

THE ROLE OF THE LAKE WINTER COVER IN THE PHOSPHORUS BUDGET
OF A SOUTHERN ONTARIO LAKE

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ABSTRACT

A winter and spring hydrologic and phosphorus budget was calculated for a small lake (10.3 hectares) in the Oak Ridges Moraine Complex, 32 km north of Toronto, Ontario, Canada. Of principal interest were contributions to the spring phosphorus load by aeolian source loading to the winter cover at the lake and terrestrial basin. Six percent of .578 kg of the total winter season phosphorus load was contributed by the winter snow and ice cover of the lake. Of this, fifty-seven percent was estimated to be derived from aeolian source loading. Total aeolian source loading to the lake from all sources was 22.3 percent.

Introduction

Over the past two decades the problem of eutrophication of lakes has occupied many researchers in the field of fresh water biology. It is an accepted fact that the eutrophication of lakes depends on the excessive discharge of phosphorus to inland waters. This in turn has led to the Nutrient Loading Concept which implies a quantifiable relationship between amounts of nutrients reaching lakes and their trophic status measurable by some kind of Trophic Scale Index. A relationship was found to exist between Total Phosphorus (hereafter referred to as "phosphorus") measurable at spring overturn, and mean summer chlorophyll-a concentration which could be used as a measure of algal abundance and therefore trophic status. At the same time, there was a need to predict acceptable levels of phosphorus in lakes before their trophic status changed through artificial or man-made additions of phosphorus. The result of these two needs was the development of a set of empirical relationships which could be used to estimate a phosphorus budget which could then be used to calculate a spring phosphorus concentration and as the basis for defining acceptable artificial loading of phosphorus to a lake (Dillon and Rigler, 1975). In its simplest form the relationship can be expressed as:

$$[P] = \frac{J(1-R)}{Q} \quad (1)$$

(Schieder, 1978)

Where [P] is the concentration of phosphorus in the lake at spring overturn in g m³; J is the sum of all atmospheric and terrestrial origin phosphorus to the lake in g year⁻¹; R is the percentage of incoming phosphorus retained annually by the lake, and Q the total annual lake outflow discharge in m³ yr⁻¹.

This model has proved useful but has not been tested against many types of lakes and the confidence levels about each empirically derived parameter are wide. In particular, winter season observations and measurements do not match other seasons since yearly estimates form the basis for the model's predictive ability

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In temperate and subarctic environments where a considerable fraction of yearly precipitation falls in solid form onto a lake's ice cover and its catchment, the atmospheric source phosphorus is not immediately available to the lake system during the winter. The lake cover limits exchange between atmosphere and lake and in fact may act to incorporate both lake and atmosphere-derived phosphorus, releasing it suddenly in the spring melt. Some studies have used the knowledge of the evolution of ice and snowcovers on lakes to fill gaps in the yearly phosphorus budget determinations for Canadian Shield lakes (Adams et al, 1978), however, this type of testing has not been extended to lakes outside the Canadian Shield which also receive substantial yearly precipitation in the form of snowfall.

This study considered the impact of the winter cover of the lake and the land over time and space, on loading of phosphorus to a lake throughout a winter season and a spring season. Of particular interest was the assessment of the quantitative significance of the lake winter cover as a factor regulating atmospheric contributions of phosphorus.

Work in this study then centred on:

- a) assessing the quantitative significance of the phosphorus load released by the lake winter cover in relation to other point sources of phosphorus to the lake for the same time period. This involved calculation of winter and spring season hydrologic and phosphorus budgets for the watershed and lake, and
- b) assessing the quantitative significance of the lake winter cover as a factor regulating atmospheric contributions of phosphorus. This included following the growth and evolution of the lake winter cover through detailed surveys of cover component, thickness and density in conjunction with measurements of phosphorus concentration in each component. Of particular interest were the processes of slushing and freeze-out and their effects on the concentration of phosphorus in each cover component.

Study Area

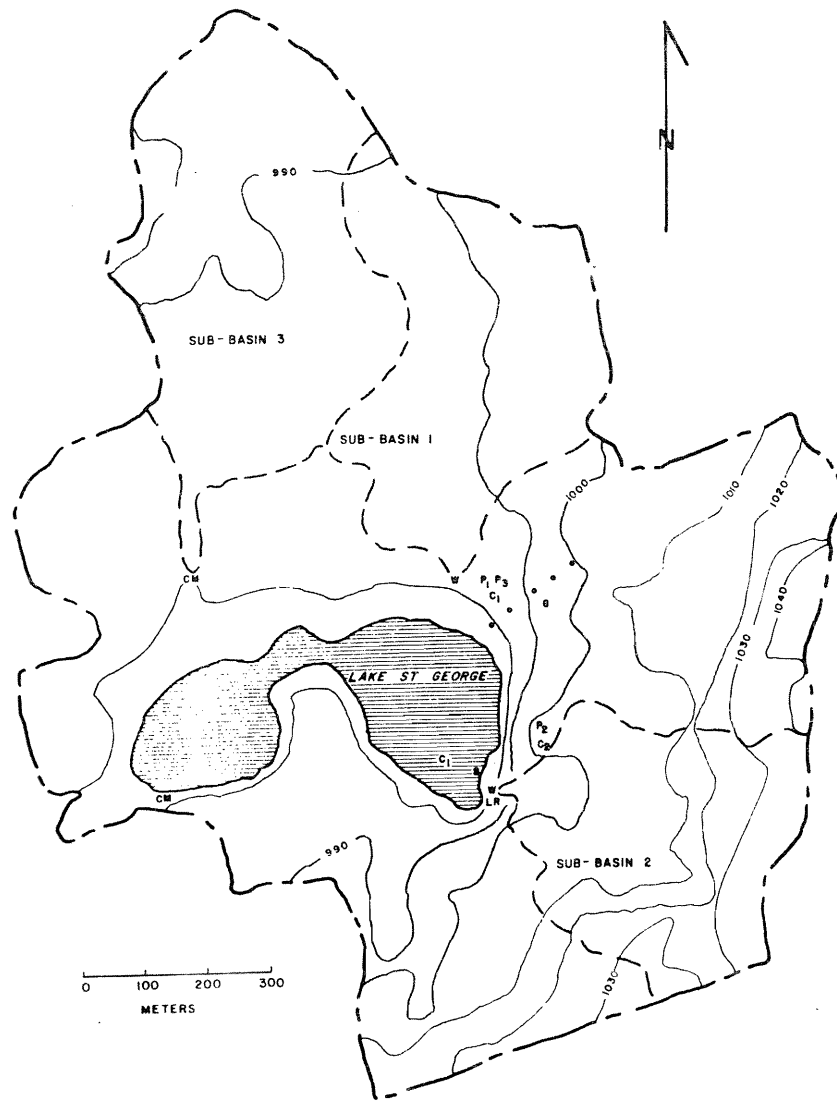
The study was carried out in the Lake St. George watershed, 32 km north of Toronto, Ontario (43°45'N; 79°30'W). The watershed falls within the Oak Ridges Moraine Complex (Chapman and Putnam, 1966) which, at the site, is characterized by unconsolidated clay, silt and Kame deposits. The water body itself is a double basin perched kettle lake, 10.3 hectares in area, 295.6 m above sea level. The catchment area including the lake is 131.5 hectares. Three artificial stream channels enter the lake in both basins, draining sub-catchments with a range of land use and vegetative types including deciduous forest, mixed forest and swamp, and improved cropland.

The site falls within the Dfb zone of the Köppen climate classification - marked cool temperate climate. At a regional level the site is characterized by cyclonic storm activity. Winter weather systems generally move south-west to north-east, the most intense activity occurring in the late winter. Annual precipitation has a value between 710 and 760 mm. Mean snowfall has a value between 15.2 and 16.3 cm or approximately 21 percent of the total precipitation for the year.

Methods and Materials

A winter and spring hydrologic and phosphorus budget was calculated for the lake. A network of instrumentation was installed in the Lake St. George catchment in November 1977 to measure water gains and losses within the system. Measurements included precipitation, stream flow, changes in surface water storage in the lake, ground water flow and evaporation (Figure 1). Data were also used from an Atmospheric Environment Service climatic station at Oak Ridges, 2 km west of the site.

Particular attention was focused on the evolution of the lake and land winter cover with respect to aeolian loading of phosphorus into both over the season. On the lake large stratified, systematic, unaligned samples were used as the basis for repeated surveys of cover components to demonstrate significant spatial trends over time following the method of Prowse (1978). Samples of black ice, white ice (ice formed from the re-freezing of a flooded snowcover), slush (if present) and water from immediately below the black ice were taken weekly for phosphorus analysis from December 1977 to breakup April



LAKE ST GEORGE WATERSHED

- BASIN BOUNDARY
- - - - SUB-BASIN BOUNDARY
- W WEIR
- LR WATER LEVEL RECORDER
- CM CURRENT METER MEASUREMENTS
- P₁ NIPHER SNOW GAUGE
- P₂ RECORDING PRECIPITATION GAUGE
- P₃ STANDARD RAIN GAUGE
- C₁ BULK PRECIPITATION COLLECTORS
- C₂ WET-DRY FALL-OUT COLLECTOR
- GROUNDWATER WELLS
- s LAKE STAGE

Figure 1. Lake St. George Catchment and Instrumentation.

24th, 1978. Samples were collected from 5 sites for each sampling period. Snow and ice samples were collected in 1000 ml plastic bags, melted and tapped into 150 ml glass bottles.

On land, standard snow survey techniques (Canada, 1976) were used to obtain water equivalent values throughout the winter at four ten point snow course transect lines. End of winter sampling included eight snow course transects of ten randomly spaced sample points to ensure coverage of all distinct vegetation zones within the catchment. Terrestrial basin snow cover samples were collected on three occasions for phosphorus analysis. An integrated sample was taken using the MSC snow samples and collection was made into 1000 ml plastic bags. Samples were melted and tapped into 150 ml glass bottles.

Complete monitoring of runoff from the entire catchment was not possible because of poorly defined channel flow to the lake from certain sections of the total catchment. As a result, inflow from two streams was gauged using 90° V-notch and rectangular weirs from November to June; and three additional streams for the snowmelt period. Discharge from the outflow stream was measured using a Price Current meter at .2 and .8 of the total water depth across a survey section of stream. Determination of surface water flow from areas of undefined drainage (areas with no clearly defined or gaugeable streams) were based upon a relationship between discharge and extent of saturated zones (zone where water table is in contact with the surface of the soil) within each gauged subcatchment. Discharge per hectare of saturated zone within each gauged subcatchment for specific time periods throughout the spring melt was averaged, then multiplied by the number of hectares of saturated zone contributing to surface water flow to the lake in areas of undefined drainage.

Bi-weekly samples of phosphorus were collected from all gauged stream inflows and outflow and additional samples were collected for streams flowing to the lake during spring melt.

Ground water flows were estimated using two approaches. The first was simply the unsolved term in the water balance equation once the other components had been measured. The second was an estimate of flow computed after the classic method of Darcy (Chorley, 1969). Phosphorus samples were collected from ground water wells by means of a weighted tube and a manual vacuum pump.

Lake storage change was measured from the period of the breakup until June. Estimates of mean lake evaporation were obtained from the map of the 30 year average for evaporation for Southern Ontario (Brown et al, 1968). Evaporation for the lake was calculated by multiplying evaporation loss by the lake area.

Two gauges were used to collect snowfall data - a Nipher shielded snow gauge and a Fischer-Porter Recording precipitation gauge. A standard Atmospheric Environment Service rain gauge was also used. Bulk precipitation for phosphorus analysis was collected from two sites--one on the lake, the other on the land. Both collectors were located approximately 1.2 metres above the ground to eliminate ground contamination. Each was open to the atmosphere and samples were collected immediately following precipitation events ideally at the same time that precipitation volume measurements were made. In the case of both collectors, samples were collected and drained into either 150 ml glass bottles (rainfall) or 1000 ml plastic bags (snowfall or sleet/hail). Collectors were rinsed with distilled water and dilute nitric acid; thus only the phosphorus in the net fallout was monitored. Lake St. George was sampled itself each week, in each basin. A 5 l capacity Van Doren bottle was used to sample at 2 m intervals.

All samples collected on site were fixed immediately by adding 1 ml of a 30 percent H₂SO₄ solution to each 100 ml sample. Total phosphorus concentrations were determined after digestion by the ascorbic acid modification of the molybdenum blue reaction.

Results

Figure 2 is a summary of temperature, precipitation and mean lake cover component thickness over the winter period. In brief, late November snowfalls produced conditions on the lake cover promoting early season growth of white ice which persisted throughout the winter season. Atypical low temperatures into April produced conditions which slowed

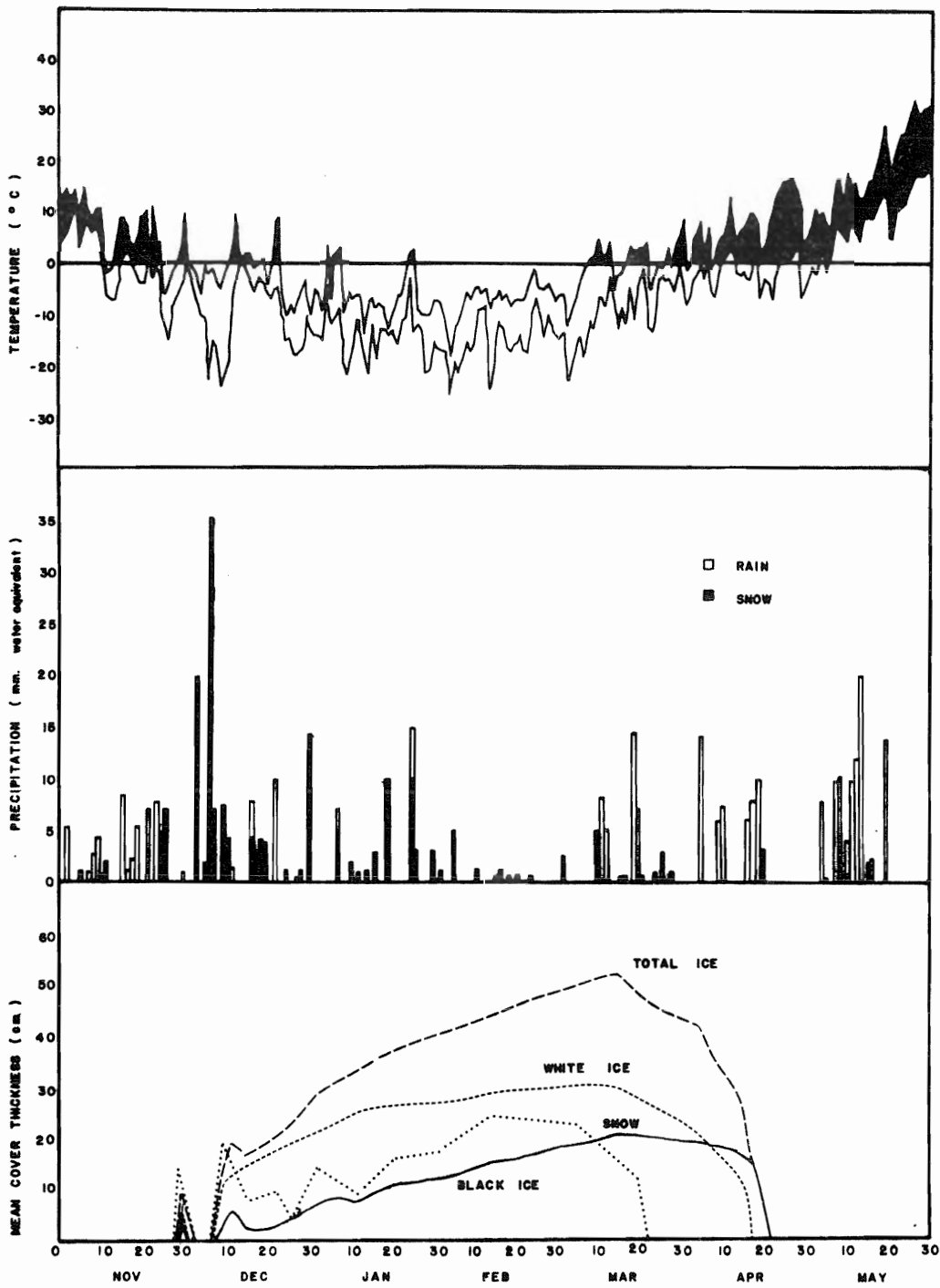


Figure 2. Climate and Winter Lake Cover of Lake St. George 1977-78.

eventual melt of the lake cover to April 24th, two weeks after the peak of the terrestrial snowpack.

Table 1 is a summary of the winter phosphorus budget for Lake St. George for all point source inputs to the lake. Principal interest in the budget centres on the contribution of the lake winter cover relative to all other inputs and the contribution of aeolian source inputs to both lake cover and terrestrial catchment.

Table 1
Winter Phosphorus Budget for Lake St. George

Source	Supply (kg)	% of Total Input	Loading (in terms of lake area) mg m ⁻²
Terrestrial	7.286	72.8	97.9
Groundwater	2.132	21.3	27.5
Aeolian	.316	3.4)	3.1
Winter Cover	.262	2.6) 6.0	2.5
Total Input	9.996	100	
Output	9.296		

Aeolian source loading to the winter cover at the lake and terrestrial basin is shown in Tables 2 and 3 for each month of the study. These calculations were based on receipts of the bulk collectors on the lake and land. Aeolian source contributions to the lake were calculated to the date of maximum ice growth and to the date of last complete cover of ice in both basins. Calculations of loading to the lake from melt of the winter cover itself were made as follows:

$$L_s = \rho \cdot d \cdot (T.P.)$$

$$L_{wi} = \rho \cdot d \cdot (T.P.)$$

$$L_{bi} = \rho \cdot d \cdot (T.P.)$$

Where L_s = loading to the snowcover of the lake
 L_{wi} = loading to white ice
 L_{bi} = loading to black ice
 ρ = density of snow, white ice or black ice
 d = mean depth over the lake
 $T.P.$ = mean total phosphorus concentration

Density of the snow was measured, density of white ice was assumed to be .877 g cm³ (Gaitskhoki, 1970) and black ice to be .90 g cm³ (Adams, 1976). The total input for the lake cover ($L_{wi} + L_{bi} + L_s$) was therefore 4.98 mg m⁻² or .578 kg.

Table 2
Terrestrial Snowmelt Export of Total Phosphorus

Month	Aeolian Input of Total Phosphorus (kg)	Terrestrial Snowpack		Terrestrial Input to Lake (Snowmelt & Surface Water Flow) (kg)
		Supply mg m ⁻²	Loading (kg)	
December	2.132	.897	1.124	0.044
January	0.737			0.010
February	0.143	2.18	2.735	0.013
March	0.755	3.023	3.788	1.446
April	0.789			10.322
May	4.847			

Using .316 kg as total aeolian input (Table 1) to the lake winter cover, this represented 57 percent, leaving 43 percent of the load to the winter cover of the lake as lake origin phosphorus (Table 4). Total contribution of phosphorus from the lake winter cover to the total winter and spring budget was .578 kg or six percent of the total. Again with reference to Table 4 the white ice component of the cover represented the highest concentration of phosphorus and the greatest thickness overall, therefore contributing the greatest percentage load of any of the winter cover components. More detailed work by the author (Wolfe, 1979) showed that the greatest concentration of phosphorus throughout the winter season was found at the black ice/white ice interface following slushing periods, therefore appearing to become incorporated into the downwind freezing white ice layers over time.

Table 3

Aeolian Source Total Phosphorus Loading to Lake Winter Cover

Month	Aeolian Input Total Phosphorus (kg)	Winter Cover Input of Total Phosphorus to Lake (kg)
December	.054 directly to lake .105 incorporated in cover	-
January	.055	-
February	.012	-
March	.079	-
April	.065 incorporated in cover .003 directly to lake	.578
Total	.251 incorporated in cover to March 15	

With respect to aeolian input of phosphorus, Table 2 shows the loading of the terrestrial basin snowpack. Calculations showed approximately 50 percent of the potential snowmelt contribution from the terrestrial winter cover reached the lake as surface flow. In determining the phosphorus contribution from the terrestrial snowmelt, it was assumed that 50 percent of the potential runoff reached the lake. Since distances travelled by the snowmelt from areas contributing to surface water drainage were not great, concentrations in the melt water could be assumed not to change markedly over the distance to the lake.

Table 4

Mean Thickness, Density, Total Phosphorus Concentration
and Phosphorus Supply from the Snow and Ice Cover of the Lake

Cover	Mean Thickness (m)	Density ρ (g cm ³)	Mean Total Phosphorus [P] mg l ⁻¹	Loading (L) mg m ⁻²
Snow	.0164	0.230	0.014	.053
White Ice	.309	0.877	0.013	3.420
Black Ice	.212	0.900	0.008	1.510
Total				4.983

Conclusions

Results make it clear that the significance of the lake winter cover's role in affecting the spring phosphorus budget of lake system is dependent upon a number of factors, in addition to the actual quantity of phosphorus which is released from the cover with spring melt. For Lake St. George, only six percent of the total winter season phosphorus load to the lake was contributed by the winter cover of the lake. Of this six

percent, over half (57%) was estimated to be derived from aeolian source input while the rest (43%) came from the lake itself and therefore was not a net addition of phosphorus to the lake. The availability of either lake-derived or aeolian-derived phosphorus is significant. In terms of lake origin phosphorus, the quantity available is primarily dependent upon the existing trophic status of the lake, and during the winter, the nature and evolution of the cover. As seen at Lake St. George the contribution of lake origin phosphorus, which was most concentrated in the white ice layer, was therefore dependent upon snowfall and rainfall upon the cover creating optimum conditions to produce slushing and more white ice. Grøterud, (1978) has shown that much of the phosphorus which is incorporated into the cover is biologically available phosphorus in the form of dissolved reactive phosphorus (PO₄).

The impact of this load in the spring season, again, ignoring other inputs for the moment, is dependent on the trophic status of the lake and the timing of the melt. If, as is the case of Lake St. George, the lake is eutrophic and concentrations of phosphorus in the lake water are not limiting to production, then the cover melt may have the effect of diluting concentrations in the epilimnetic waters. The opposite case may be envisaged where a high concentration of phosphorus in the cover relative to the lake water will increase concentration in the epilimnetic waters (Grøterud, 1972). The later the melt in the spring season in comparison to runoff from the terrestrial basin, the more significant the impact one way or the other. As was the case at Lake St. George, the peak runoff from the terrestrial basin occurred prior to the melt of the lake winter cover, noticeably increasing phosphorus concentrations for the water column beneath the ice. Much of this melt appeared to be flushed through the lake prior to the lake cover melt but concentrations in surface waters were lower following the lake cover melt.

At Lake St. George it is necessary to view the input of phosphorus from the lake winter cover with respect to inputs from other sources. For example, the aeolian input for the month of May alone exceeds that for the entire winter and occurs into open water during a period of warming and stratification when biotic growth would be stimulated the most.

Finally terrestrial input of phosphorus accounts for 73 percent of the total load to the lake with spring melt and of this 26 percent is atmospherically derived. This accounts for 19 percent of the total input, bringing the total aeolian input for the winter season to 22.3 percent. This percentage is estimated to be supplied to the lake in spite of an approximate 50 percent retention of water by the catchment due to the effects of topography, vegetation and soils.

These conclusions show the winter cover of the study lake to contribute a minimal quantity of phosphorus to the lake in relation to other sources for the same time period. In this respect the results support the conclusions reached by several authors, that the winter cover would be expected to be of greater importance for shallow lakes, with limited through flow and a small catchment to lake area ratio. (Grøterud, 1978; Schindler and Nighswander, 1971; Nichols and Cox, 1977). These conditions were cited after work on the Precambrian Shield.

Acknowledgements

I am grateful to Dr. Peter Adams and other faculty members at Trent University for their support of this project. I am also grateful to Mike Sturk and Nigel Roulet of Trent for their advice and assistance. Drs. David Lean and Barry Goodison, particularly the former, provided assistance in a variety of forms including equipment. Pat Strode, Shirley Hill and Kathy Outerbridge assisted in the production of this manuscript. The research was funded in part by NSERC, Environment Canada (Inland Waters) and Trent University.

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