fact, most of the year can be a growing season in low-altitude lakes of coastal B.C.

An approach which was *not* used, was to determine the average concentration of all depths of water in the lake throughout a year. In late summer, deep-water samples would have high concentrations of phosphorus because of release from the sediments. A deceptively high average concentration would be produced by averaging in those high values in deep waters. The average would fail to take into account the relative amounts of water represented by the various sampling-depths. The deep sample would actually represent a small volume of water in a deep hole of the lake, while the surface sample would represent a very large volume of water. Weighting the average for volumes of water would be a time-consuming exercise in number-crunching, made more difficult by irregularities of depth-series. This was not attempted, and surface (epilimnetic) sampling was used instead, as recommended by the ministry. Samples from depths greater than 3.1 metres were not used in the all-seasons analysis.

The data for these analyses are shown in Table A1 on the next page.

Table A1. Yearly average values of total phosphorus in Cusheon Lake. Springtime data are for samples during spring mixing (February to April) at any depth. The all-season data are for surface values at any season including springtime (surface = zero to 3.1 metres depth). No. of measurements includes all separate measurements; those on the same day would be averaged to yield a daily value. The daily values were averaged to yield the yearly average. Gaps indicate absence of data for that time. Data are from MWLAP (2003), Reimer (2003) and Epps (2006).

Year	Springtime			All-seasons		
	Average, ppb	No. of measure-ments	No. of days	Average, ppb	No. of measure-ments	No. of days
1974				29.00	7	5
1975	11.75	4	1	11.00	4	2
1976	13.17	6	2	17.20	10	5
1980	16.67	9	3	21.50	24	13
1987	9.50	2	1	10.00	1	1
				8.50	2	1
1990	13.67	3	1	15.00	2	1
1992	14.00	3	1	14.00	2	1
1993	18.00	2	1	15.00	1	1
1994	3.00	2	1	3.00	1	1
1995	6.50	2	1	5.00	1	1
				20.00	1	1
1997	19.33	3	1	18.00	2	2
1998	16.00	1	1	16.00	1	1
1999	19.00	5	1	23.58	11	6
2000	22.67	5	1	18.33	8	4
2001	18.00	2	1	16.81	15	8
2002	11.00	2	1	21.50	2	2
2003	13.00	2	1	10.50	2	2
2004	15.00	2	1	13.77	3	3
2005	14.50	2	1	8.33	3	3
2006	19.00	2	1	15.00	1	1

APPENDIX B. ESTIMATING WATER FLOWS IN THE CUSHEON BASIN.

One of the questions on water flows was how much water was being taken from the Cusheon lakes for irrigation and domestic use. There is good information on the licences granted for taking water (Barnett et al. 1993), and updated values are available on-line from the provincial government. A tabulation of licensed uses is provided in the management plan (CWMPSC 2007). However, the licensed amounts do not necessarily correspond to the amounts actually used. In most cases, these actual amounts cannot be determined, since there is no measurement by water-meter or other means. Best estimates were made, following the methods outlined below. The results of calculation are shown in Table 4 in the main text.

Withdrawals for irrigation

It was assumed that the amounts licensed were actually used for irrigation. The amounts are not checked by the government. In some cases, the licensed amounts might not be fully used, or alternatively the actual use might be greater than licensed (personal communication, Chris Morgan, Water Management Branch, Victoria).

Withdrawals by the Beddis waterworks

This is the one case where there is an exact tabulation of water use. The actual amount pumped in 2003 was 33,500 m^3, and that amount was used in this report.

Withdrawals for individual households

The licensed amount for an individual household is usually 2,273 litres/day (2.273 m^3, derived from 500 imperial gallons). It is unlikely that a household would use so much water, so the probable amount per licence has been estimated in the manner described below.

The North Salt Spring Water District estimates for the year 2002, that the average amount used per family (i.e. household) was 263.81 m^3/year, which is 722 litres/day (0.722 m^3/day). Because the North Salt Spring district has by far the largest number of customers of any water district on Salt Spring Island, its number has been adopted as the probable use by an individual household licensed in the Cusheon basin.

The estimate seems reasonable. The average water use for household purposes by a Canadian is 343 L/day (Brandes and Ferguson 2003). The average number of people per dwelling on Salt Spring Island is 2.2 (Statistics Canada, 2001 census for the island, with 9381 people in 4250 private dwellings). From that, 2.2 x 343 = 755 L/day, very close to the North Salt Spring number being used. Also in agreement is the amount pumped in 2003 by the Beddis Water District. The District pumped 33,550 m^3/year for 122 households. That represents 753 L/day for each household, almost exactly the same as the Canadian average and very similar to the 722 L/d based on North Salt Spring.

Some household licences are for special larger amounts, as are some licences for "enterprises" such as resorts or trailer courts. It was easy to detect these, since the licences were in steps of 500 gallons. The equivalent number of household units was used to multiply the standard value of 722 litres/day.

Some households draw water from Cusheon Lake, but do not have a licence to do so. Local knowledge indicated that there might be 20 such households, and they have been included in calculations at the standard household rate.

Withdrawals from springs

There are licences for use of water from six springs. Three are for the usual household amount (722 litres was credited to them), two are for double that amount, and one is for nine times that amount. It is assumed that these withdrawals are active for household purposes, so the standard number has been assigned, appropriately scaled up for the larger licences. The location of the springs was not evident, so calculations assumed that they were all tributary to Roberts Lake.

Groundwater

Aside from groundwater reaching the surface as springs at the head of creeks, mentioned above, there might be groundwater entering or leaving the lakes. If there is such import or export, it was necessary to ignore it in this analysis, for lack of information. Probably, any such movements are not large. For example, Nordin et al. (1983) estimated that groundwater input was less than 5% of the total supply to St. Mary Lake. Since the total supply for that lake is itself small, 5% of it would indeed be a small amount.

APPENDIX C. MODELLING PHOSPHORUS DYNAMICS IN THE TWO UPPER LAKES.

General strategy

In a nutshell, the strategy is (1) to estimate the phosphorus runoff from the land by modelling the upper lakes, (2) to apply that estimated land runoff factor in a model for Cusheon, the lower lake, and (3) add into the model, estimates of the direct human input to Cusheon Lake, using standard factors or known values. The whole strategy assumes that land runoff in the upper and lower parts of the basin is reasonably similar, an assumption that is probably approximately correct, judged by walking the land, and by land use classifications (see map of *Landscape classifications* in the management plan, CWMPSC 2007).

As stated in section 3, each of the upper lakes in the Cusheon watershed can be used to estimate the runoff of phosphorus from the land. Roberts and Blackburn Lakes do not have seepage fields for septic systems on their shores, nor do they have other apparent direct human inputs. The average of the two estimates of phosphorus runoff was used as an estimate of the phosphorus runoff from the land to Cusheon Lake.

The land runoff to the upper lakes will not be the "natural" amounts since parts of the land have been modified by tree harvesting, some agriculture, a low-impact organic golf course, housing, a school and conference centre, and garbage transfer station. However, these operations are distributed in various parts of the watershed (see map in the management plan), so it seems reasonable that the values for sub-basin runoff of phosphorus should be similar.

The Ontario "cottage-country" factors for land runoff of phosphorus

Logical starting-points in choosing trial values for phosphorus runoff are the factors used in the Ontario model for lake enrichment. The procedural handbook (Dillon et al. 1986) first divides drainage areas into *igneous* and *sedimentary*. Clearly the sedimentary factor fits the Cusheon basin. The rock underlying the Cusheon watershed is sedimentary (Hodge 1995). Above that there is appreciable deposit of soil in the basin, for example the area upstream from Blackburn Lake has soil up to 30 m deep (Hodge 1995).

For sedimentary regions, the cottage-country model gives a choice of two factors for phosphorus runoff. The lower value is for *forest*, about 0.10 kg of P per hectare of land, per year. The higher value is for *forest and pasture* (0.20 kg P /hectare • yr).

Ontario's igneous category is intended for the areas of granitic rock around Georgian Bay and Muskoka, which have thin layers of soil, described as "unproductive primitive rock with oligotrophic soils" (Dillon et al. 1986).

For Salt Spring Island, there is little information on values for runoff of phosphorus from the land. Data collected for the two northerly creeks feeding St. Mary Lake can be used to estimate a runoff of 0.16 kg P /hectare • yr (Nordin et al. 1983).[6] Those creeks drain a section of land that has been largely deforested and left open or used for farming. That value near St. Mary Lake is intermediate between the choices offered in the Dillon-Rigler-Hutchinson procedures. Notably, it is lower than the 0.20 kg for similar deforested land in the Ontario model; perhaps the Salt Spring soil does not contribute so much phosphorus to runoff. An independent survey in the upper Cusheon basin (Sprague 2007b) estimated that runoff would be 0.106 kg P /hectare • yr in a typical year, however the estimate was an approximate one.

Modelling Roberts Lake

There is no documentation of the extent of algal blooms in Roberts Lake. Indeed this lake appears to have been virtually ignored by scientific investigators. The only useful measurements of phosphorus concentrations were those done in this study, since two earlier ones were considered invalid. Judging by the phosphorus found in this study, the algal situation in Roberts Lake would be similar to those in the lower lakes.

Land runoff. Most of the sub-basin which drains into Roberts Lake is classified as *Young Forest* by planners of the Island Trust, as shown by a map in the management plan (CWMPSC 2007). There is some *Old Growth* forest. There is at least one cultivated field near the lake, and some pastures and field upstream.

From this, it would seem that the cottage-country category *forest and pasture* would best fit the Roberts sub-basin, and its value of 0.20 kg P / hectare • yr was adopted for the initial run of the model.

Other variables. The size of the lake (3.44 hectares) and sub-basin including the lake (134.7 hectares) are reported in Table 3. The water runoff is estimated as about 660,000 m^3 per year in Table 4.

Rainfall and other forms of direct input from the sky make a contribution of nutrients to lakes. A value of 0.11 kg of phosphorus per hectare of lake surface, every year, was estimated from the scanty available data (see section 6.4).

The hypolimnion of Roberts Lake is assumed to be anaerobic, like the lower two lakes which have similar degrees of enrichment. Accordingly, when deep water is isolated for the summer, some phosphorus should emerge from the bottom sediments and enter the water. The Dillon-Rigler-Hutchinson model used in this report makes an allowance for the reappearance of this sediment phosphorus.

[6] There is some uncertainty about the calculation of 0.16 kg. For one of the creeks entering St. Mary Lake, the authors report runoff values for phosphorus which are about twice as high as the value which can be calculated from their basic data.

Direct human activity is low for Roberts Lake. Although there are water-use licences equivalent to 16 households issued for the basin, they are not close to the lake and so the households would contribute little or no phosphorus to the lake, from septic fields. Two houses appear to be within 300 m of the lake shore, but further than 200 m away, so standard input for septic fields is included, but reduced by two-thirds because of the distance (Hutchinson 2002). This might be over-estimating the contribution from these two houses, but the allowance has been made as follows:

- 2 households
- 2.2 people each (Statistics Canada census in 2001 for Salt Spring Island)
- 0.6 kg of phosphorus in human waste from one person (Hutchinson 2002)
- 74% retention of P in the septic field, for normal operation in a typical soil (Hutchinson 2002).
- houses more than 200 m away from lake, and therefore estimated input is reduced by two-thirds (Hutchinson 2002). (From 100 to 200 m away would call for a reduction of one-third.)

Initial model, for "forest and pasture"

This was the first trial of input level, and it proved to be far too high. However the steps are explained below, since this is the procedure used in this report for all the runs of the Dillon-Rigler-Hutchinson model.

Table C1. Enrichment calculations for Roberts Lake with a "forest/pasture" basin.
Calculations use the Dillon-Rigler-Hutchinson "cottage-country" model (Dillon 1986).

V = Volume of lake =		140,000	cubic metres
Q = outlet discharge per year =		520,372	cubic metres
Ao = area of lake = 3.4 hectares =		34,400	square metres
Ad = area of watershed including lake =	119.9 hectares =	1,199,000	square metres
Ad2 = area of watershed without lake =	16.5 hectares =	1,164,600	square metres
r = runoff = Q / Ad =	520,372 / 1,199,000 =	0.43401	metres / year
qs = areal water load on lake = Q / Ao =	520,372 / 34,400 =	15.127	metres / year
Tw = turnover time = V / Q =	140,000 / 520,372 =	0.2690	years
Rp = retention coefficient of P in lake =	7.2 / (7.2 + qs) =	0.32248	
JA = input of P by direct human activity =	2 x 2.2 x 0.6 x 0.26 x 0.33 kg =	0.227	kg / year
JN = input of P from sub-basin land =	116.5 x 0.20 kg =	23.3	kg / year
JPr = input of P from precipitation to lake surface =	3.44 x 0.11 kg =	0.378	kg / year
	Total input =	**23.90**	**kg / year**
Loading = (JA + JN + JPr) / Ao =	(Total input) / 34400 =	0.6947	$gm / m^2 . yr$

Predicted P concentration, in ice-free season

= [Loading (1 - Rp)] / [0.956 * qs] = $\frac{[(0.6947) \times (1- 0.32248)]}{[0.956 * 15.127]}$ = 0.032546 gm / m^3

= 32.5 ppb, rounded off.

The steps of the initial calculation in Table C1 are those set out in the Ontario model (Dillon et al. 1986). The steps shown are largely self-explanatory, but some features might be mentioned. Fixed physical characteristics include: *V* and *Ao*, the volume and surface area of the lake; *Q*, its discharge of water; and *Ad*, the area of the sub-watershed feeding Roberts Lake. From those variables, other physical items are calculated: *r*, the runoff from the drainage sub-basin; *qs*, the areal water load (the height that inflowing water would reach if it could not exit the lake, but stacked up on the surface); and *Tw*, the poorly-named "turnover time" (the time required, at average inflow, to fill the lake if it were empty).

The flow of phosphorus through the lake is then modelled from those fixed variables. The *retention coefficient (Rp)*, is the proportion of phosphorus entering the lake which stays in the lake, through deposit in the sediment or other sinks which bind it up. The estimate of this item is based on constants derived in Ontario, and it is not known whether it is totally appropriate for Pacific coastal lakes. The constant used in the calculation (7.2) is for a lake that becomes anoxic in the deep waters during summer. (For lakes which stay aerobic in the bottom waters, the constant would be 12.4, in other words more phosphorus would be retained.)

The inputs are estimated in four lines near the bottom of Table D1. The direct input from septic fields *(JA)*, is very small as discussed above. Yearly drainage from the land *(JN)* uses the runoff factor 0.20 kg of phosphorus (P) multiplied by the area of the sub-basin in hectares. The *input from precipitation (JPr)* was mentioned above and depends on the surface area of the lake.

The *total input* (towards the bottom of the table) is estimated as 23.9 kg of phosphorus per year. That is recalculated as the *loading* per square metre of lake surface. The *predicted P concentration* is estimated by the formula supplied in Dillon et al. (1986). It can be seen that the predicted concentration would rise as the retention coefficient *(Rp)* became smaller, and as the *areal water load (qs)* became smaller, in other words as less water flowed through the lake.

Conclusion. For the assumed runoff, this calculation predicts that the average concentration of phosphorus in the lake would be 32.5 ppb. This is far higher than the observed average concentration of 16.5 ppb and is much too high to be accepted. By far the biggest input of P is from land runoff, so it is concluded that the factor of 0.20 kg P/hectare • yr for "forest and pasture" is too high for this sub-basin. This runoff value is rejected for the Cusheon basin.

Model based on "forest" runoff

The cottage-country factor for sedimentary areas that are in their natural forested state is 0.10 kg P/hectare • yr. This was used in a run of the model, exactly parallel to the run shown in Table C1. The estimated input to Roberts Lake would be 12.25 kg/year and the predicted average concentration would be 16.7 ppb. That is only slightly higher than the observed concentration in the lake, so the “forest” runoff factor appears to be very close to the actual runoff in this basin.

Empirical value for phosphorus runoff

The model was run on a trial-and-error basis, with various values for phosphorus runoff which were slightly less than 0.10 kg/hectare • yr, until one predicted a concentration of 16.54 ppb of phosphorus in the lake. The appropriate runoff value turned out to be 0.09909 kg and the rounded value of 0.099 was accepted for the sub-basin.

Modelling Blackburn Lake

Direct human input. There appear to be only two households within about 200 m of the lake, but further away than 100 m. A standard performance of their septic fields has been assumed, with 74% retention of P in the fields, and one-third reduction for distance, in similar fashion to the calculation used for Roberts Lake (following Hutchinson 2002).

Upstream lake. In the calculations for Roberts Lake, it had not been necessary to include this item. The outflow of phosphorus from Roberts is added to the input for Blackburn Lake. The calculation uses the "retention coefficient" that was calculated for Roberts (Table C1). The coefficient estimates what proportion of phosphorus is retained in Roberts (32% of the input), while the rest of it is carried by the flowing water down to Blackburn. This is allowed for in calculations (Table 6, 100% minus 32%).

Phosphorus recycling. The hypolimnion of Blackburn Lake is not large because the lake is relatively shallow, and hypolimnion volume decreases during the summer and disappears in August (McKean 1981). The volume shrinks from 26% of the total lake volume to zero (from 35,000 m^3 to zero). McKean (1981) also concluded that the phosphorus concentration in the hypolimnion increased from 21 ppb to 101 ppb, a rise of 80 ppb from the whole-lake mixed concentration present in May.

These observations of McKean (1981) allow an approximate estimate of the contribution of recycled phosphorus from the sediments, ready for mixing into the whole lake at the time of autumn overturn. We might assume an average volume of 18,000 m^3 (half-way between the initial and final volumes of hypolimnion) and an increase of 80 ppb. That calculates out to a loading of 1.44 kg of phosphorus recycled into the lake. This value is not used in the model, since the model estimates its own value of regenerate phosphorus.

Results of the model

The modelling for Blackburn Lake started in the same way as described above for Roberts Lake. The standard values for land runoff from the research in Ontario were tried first, and predictions were compared with the observed lake concentration of 16.3 ppb. The values in the model were those seen in Table 6 of the main text, except for the different land inputs and different predictions.

A "forest and pasture" runoff value of 0.20 kg P/hectare • yr resulted in a prediction of 36.8 ppb of P in the lake which is more than double the observed average. A "forest" runoff value of 0.10 kg predicted an average phosphorus concentration of 19.9 ppb in the lake, somewhat higher than the observed average. By trying various lower values for phosphorus runoff, it was determined that a runoff value of 0.07876 kg predicted the observed average concentration of 16.33 ppb in the lake. This runoff value was accepted (see Table 6 in the main text).

APPENDIX D. ESTIMATING THE CONTRIBUTION OF RECYCLED PHOSPHORUS FROM THE BOTTOM SEDIMENTS OF CUSHEON LAKE.

Available data

Table 7 in the main text shows year-to-year variation, but some patterns are evident. Phosphorus became elevated in the deep water as early as June. The deep water became elevated , compared to surface values and also compared to starting-points of 15 to 20 ppb (the whole-lake concentrations at the time the hypolimnion was sealed off, in various years).

By August of some years, concentrations in the deep water were astonishingly high, and the single set of measurements in October was also extremely high.

Data in Table 7 show a gradual increase of phosphorus concentrations in the deep water, during the warm season. The trend can be seen by comparing values in June with those in August, and those in turn with September and October.

The data are too sketchy to make a definite conclusion on whether deep–water concentrations became higher as decades passed. Over the years, people conducting the surveys chose different sampling depths and different seasonal schedules, or no seasonal program as indicated by blank blocks in Table 7.

There is a potential difficulty in interpreting the values shown in Table 7. For the deepest samples, it is possible that the sampling device touched the sediment, and stirred it up so that some sediment was included with the collected water. Solids could have caused misleading high concentrations of phosphorus. Results for October 1980 are a possible example. The deepest value given in Table 7 is actually the average of measurements for the two depths 7.2 and 7.4 m. The original deep-water measurements of phosphorus and nitrogen are given in the following text-table.

Depth, metres	Total phosphorus, ppb	Total nitrogen, ppb
6	40	470
7	368	1,150
7.2	784	14,000
7.4	725	15,600

We would expect a graded increase in concentration as samples approached the sediment, but the values in the text-table are a little surprising. In the 20-cm change in depth from 7 to 7.2 m, the phosphorus doubled, then in the next 20-cm step it stayed about the same, in fact showing a slight decrease.

Similarly, for nitrogen, the 12-fold jump from 7 to 7.2 m is unexpectedly large, but there was little change from 7.2 to 7.4 m. It seems likely that there was sediment involved with samples at the two lower depths.[7]

Therefore, it would be prudent to interpret with caution, the deep-water concentrations of phosphorus.

Estimate of phosphorus load from sediment

The data of Table 7 can be used to estimate the *mass* of phosphorus (in kg) that is released from the sediments each year. This old, recycled phosphorus acts as if it were part of the new load of phosphorus entering the waters of the lake in any given year. The dissolved phosphorus that was regenerated from sediments during the summer would enter the mixed waters of the lake during the autumn overturn. For the algae involved in a spring-time bloom, the recycled phosphorus would be indistinguishable from new phosphorus that came in during the winter as external input from a creek.

In making the estimate of regenerated phosphorus, judgemental interpretation was required to make the best use of the irregular data, and to avoid anomalous values. Some of the assumptions might seem arbitrary when baldly stated, but were adopted after careful inspection of the data, and in light of general limnological knowledge. The assumptions allow an approximation that is useful in this initial evaluation of Cusheon Lake enrichment. The following procedures were adopted.

- The final estimate of load was based on data from 2001, representing recent conditions. Other series were at least two decades earlier (but they provided data for earlier stages of analysis.)

- The top of the hypolimnion was taken as 6 m depth. If there was no measurement of phosphorus at 6 m., a value of 47 ppb was assigned, as derived from all data in the file of MWLAP (2003).

- For a given date, the deepest sample of 8 m depth or more, was taken to represent water close to the mud-water interface. If there were data below 6 m, but not as deep as 8 m, the results for that date were extrapolated to a presumed concentration at 8 m. That was assumed to represent water near the sediment in the deepest part of the lake. Samples on all dates were then assumed to be equally close to the bottom (see the explanatory footnote no. 7).

- If sampling stopped before the end of a given summer, an extrapolation was made to the probable deep-water concentration of phosphorus at the end of the first week in October, which was assumed to be just before the autumn overturn.

---

[7] Some explanation of the usual sampling procedures might be given. The maximum depth of Cusheon Lake is taken as 9.1 m, in the western arm of the lake. Investigators sampling a depth profile would normally attempt to work at this deepest point, but they might not be able to locate it exactly. On different dates they would get different maximum depths, which probably explains the diversity of maximum depths shown in Table 7.

The irregularity of depths is not as great a difficulty as it might seem, for interpreting phosphorus concentrations. There would be a similarity of chemical conditions for similar distances above the bottom, whether the bottom at a given point was at 9 m or 7 m. The chemical conditions would represent a gradation from the mud-water interface upwards into the water. Investigators would usually attempt to get close to the bottom for the deepest sample, something of the order of half a metre, without stirring up the sediment. Thus they would be sampling a similar section of the gradation above the mud. Then they would complete a series, higher in the water column. Accordingly, it is considered appropriate to compare, with caution, deep-water samples on different dates, even though the maximum depths are not identical.

The preceding techniques were applied for each year which provided sufficient data. Although only one recent year is reported below, analysing every suitable year aided in verifying dependable techniques. Analysis of the *amount* of phosphorus regenerated (i.e. the *mass)* then proceeded as outlined below.

A ***stratified average concentration of phosphorus in all the water of the hypolimnion*** was then made for early October of 2001. Figure D1 is a schematic of the model and the numbers used in calculations.

- Each calculation was based on hypothetical 10-cm horizontal "slices" of water from 6 m depth, down to the deepest part of the lake, 9 m. Thus, the average made use of 30 slices down through the 3 m from top to bottom of the hypolimnion.

- The stratified average was calculated by assuming a steady increase in concentration from that found at 6 m (assigned 47 ppb) to that found at the deep sample (extrapolated value 1,050 ppb).

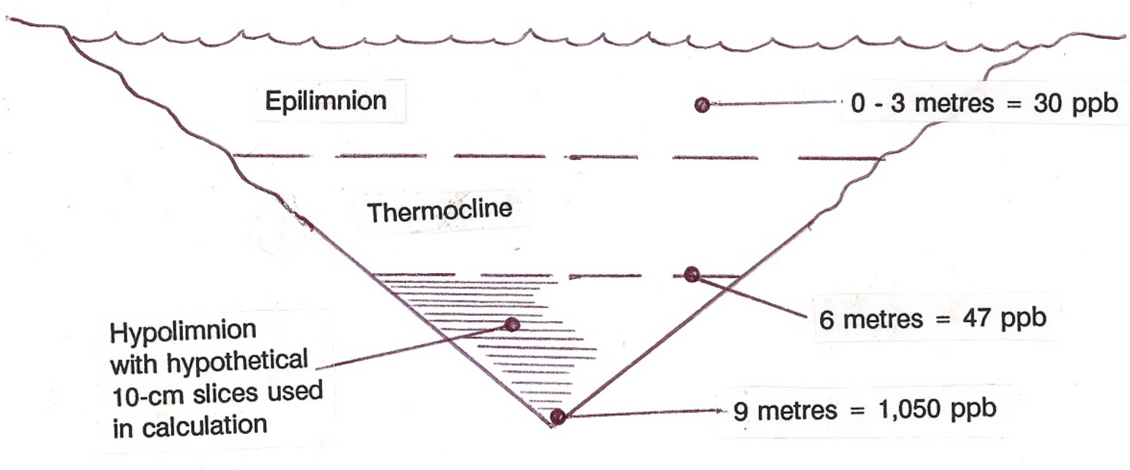


Figure D1. A diagram of the approach for calculating the load of phosphorus regenerated from the sediments of Cusheon Lake, in October 2001. Concentrations of total phosphorus (ppb) at the top and bottom of the hypolimnion are derived values, not measurements at the time.

- The volume of water in each slice was estimated by assuming that the hypolimnion of the lake had the shape of an inverted pyramid. The surface area of the top slice at 6 m was known (Goddard 1976), and hence the length of its hypothetical side. The sides of the successively deeper slices would decrease steadily in length, reaching zero at the deep apex of the inverted pyramid. Calculating the volumes of slices was then straightforward arithmetic. In practice, results from such a standardized shape correspond reasonably with results for less regular shapes in real lakes.

- With an average phosphorus concentration for each slice, and the volume of water in the slice, the mass of phosphorus for that slice could be calculated. A summation of masses from all the slices provided an estimate of the total amount of phosphorus mixed into the lake from the hypolimnion.

- For each slice, the hypolimnetic concentration was corrected for the normal concentration in lake water, thus it was the "excess" that represented the loading regenerated from the sediment. A phosphorus concentration of 24 ppb in the mixed lake water at the time of spring overturn was derived for 2001 from the data-file of MWLAP (2003), and was used for this correction.[8]

By the methods above, a **loading of 25 kg per year** was estimated for the lake from the phosphorus regenerated from bottom sediment (25.46 before rounding).

This estimation procedure involved best judgement, as stated. However the steps appeared reasonable and the pattern of data was fairly consistent when adjustments were applied. In fact, the model seemed to be robust. Several alternative but less-favoured procedures were explored and the final estimates of loading were similar to that given here, i.e., the estimate seemed to be approximately correct. Nor was the estimate greatly changed if alternative values were taken for phosphorus concentration at the top and/or bottom of the hypolimnion. A hand-written record of the steps in the calculations is available upon request.

Historic regeneration

Only about 7 kg of phosphorus regeneration occurred in 1974 and 1975, according to estimates made in the manner described above. These earlier estimates are not used here, but loading from the sediment appears to have become more important over the years. This adds a note of urgency to remedial action for the lake. If regenerated phosphorus becomes greater, it could keep the lake enriched no matter what improvements were made in surface inputs. This is somewhat parallel to the efforts in the 1960s and 1970s to "save" Lake Erie from severe eutrophication. Bottom deoxygenation and regeneration of phosphorus were increasing. The situation almost reached the point where the strictest controls and remedies for land-based input of nutrients would not have saved Lake Erie; regeneration alone would have kept the lake green.

It seems possible that before European settlers arrived in the basin, Cusheon Lake retained some oxygen in the deep waters, with much less regeneration of phosphorus taking place.

Additional comments on stratification and oxygen levels

The summer-time stratification of Cusheon Lake was described above. Most lakes in other parts of Canada would have a more complicated annual cycle. They would show winter stratification, which is quite different from conditions shown in Figure 3. A cold winter on Salt Spring could produce such stratification. If surface waters were cooled to freezing or near-freezing, that cold water would float on top because of its lower density. Water with maximum density (at 4°) would lie underneath, down to the bottom. Accordingly, ice forms on the surface of Canadian lakes -- a phenomenon that is well-regarded by generations of skaters. Deoxygenation of bottom waters is usually not as severe in winter as in summer.

Section 6.1 and Figure 3 showed that dissolved oxygen concentrations during springtime mixing were about 10 ppm throughout the lake. That is somewhat depressed from about 13 ppm that would prevail for saturation. That suggests some enrichment of waters with some decomposition taking place.

---

[8] For example, of the 1,050 ppb of phosphorus in water at the bottom of the lake, 24 ppb had been there when the lake first stratified at the end of the springtime mixing. The remainder, 1,050 - 24 = 1,026 ppb, was apparently derived from the sediment and was used in calculations for the bottom slice of hypolimnion. This correction made little difference to the estimate of loading, nor did other refinements of calculation.

Metabolic activities of algae can cause wild gyrations of the oxygen levels in surface waters. A clean oligotrophic lake retains a high oxygen concentration because of contact with the air. However, if a lake has an algal bloom, there would be deoxygenation of the surface layer at night because of respiration by the algae. During daylight hours, photosynthetic activity of the algal bloom would usually outstrip the respiratory activity, and could create oxygen *supersaturation* (oxygen would temporarily exceed its maximum solubility). Such variation occurs in the surface waters of Cusheon Lake when algae are present. For this reason, it is not very useful to make a single measurement of oxygen concentration in surface waters during the growing season. The morning, afternoon, and night-time measurements could be very different.

APPENDIX E. PHOSPHORUS IN PRECIPITATION

It is desirable to know the P content of rain and snowfall falling directly onto the surface of a lake. The information is needed elsewhere in this report, to model the inputs to Roberts Lake. There are only a few measurements of P in precipitation for this part of the Pacific coastal region.

One excellent study measured nutrients in the rain and air near Chilliwack B.C. (Vingarzan et al. 2003). The study found an average of 7.2 μg/L of P in precipitation during the year. For the average amount of precipitation in the Cusheon watershed (0.98 m), that provides an **estimate of 0.071 kg/year** of phosphorus onto each hectare of lake and land surface.

The senior author of the report, Dr. R. Vingarzan (2006), kindly searched for other published information. No other recent studies were found for coastal British Columbia. Her opinion on relevance of the Chilliwack value was that coastal precipitation would not have more phosphorus, but it was uncertain whether there would be less. The estimate from Chilliwack has been taken as a very useful value.

Unpublished information from a state-of-the-art rain gauge at the Sooke reservoir near Victoria was provided by Dr. Richard Nordin of the water research group at University of Victoria. The total P in precipitation during 14 months was 0.136 kg/hectare • yr (Nordin 2006). Adjusting downwards to the Cusheon rainfall from the high amount of 1.659 m at Sooke Lake (Environment Canada 2006) yields another useful **estimate of 0.065 kg/ha of P in 12 months** for the Cusheon watershed.

In older work, an area north of Vancouver had 0.40 kg/ha • yr of dissolved and particulate P in its very heavy precipitation of 4.50 m/yr (Zeman and Slaymaker (1978). Adjusting downwards to the Cusheon precipitation yields an **estimate of 0.087 kg/ha • yr**.

Another older report for a coastal area of Washington state reports 0.13 kg/ha • yr of dissolved P in precipitation of 0.90 m (Ellsworth and Moodie 1964). Adjusting that slightly upwards for the precipitation at Cusheon provides an estimate of 0.142 kg/ha • yr. However, Gilliom (1980) concludes that the dissolved P would only be 60% of the total P in the samples of Ellsworth and Moodie, so the **estimate becomes 0.24 kg/ha • yr** of total phosphorus. The value seems high but there is no apparent reason to exclude it from consideration.

The four estimates have been averaged to provide a value of 0.1147 kg/ha • yr (rounded to 0.11 kg/ha • yr) for P in the precipitation in the Cusheon basin, and that is used in modelling for this report.

APPENDIX F. CONVERSION FACTORS

Imperial gallons to litres or cubic metres:	• gallons x 4.5461	=	litres (L)
	• 1,000 litres	=	1 cubic metre (m^3)
Acres to hectares:	• acres x 0.40469	=	hectares (ha)
	• 10,000 m^2	=	1 hectare (100 m x 100 m, the size of two football fields)
	• 100 hectares	=	1 square kilometre (km^2)
Feet to metres:	• feet x 0.30480	=	metres (m)
Acre-feet to cubic metres:	• acre-feet x 1233.5	=	m^3
Grams per square metre:	• 1 gm/ m^3 (Used in Figure 4, the Vollenweider graph)	=	10 kg / ha

If calculations involve data in different systems of measurement, it is easiest to convert the old units to metric ones immediately. Calculations are then simpler because they are usually based on ten and sometimes involve only the moving of a decimal point.