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The Relative Effects ofMajor Sources of Phosphorus Loading on Phosphorus Concentration in Cook's Bay of Lake Simcoe

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by

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Introduction

Lake Simcoe is an extremely valuable natural resource, generating many millions of dollars annually in revenue to local economies from tourism and recreational activities (LSEMS 1995). Ironically, the very features that attract so many people to the lake (good fishing, swimming and boating opportunities) may be threatened by continuing population growth in south-central Ontario and increasing demands for multiple use of the lake. Continuing inputs of phosphorus and other plant nutrients to the lake from urban wastewater treatment facilities, urban and agricultural runoff and other sources have increased approximately 3-fold since Europeans settled in the Lake Simcoe basin in the late 1700s, and late summer bottom water dissolved oxygen in the lake has declined from about 8 mg/L to about 3 mg/L (Johnson and Nicholls 1989; Nicho'1s 1997). Despite the near tripling of human population in the Lake Simcoe basin in the past 30 yea~s, there is no clear evidence for a recent worsening ofwater quality (Nicholls 2001), likely because of phosphorus removal at municipal wastewater treatment facilities and other remedial activities targeting specific sources of phosphorus loading in the basin in recent years (LSEMS 1995).

Phosphorus export from all known sources in the Lake Simcoe basin (except shoreline cottages) was measured during the 19905 (Scott et al. 200 I). The major sources include atmospheric deposition, urban runoff (storm sewer discharges), streams and rivers draining agricultural lands, drainage water pumped from areas of intensive vegetable production, and municipal wastewater treatment facilities.

Since the publication of the Scott et al. (2001) findings, questions have arisen from certain public sectors and stakeholder groups about the relevance of the some of these sources with specific reference to Cook's Bay. Cook's Bay (Fig. 1) receives drainage from the largest river in the Lake Simcoe basin (the combined east and west branches of the Holland River). Although the treated sewage from the towns of Aurora and Newmarket have been directed to Lake Ontario through the major north-south York-Durham Trunk Sewer since 1984, the runoff from these two urban areas continues to flow northward to Cook's Bay via the East Holland River (LSRCA 2000). Other sources of phosphorus draining to the Holland River include drainage water pumped from the Holland Marsh and other dyked areas of organic soil used for vegetable production. Nicholls and MacCrimmon (1975) first identified very high concentrations of phosphorus in drainage waters from these areas 30 years ago - levels that were confirmed in later investigations by Peat and Walters (1994) and Scott et al. (2001). The lower Holland River demonstrated some improvements in water quality over the period 1982-1997 (Nicholls 1998), however the most recent data revealed levels were still well above the Provincial guidelines for streams and rivers (OMEE 1994).

The purpose of this brief report is to utilize a phosphorus mass balance approach to rank the known sources of phosphorus for their impact on phosphorus concentrations in Cook's Bay. The findings should help to prioritize efforts to control phosphorus loading to Lake Simcoe.

Methods

a) *mass balance approach*

The basic assumption in "Vollenweider-type" mass balance models that relate phosphorus loading rates to lake water phosphorus concentrations (OECD 1982) is that lakes behave as mixed reactors on an annual basis:

$$[TP]_{\lambda}=\frac{K*[TP]_{\delta}}{1+\sqrt{T_{(\omega)}}} \qquad (1)$$

where,

$[TP]_{\lambda}$ = average lake total P concentration ($g{\cdot}m^{-3}$); $[TP]_{\delta}$, the average inflow total P concentration ($g{\cdot}m^{-3}$), = the total P input (mass in g) / the total water outflow (volume in m^3); $T_{(\omega)}$ = the theoretical water residence time in years and K is a factor related to the phosphorus sedimentation rate.

The phosphorus sedimentation rate factor is incorporated directly as a retention coefficient in another form of this mass balance equation used by Dillon et al. (1994):

$$[TP]_{\lambda}=\frac{L_T(1-R_p)}{k*qs} \qquad (2)$$

where,

L_T is the annual per unit areal TP loading to the lake (mg P•m^{-2}•yr^{-1}), R_p is a TP retention coefficient (the difference between the annual TP input to the lake and the loss in the outflow as a fraction of the total input), qs is the areal water load (total annual outflow volume/lake area) and k is the fraction of the lake water TP concentration measured in the outflow.

[*NOTE: Kortman (1991) and Walker (1990) have provided semi-technical overviews of related phosphorus mass models, while Reckhow and Chapra (1999) and Cassell et al. (1998) provide more technical accounts of the history of development and specific applications of mass balance modelling for identification and management of lake pollution problems*].

There are may be difficulties in applying these models to embayments (like Cook's Bay of Lake Simcoe) where hydraulic transfers between the main lake and the bay are unmeasured or unpredictable, thus complicating the estimation of TP export from the bay to the lake and hence the phosphorus sedimentation rate in the bay cannot be obtained. In order isolate the phosphorus mass balance components of the bay from those of the whole lake, a different approach was used by Johnson and Nicholls (1989) whereby radio-isotope dating of Lake Simcoe sediment cores, combined with measurements of phosphorus concentration at regular and close intervals of depth in these cores, allowed direct estimates of phosphorus sedimentation rates for Cook's Bay and for the main lake. Because TP sedimentation rate is dependent on loading rate and hydraulic flushing rate, the estimates of TP sedimentation rate made by Johnson and Nicholls (1989) were updated by applying a correction factor derived from the most recent (1990s) data on hydrology and TP loads to Cook's Bay as follows: First, an assumption was made that any changes in TP sedimentation rate in Cook's Bay would be in proportion to those in the main lake over relatively short periods of time (i.e. 1-2 decades spanning the period of time between the data collection periods used in the Johnson and Nicholls and Scott et al. studies). For the late 1970s/early 1980s, Johnson and Nicholls method showed that the Cook's Bay sedimentation basin retained 26% of the total phosphorus retained by the whole lake. An updated (1990s) estimate of the whole lake phosphorus retention was calculated from the monthly export of phosphorus at the Atherley Narrows where water quality sampling was conducted approximately twice weekly, year round by the Ministry of the Environment (see fig. 3 in Nicholls 1998). The monthly mean phosphorus concentrations were applied to monthly flows generated by Scott et al. (2001) to produce annual estimates of phosphorus export from the lake. Next, for each hydrologic year (June-May), a whole-lake P retention (R_p) was calculated as (input-export)/input, where total input data were from Scott et al. (2001). R_p for Cook's Bay was calculated as 26 % of the whole-lake TP retention.

Nicholls (1995, 1997) used both equations (1) and (2), above, to generate a predicted whole-lake phosphorus loading reduction required to achieve a target phosphorus concentrations (previously set to achieve an end-of-summer bottom water dissolved oxygen target). In that work, k (per equation (2), above) = 0.87 for the whole lake. Here, because there is no well-defined Cook's Bay "outflow" in the traditional mass balance sense, and because Cook's Bay phosphorus concentrations were determined directly from the volume-weighting of the sector data (see below) and Cook's Bay "outflow" data were not used to calculate R_p, there is no need to incorporate k in the mass balance equation. Because all mass balance components for Cook's Bay except R_p were measured, R_p for Cook's Bay was solved directly from the simplified mass balance equation:

$$[TP]_\lambda = \frac{L_T(1-R_p)}{\bar{Z} * \rho} \qquad (3)$$

where $\overline{Z}$ is the mean depth of Cook's Bay and ρ is the flushing rate (times/yr).

Calculation of the effect of each of the major phosphorus loading sources on Cook's Bay phosphorus concentration was done by reducing each load in turn by 50 % from the present-day total (L_T). It was not considered necessary to adjust ρ for each of these hypothetical treatments because it was assumed that any reductions in source loading will be achieved by reducing TP concentrations from that source (water exports remain unaffected). Re-application of Equation (3) for each hypothetical treatment resulted in a predicted new Cook's Bay TP concentration. For inter-comparison of the treatments, the new (predicted) concentrations were expressed as a percentage of present-day (1990's) Cook's Bay spring, mixed water-column concentration of 0.0216 mg/L.

b) *P concentration and loads to Cook's Bay*

Phosphorus concentration for Cook's Bay was determined according to the "sector" method used in Nicholls (1995, 1997), whereby the lake surface was divided into sectors such that sector boundaries enclosed at least one of the regular MOE sampling stations at approximately the centroid of a sector. There were three sectors in Cook's Bay (Nicholls' (1997) sectors 5, 6, and 7), of which the boundary between sectors 4 and 5 can serve as the northerly boundary for definition of Cook's Bay for this exercise (Fig. 1). Sector volumes were applied to spring (pre-thermal stratification) sampling data to generate volume-weighted estimates of phosphorus concentration for Cook's Bay that were appropriate for use in the mass balance equation.

The entire Holland River catchment drains to Cook's Bay, so all relevant data pertaining to that catchment [total export from gauged and ungauged sources, as well as urban point- and non-point sources as documented in Scott et al. (2001)] were applied directly. The northerly portions of two other subwatersheds (West Cook's Bay tributaries and the area north of the Maskinonge River on the east side of the bay) were outside the boundaries deemed to drain to Cook's Bay, so inputs from only the relevant portions of their watershed areas (65 and 129 km^2, respectively, were determined (from digitized tracings). Both areas were ungauged and unmonitored in the Scott et al. study, so areal runoff and TP export values applied to these subcatchments were based on average values for other monitored and gauged catchments in the Lake Simcoe basin (Scott et al.'s Tables 4 and 34). The atmospheric loads determined by Scott et al. (2001) for the whole lake were applied to Cook's Bay on a per unit area basis (total Cook's Bay surface area = 4.4×10^7 m^2).

The urban areas of Aurora, Bradford, Holland Landing, Keswick, Newmarket and Schomberg were based on the 1995 values listed by Scott et al. (2001) and represent the means of 1990 and 2000 values. These were 36, 4.3, 4.1, 5.1, 29.3 and 1.2 km^2, respectively. Similarly, a value of 0.7 km^2 was assigned to Sharon, accounting for the fact that about one-half of the

Sharon catchment was in the East Holland River subwatershed (the remainder, in the Black River subwatershed, was therefore outside the scope of this work). The TP export value (132 kg/km^2) used by Scott et al. (2001) for urban runoff was applied directly to the above urban areas.

Results and Discussion

Cook's Bay TP Concentrations and Whole-lake TP Retention

The spring (mixed water column, in April-May) TP concentrations over the 1990-1998 period averaged 0.025, 0.022 and 0.017 mg/L for Cook's Bay stations C1, C6 and C9, respectively (Table 1). When the sector volumes represented by these locations were applied, a springtime total P mass of 1.22 x 10^7 g was calculated; division by the total Cook's Bay volume yielded a volume-weighted springtime average TP concentration of 0.0216 mg/L for use in the mass balance equation.

Except for four relatively high values in the 0.022 - 0.026 mg/L range, monthly mean Lake Simcoe outflow concentrations averaged about 0.01 mg/L (Fig. 2). These data excluded two apparent "outliers", however. Values of 0.10 and 0.118 on October 13, 1993 and August 12, 1994, respectively, were replaced by interpolated values from sampling dates immediately before and after, when more typical values were measured (0.016 and 0.002 mg/L on October 6th and 20th, and 0.014 and 0.012 mg/L on August 9th and 16th). Much more interannual and seasonal variability was apparent in the flow data. Lowest flows were found in the fall and winter of 1991-92 and 97-98, while high flows were observed in the spring of 1991, the falls and winters of 1992-93 and 1995-96 (Fig. 2). These data were used to generate annual estimates of exports from the lake at the Atherley outflow that ranged from 4600 kg in 1991-92 to 17,500 kg in 1996-97 (Fig. 3). When combined with Scott et al.'s (2001) estimated total loading to the lake, corresponding whole-lake TP retention coefficients ranged from 0.83 (1996-97) to 0.95 (1991-92) with an 8-year average of 0.91. These values are high, compared to other lakes of similar morphometry, but most of Lake Simcoe's TP loading is delivered to the ends of embayments (Cook's Bay and Kempenfelt Bay), so it is reasonable to expect that considerable TP sedimentation takes place in these bays before transport to the main lake (Johnson and Nicholls 1989).

Summary of Major Sources of TP Supply to Cook's Bay

Average annual total TP loading to Cook's Bay over the 8-year period was 27 metric tons. In terms of absolute loads (uncorrected for dilution effects of associated water loads), the largest source of phosphorus to Cook's Bay was urban runoff with an annual contribution of more than10 metric tons (Table 2). Next was the tributary load (the Holland River + miscellaneous drainage on the east and west sides of Cook's Bay) at about 7370 kg/year, followed by vegetable polders at about 5300 kg/Yr. Significantly, treated wastewater form urban sewage treatment facilities contributed only about 800 kg/year (Table 2). Not included among these totals is an estimate for private waste treatment systems (septic tanks-tile field systems) for shoreline cottages and homes along the Cook's Bay shore. Reliable estimates of numbers and failure rates for these systems are not available for the Cook's Bay shoreline, but Walker (1997) estimated their total phosphorus contribution to the whole lake comprised only about 2 % of the TP load to the lake. Omission of a possible septic tank contribution to the Cook's Bay TP mass balance is therefore not expected to have introduced a major error.

Average total phosphorus concentrations for major sources ranged from 0.049 mg/L for tributaries to 0.500 mg/L for the polders to 0.049 mg/L for tributaries (Table 4). It is noteworthy that the TP concentrations in water pumped from dyked areas of vegetable production (polders) were about 3.5 times higher than those found in samples of treated sewage effluent at wastewater treatment facilities and about 10 times higher than in streams draining areas of mixed agriculture, forest and other "greenspace" land uses. To help place these data in the context of Cook's Bay impacts, they need to be applied in a mass balance framework. Data on TP mass loads and associated water loads from the major sources (Table 2) were applied to equation (3), below.

Cook's Bay TP Mass Balance

All input quantities for Equation (3) are tabulated here (text table A, below):
All quantities except R_p were measured (based on 1990's data); their inclusion in Equation (3) yielded a value for R_p of 0.84.

Next, each of the sources, in turn, was theoretically reduced by 50 % from the total and a new $[TP]_\lambda$ was calculated using Equation (3) as shown in Text Table B, below.

Text Table A. Input quantities for Equation (3) for determination of the Cook's Bay response (response determined as change in spring total phosphorus (TP) concentration).		
Variable	Description	Present-day value
$[TP]_\lambda$	spring (mixed water-column) total phosphorus concentration (mg P/m^3)	21.6
L_T	the annual TP loading to Cook's Bay (mg $P/m^2/yr$)	613.5
R_p	retention coefficient	0.84
$\overline{Z}$	is the mean depth of Cook's Bay (m)	12.8
ρ	the flushing rate (times/yr) of Cook's Bay determined as total water input divided by the bay volume	0.35

Text Table B. Effects on spring (mixed water-column) Cook's Bay total phosphorus (TP) concentration of a 50 % reduction from each of the known major sources of TP supply		
TREATMENT	EFFECT (new $[TP]_\lambda$ in Cook's Bay in mg/m^3)	Percentage reduction
none (all sources included)	21.6 (present-day value)	0
reduce tributary load by 50 %	18.65	13.7
reduce urban runoff load by 50 %	17.34	19.7
reduce urban point-source load by 50 %	21.28	1.5
reduce atmospheric load by 50 %	20.46	5.3
reduce vegetable polder load by 50 %	19.47	9.9

Among all of the 50 % reduction scenarios, the greatest predicted change (about 20 %) in Cook's Bay TP levels results from a reduced urban runoff load. Moderately effective reductions can be achieved by 50 % reductions in polder and tributary load of about 10-15 % (Text Table B, above). Interestingly, reductions in the atmospheric and urban point-source loads achieve relatively minor improvements in Cook's Bay TP concentration .

This exercise does not take into consideration the practicality of each of load reduction scenarios - a necessary consideration for planning and prioritizing remedial actions in the Lake Simcoe basin. For example, a reduction of 50 % in the tributary loads may be difficult to achieve because it would likely involve remedial activities at a large number of sites in several subcatchments. In contrast, the polder load might be treated as a point source (effluent is pumped from dyked areas). This source also has the highest TP concentrations of all sources, money spent on control of loads from polders will likely be more cost-effective than at other sources, especially if the level of control can be increased beyond the 50 % reduction used here for demonstration purposes. For example, earlier studies by wastewater treatment technologists at the Ministry of the Environment had determined that conventional phosphorus flocculation and sedimentation procedures routinely used for phosphorus removal in municipal wastewater treatment plants could reduce the P content of polder pump-off water by about 90 % (LSRCA, unpublished data). Application the mass balance calculations to this level of control at all polders discharging drainage water to the Holland River would result in new Cook's Bay spring TP concentrations of about 18 % (a predicted spring TP concentration of 17.8 mg/m^3).

Summary

Data gathered during the hydrologic years of 1990-91 to 1997-98 on phosphorus concentrations and flow rates in streams, rivers, urban wastewater and runoff, precipitation, vegetable polders drainage and other sources has enabled the calculation of total phosphorus (TP) loads to Cook's Bay of Lake Simcoe. The average annual TP loading to Cook's Bay over the 8-year period was 27 metric tons. Of this, tributaries (mixed agriculture + "greenspace") contributed 27 %, urban runoff contributed 39.5 %, municipal wastewater discharge (treated sewage treatment plant effluent) contributed 3 %, atmospheric deposition (rain, snow, dustfall) contributed 10.6 % and polders (dyked areas of organic soil used for vegetable production) contributed 20 %. A mass balance approach was used to determine the relative impacts of each of

these sources on spring TP concentration in Cook's Bay. Hypothetical loading reductions of 50 % for each of the major sources were applied to a mass balance equation to predict the resulting Cook's Bay TP concentration. Greatest potential reductions in Cook's Bay TP concentration (about 20 %) are possible from a reduction in urban runoff TP load. A similar effect was predicted with a 90 % reduction in loads from polders. Remediation should be directed to sources with the greatest potential for reduced impacts on Lake Simcoe, and include analyses of cost-effectiveness. Cost-effectiveness analyses will include the potential for implementation of existing technology as well as the physical requirements and capital costs of facilities required for implementation of remedial measures. Polder drainage appears to offer good opportunities for TP load control owing to the point-source nature of the discharges and their high TP concentrations. TP concentrations in water pumped from polders were about 3.5 times higher than those found in samples of treated sewage effluent at wastewater treatment facilities and about 10 times higher than in streams draining areas of mixed agriculture, forest and other "greenspace" land uses.

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Table 1. Total phosphorus concentrations (mg/L) during the mixed water column periods of 1990-1998 (usually the mean of two runs during late April-May) at the three Cook's Bay sampling stations, C1, C6 and C9.

	C1	C6	C9
1990	0.027	0.023	0.015
1991	0.015	0.018	0.013
1992	0.045	0.025	0.021
1993	0.028	0.029	0.022
1994	0.024	0.025	0.020
1995	0.020	0.019	0.014
1996	0.014	0.016	0.020
1997	0.027	0.032	0.015
1998	0.023	0.013	0.009
Mean	0.025	0.022	0.017

Table 2. Areas and annual average total phosphorus loading (kg), and the water volumes (m^3) associated with each source supplied to Cook's Bay of Lake Simcoe.

	Area (km^2)	TP supply (kg)	Water supply (m^3)
Cook's Bay West Side[1]	65	862	1.76×10^7
Cook's Bay East side[2]	129	1705	3.48×10^7
Holland River[3]	463	4802	9.801×10^7
Urban runoff[4]	80.7	10652	2.889×10^7
Urban STP[5]	NA	803	5.706×10^6
Atmospheric[6]	44	2850	3.608×10^7
Polders[7]	49	5321	1.064×10^7

[1] Mean values for TP concentration (0.049 mg/L) and runoff (0.270 m/yr) were applied as determined from data in Tables 4 and 34 of Scott et al. (2001).

[2] Cook's Bay east side subwatershed included the Maskinonge River as well as additional northern drainage in diffuse intermittent sources [outside of the Maskinonge subcatchment as defined in LSRCA (1998)] for which mean values for TP concentration (0.049 mg/L) and runoff (0.270 m/yr) were applied as determined from data in Tables 4 and 34 of Scott et al. (2001).

[3] The Holland River data excluded all urban and polder areas and their associated TP and water loads and thus represents only mixed upland agriculture and miscellaneous "greenspace" (forest, scrublands, wetlands). Mean values for TP concentration (0.049 mg/L) and runoff (0.270 m/yr) were applied as determined from data in Tables 4 and 34 of Scott et al. (2001).

[4] The value shown is the sum of areas for Aurora, Bradford, Holland Landing, Keswick, Newmarket and Schomberg (New Tecumseth), and 50% of the total area of Sharon.

[5] The urban STP loads were based on a sum of all point-sources as identified in Table 3.

[6] The area shown here is Cook's Bay area; loads were calculated using an 8-year average concentration of 0.079 mg/L and a precipitation depth of 0.82 m (original data in Scott et al. 2001).

[7] Based on measured values for the main Holland Marsh, but extrapolated to include the total polder area (including the Bradford, Colbar and Keswick polders). Note that the unit area export of 109 kg P/km^2, excluded estimates for 1996-97 and 1997-98 (per Scott et al. 2001).

Table 3. Summary of urban sewage treatment facility water and total phosphorus (TP) loads discharged directly to, or upstream of, Cook's Bay. Data are based on eight hydrologic years, 1990-91 to 1997-98.

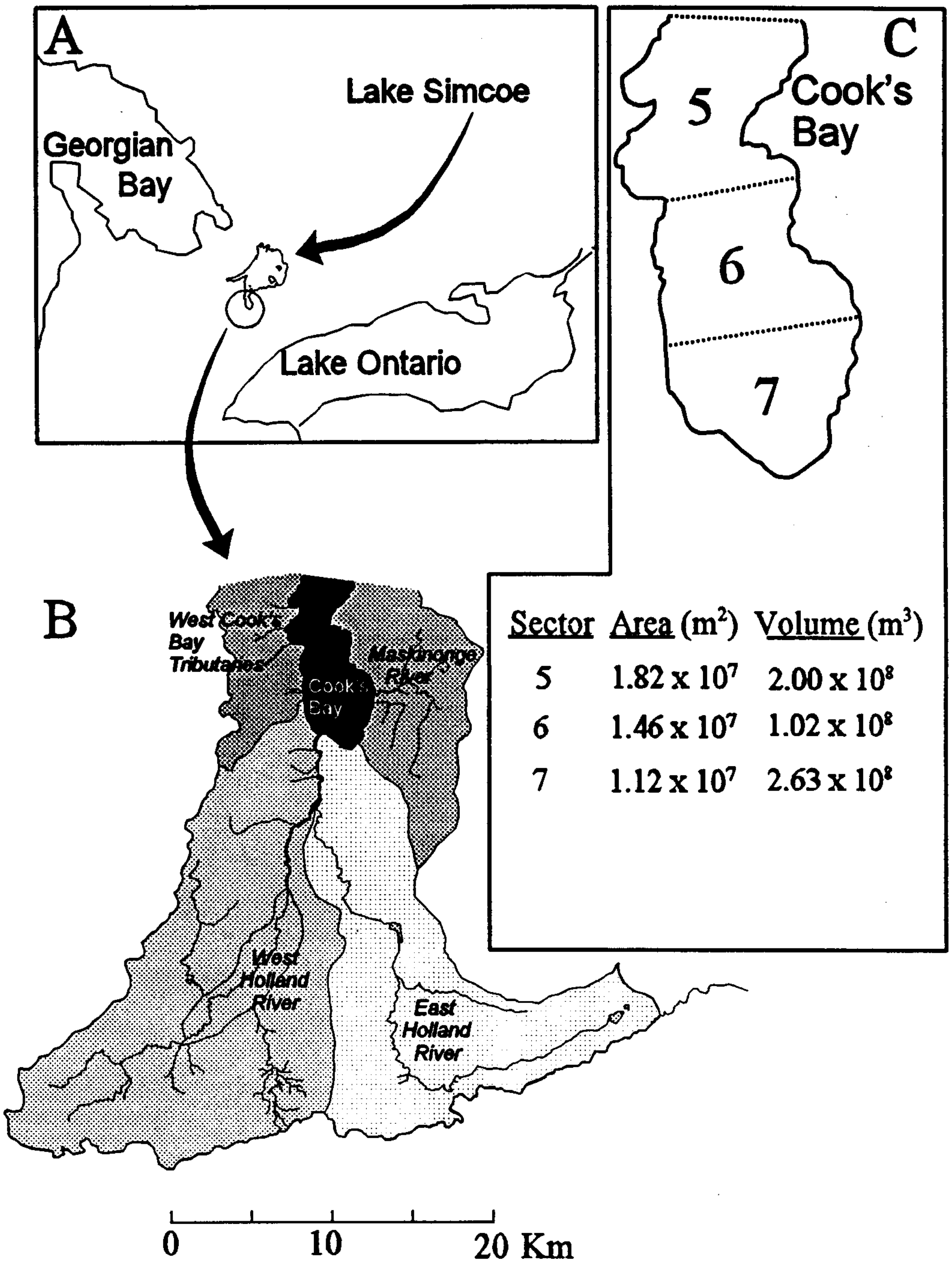
SOURCE	Water load (m3)	TP load (kg)
Innisfil (Alcona) WPCP	1349254.5	197.6
Keswick WPCP	1895879.5	231.2
Bradford WPCP	1953318.5	277.7
Holland Landing Lagoon	397928.9	83.9
Schomberg Lagoon	109305.5	13.0

Table 4. Annual average concentration (mg/L) of total phosphorus in the major sources of TP supplied to Cook's Bay of Lake Simcoe, calculated from data presented in Scott et al. (2001) for eight hydrologic years (1990-91 to 1997-98).

Atmospheric	Urban point-source	Urban non-point source	Tributaries[1]	Polders[2]
0.079	0.141	0.369	0.049	0.500

[1]Note that any upstream urban sources were removed from the calculated TP concentrations for tributaries.

2 The value for the total area of vegetable production (polders) excluded 1996-98, for which data were not available



Sector	Area (m^2)	Volume (m^3)
5	1.82×10^7	2.00×10^8
6	1.46×10^7	1.02×10^8
7	1.12×10^7	2.63×10^8

Figure 1. Location of Lake Simcoe's Cook's Bay in southern Ontario (A), the subcatchments draining to Cook's Bay (B) and the water surface areas and volumes of sectors 5, 6, and 7 of Cook's Bay, represented by sampling stations C9, C6 and C1, respectively (C; see Nicholls 1995, 1997).

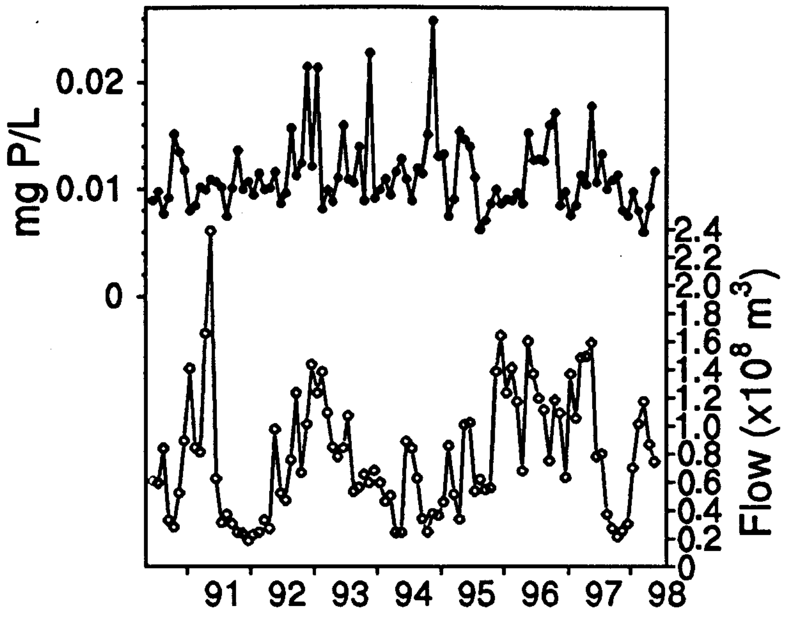


Figure 2. Monthly mean total phosphorus concentrations (mg P/L)and total monthly flow at the Atherley outflow between June of 1990 and May of 1998.

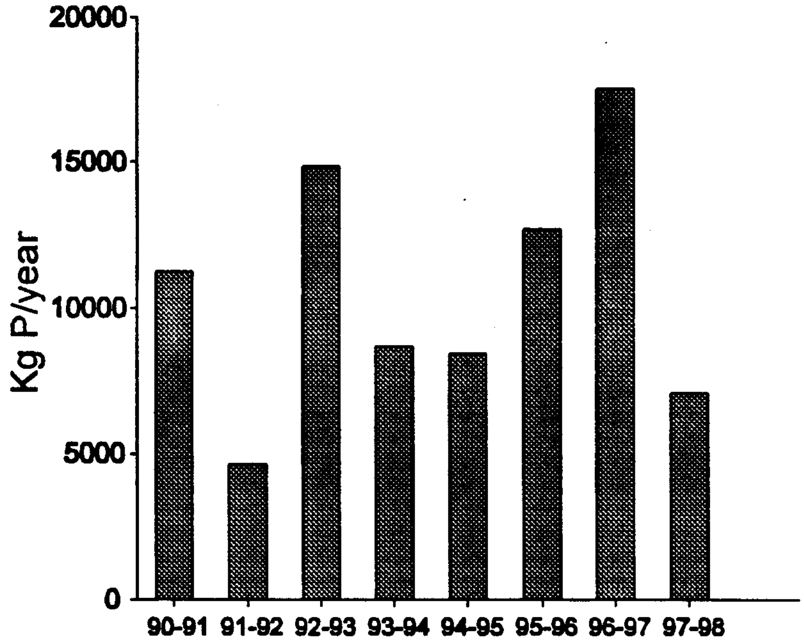


Figure 3. Annual export of total phosphorus (kg/year) from Lake Simcoe at Atherley for eight hydrologic years 1990-91 to 1997-98.