PROC. N.S. INST. SCI. (2002)
Volume 42, Part 1, pp. 37-64.

THE CHEMICAL OCEANOGRAPHY OF THE BRAS D'OR LAKES

PETER M. STRAIN[1] and PHILIP A. YEATS
Marine Environmental Sciences Division
Department of Fisheries and Oceans
Bedford Institute of Oceanography
Dartmouth, Nova Scotia, B2Y 4A2

Considerable research has been done on the Bras d'Or Lakes since the 1960s. Many of these studies have either focussed on chemical conditions in the Lakes, or have included chemical measurements in support of other research. Substances studied include major ions, inorganic nutrients, dissolved oxygen, chlorophyll, heavy metals and organic contaminants. What is known about the chemistry of the Lakes is reviewed and some model results are presented that combine what is known about the water circulation and external inputs of chemicals to estimate some parameters of biological productivity and to predict chemical distributions where data are currently unavailable. Overall, the low nutrient inputs to the Lakes can only support a relatively low level of natural biological productivity, and the contribution of sewage and other man-made sources of nutrients is very small. However, localized build-ups of both natural and anthropogenic nutrients have affected the water quality of some microenvironments in the Lakes, resulting in the eutrophication of sites like the west end of Whycocomagh Bay and some of the barachois ponds around the Lakes. Although the available data on contaminants are limited, there is no indication that any persistent organic or heavy metal contaminants are a concern within the Lakes. The environmental quality is in general very good. This status is a result of the small population density and the very limited industrial development around the Lakes. Maintaining or improving this status will require good management of current and future activities in the Bras d'Or Lakes and their watershed.

Depuis les années 1960, des recherches considérables ont été effectuées au sujet du lac Bras d'Or. Un bon nombre de ces recherches étaient axées sur les conditions chimiques dans le lac ou comportaient des mesures chimiques à l'appui d'autres études. Les substances étudiées comprenaient les principaux ions, les éléments nutritifs inorganiques, l'oxygène dissous, la chlorophylle, les métaux lourds et les contaminants organiques. On examine ici les connaissances dont on dispose au sujet des conditions chimiques du lac et on présente les résultats de certaines modélisations qui combinent nos connaissances sur la circulation de l'eau et les apports allochtones de produits chimiques dans le but d'estimer certains paramètres de la productivité biologique et de prédire la distribution des substances chimiques dans les cas où on ne dispose pas actuellement de données à ce sujet. De façon générale, le faible apport d'éléments nutritifs dans le lac ne peut alimenter qu'une production biologique relativement faible et la contribution des eaux usées et autres sources d'éléments nutritifs d'origine anthropique est minime. Toutefois, des foyers d'accumulation d'éléments nutritifs naturels et anthropiques ont influé sur la qualité de l'eau de certains micro-environnements du lac, ce qui a abouti à l'eutrophication d'endroits comme la partie ouest de la baie Whycocomagh et de quelques-uns des étangs-barachois alentour du lac. Quoique les données sur les contaminants soient limitées, rien ne révèle la présence dans le lac d'une contamination persistante par les matières organiques ou les métaux lourds qui donnerait matière à inquiétudes. La qualité du milieu est en général très bonne. Cela est dû à la faible densité de population et au développement industriel très limité alentour du lac. Le maintien ou l'amélioration de cette situation nécessitera une bonne gestion des activités actuelles et futures dans le lac Bas d'Or et dans son bassin hydrographique.

Introduction

The Bras d'Or Lakes (Fig 1) are a group of interconnected saltwater basins located in Cape Breton Island at the north-eastern end of Nova Scotia. They cover a total area of 1080 km^2, and have an average depth of ~30 m. There are a wide variety of physical environments in the Lakes. Some areas are shallow and flat-bottomed (e.g. Denys

---

[1] Author to whom correspondence should be addressed

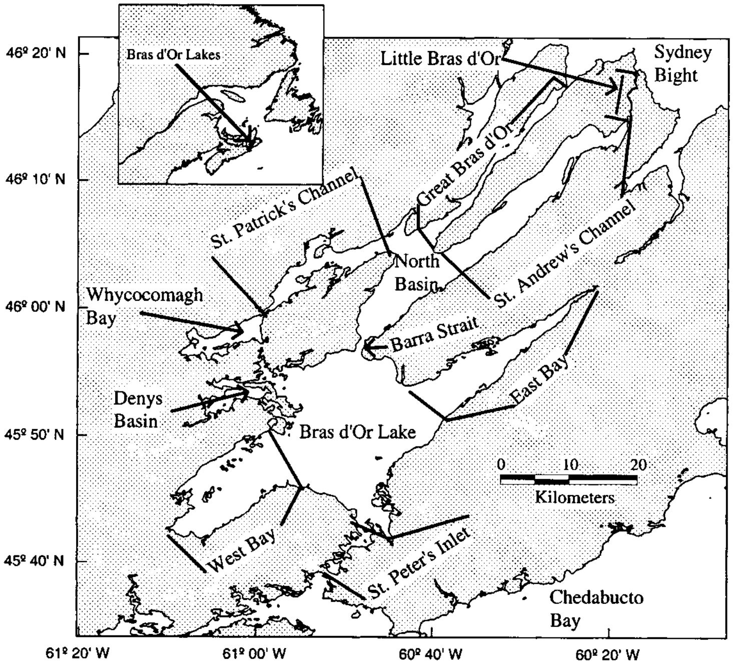

Fig 1 The Bras d'Or Lakes.

Basin, mean depth ~5 m); others are steep-sided and deep (e.g. St. Andrew's Channel, whose depths reach ~280 m). Small ponds that are partially or completely isolated from the Lakes by sand and gravel barriers are found along the shorelines. Locally, they are known as barachois ponds. There are 3 connections between the Lakes and the North Atlantic. There is significant exchange only through the Great Bras d'Or Channel, a long (~30 km), narrow (~1 km) channel that connects the Lakes to Sydney Bight, on the Nova Scotia side of Cabot Strait. The Great Bras d'Or Channel has an average depth of ~20 m and a maximum depth of ~95 m. A shallow (~12 m) sill near its mouth further restricts water movement into and out of the Lakes. There is negligible flow through the second permanently open connection to the Atlantic, the Little Bras d'Or Channel, which is located at the north-east end of St. Andrew's Channel. The third connection to the Atlantic is through a seasonally operated lock at the south-eastern end of St. Peter's Inlet that connects the Lakes to Chedabucto Bay on the Atlantic coast of Nova Scotia.

The complex geometry of the basins and embayments makes it necessary to consider processes that determine chemical distributions and behaviour on a number of different spatial scales. Chemical inputs and processes, and water circulation, mixing, and residence times are very different for some small bays and basins in the Lakes than they are for the Lakes as a whole. Within the Lakes, the different basins range in size from barachois ponds that are a few hectares in area and a few meters deep with volumes of $10^4 m^3$ to St. Andrew's Channel which has an area of approximately 13,000 hectares, depths up to 280 m, and a volume of $8.5 x 10^9 m^3$. Freshwater flows, which provide one pathway for the transport of both natural and contaminant chemicals into the Lakes, are also variable. The North Basin is about 6 times larger in area, and more than 20 times larger in volume, than the west half of Whycocomagh Bay, but the freshwater inputs into the 2 basins are approximately the same. Flushing time estimates vary from about one week in the Great Bras d'Or Channel to 40 weeks for the deep water of St. Andrew's Channel to 96 weeks for the deep water in the west end of Whycocomagh Bay (Gurbutt *et al.*, 1993). The intensity of vertical mixing in different areas of the Lakes also varies over a wide range (Gurbutt and Petrie, 1995).

It is important to understand the inputs of chemicals and their subsequent fates in coastal waters for a number of reasons. Inputs of nutrients may control the primary productivity of the Lakes' ecosystem, and the resulting growth and decay of organic matter will in turn determine the concentrations of dissolved oxygen that are available to support other marine life. Wastes from sewage, agriculture, aquaculture and other man-made sources add to these nutrient inputs and have the potential to alter both the natural concentrations and the ecosystem dynamics that depend on them. Enrichment of aquatic environments with dissolved nutrients is known as eutrophication. Other contaminants, such as heavy metals and persistent organic pollutants, also have the potential to affect the health of marine organisms and/or their suitability as food.

This article will review and discuss what is known about the chemistry of the Lakes, in terms of the inputs, distributions and dynamics of chemicals both in the Lakes as a whole and in the basins and embayments that make up the Lakes. It will also compare the chemical conditions in the Lakes to other marine environments in the region and use models of circulation and chemical behaviour to predict concentrations and transports.

Chemical Studies in the Bras d'Or Lakes. Sporadic interest in the Bras d'Or Lakes from the 1960s to the 1980s generated a number of studies of contaminants and the chemical oceanography of the Lakes. Young *et al.* (1959) measured the major ion concentrations in water, and concluded that the composition resulted from simple mixing between freshwater and coastal seawater, a conclusion supported by carbonate system and stable isotope measurements made by Mucci and Pagé (1987). Smith and Rushton (1964) measured dissolved oxygen levels in a number of the barachois ponds around the Lakes. Geen (1965) and Geen and Hargrave (1966) studied the primary and secondary production at a few sites, and made some measurements of nutrients, plant pigments and dissolved oxygen in support of this research. A large study of the suitability of the Lakes for aquaculture in 1972-73, summarized in Young (1976), included chemical measurements of heavy metals, nutrients, plant pigments and dissolved oxygen in molluscs, water and sediment samples from the Lakes and water and sediments from the influent rivers. Arseneau *et al.* (1977) measured a number of chemical parameters in surface waters in East Bay and the barachois pond at the northeastern end of East Bay, and dissolved oxygen profiles at one location in East Bay and several in St. Andrew's Channel. However, the technology Arseneau *et al.* were using was not well suited to making these measurements in salt water. Wright (1976) measured nutrients and plant pigments at a few locations from 1973 until 1975. Krauel (1975) made extensive physical oceanographic measurements, and included measurements of dissolved oxygen during one survey in July, 1974. Gurbutt and Petrie (1995) extended the analysis and interpretation of Krauel's physical oceanographic measurements, developed a box model describing water flow between different layers and basins in the Lakes, and examined the oxygen distribution and oxygen uptake rates. An Environment Canada survey of organic contaminants in the aquatic environment of the Atlantic Region in the late '70s and early '80s included results for water and sediments at a station in St. Patrick's Channel near Baddeck and the Baddeck River (Bailey and Howell, 1983; O'Neill, 1988; O'Neill and Kieley, 1992). In addition, Environment Canada's water quality monitoring program for contaminants in natural waters includes a number of stations in the Lakes and surrounding watershed.

During the 1990s a number of the gaps in our understanding of chemical conditions in the Lakes were addressed. Dalziel *et al.* (1998) measured the concentrations of a large number of chemicals, including nutrients and trace metals, in coastal rivers around the Maritime Provinces. This survey included spring, summer and fall measurements in 1994, 1995 and 1996 in the Baddeck and Middle Rivers, which flow through Nyanza Bay into St. Patrick's Channel, and River Denys, which is the principal freshwater flow into Denys Basin. Strain *et al.* (2001) conducted extensive surveys of the concentrations of nutrients, dissolved oxygen, and plant pigments and selected measurements of heavy metals in the Lakes from 1995 to 1997. Chou *et al.* (1999) measured metals in winter flounder and sediments from 5 locations in 1997. Willis (1999) measured levels of mixed-function oxidase activity, which is a response to exposure to contaminants, in winter flounder and organic contaminants (polychlorinated biphenyl compounds, PCBs, and polycyclic aromatic hydrocarbons, PAHs) in sediments from the same sites.

Nutrient Inputs to the Bras d'Or Lakes

The first studies of dissolved inorganic nutrients, oxygen and chlorophyll in the Bras d'Or Lakes focussed on freshwater inputs or areas very close to shore, sampling only a few offshore sites. For example, Smith and Rushton (1964) studied oxygen levels only in barachois ponds; Geen's study (1965) focussed on four sites in the open Lakes and one barachois pond; and Young (1976) concentrated on sampling the influent rivers, with a few sites in the Lakes. Since the surveys reported by Strain *et al.* (2001) provide extensive coverage of the major basins in the Lakes in 3 different seasons, they will form the basis of most of the discussion that follows. Generally good agreement was found among the different studies when data are available for the same locations and seasons, although some care must be used in interpreting the earlier data in the context of the analytical methods available at the time.

The biological productivity of an aquatic ecosystem may be determined by the available external supplies of the nutrients required for the growth of phytoplankton, provided that both light conditions and water column stratification are suitable for growth. Light intensity must be high enough to support photosynthesis and the water column must be sufficiently stratified to keep phytoplankton cells in surface waters with adequate light levels. Both of these physical factors are generally favourable for growth in the Bras d'Or Lakes. The median value of the attenuation factors for photosynthetic active radiation reported by Strain *et al.* (2001) was 0.20, showing that Bras d'Or waters are relatively clear for coastal waters (Kirk, 1983). Furthermore, the surface mixed layer is very shallow during the growing season in the Bras d'Or Lakes (3 – 5 m in the summer, deepening to 10-15 m in September and October, Petrie and Bugden, 2002). Given these favourable physical conditions, nutrient levels are most likely the factor controlling the surface layer productivity. The possible external sources of nutrients are rivers, atmospheric deposition (including precipitation), sewage, aquaculture and other man-made sources, and exchange with coastal waters in Sydney Bight. Estimates of these nutrient fluxes are shown in Fig 2. River inputs are derived from the data in Dalziel *et al.* (1998) for Cape Breton Rivers, weighted to account for the varying geology in the surrounding watersheds (Loring and Nota, 1973). Fluxes of nutrients in precipitation are based on data from GESAMP (1989). Sewage inputs are based on the population around the Lakes and typical *per capita* discharges for untreated sewage (Mueller and Anderson, 1983). Inputs from finfish aquaculture are calculated from estimates for total 1999 production from the Lakes

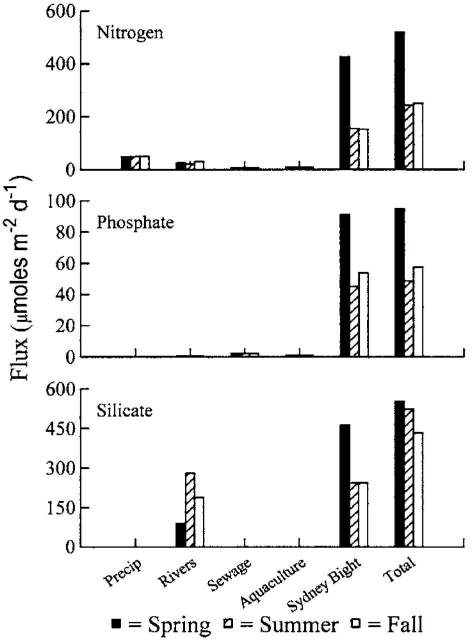

Fig 2 Inputs of nitrate + nitrite + ammonia, phosphate, and silicate to the Bras d'Or Lakes. Fluxes are given as the amount of nutrients entering the Lakes per day, averaged over the total area of the Lakes.

(Chandler, 2001) and estimates of loading from steelhead and salmon cage farm operations (Strain *et al.*, 1995; Ruohonen *et al.,* 1998). Inputs from Sydney Bight through the mouth of the Great Bras d'Or Channel are derived from the concentrations of nutrients in Sydney Bight (Petrie *et al.*, 1999) and the water flows from Gurbutt and Petrie's (1995) model of the circulation. The fluxes are reported as the amount of nutrient delivered per day to each m^2 of the Lakes, and represent conditions averaged over the entire Lakes ecosystem. The Sydney Bight fluxes are the inputs through the mouth of the Great Bras d'Or Channel, uncorrected for the export of nutrients in the outflowing surface water. The latter are generally small, because surface concentrations are low, except for silicate which is present at higher concentrations in the surface during the fall.

Inflowing water from Sydney Bight is the largest source of nitrogen and phosphate to the Lakes in all seasons (Fig 2). Lesser amounts of nitrogen but little phosphate are derived from precipitation and river inputs. River inputs are relatively more important for silicate, especially in the summer and fall. Also, there is more spatial variability in silicate than for nitrogen and phosphate: silicate concentrations are much higher in rivers that drain areas with mostly Triassic-Carboniferous rock formations, such as those areas that drain into St. Patrick's Channel, than in areas with mostly Cambrian-Devonian rocks, such as those areas that drain into East Bay. For example, the median silicate value reported by Dalziel *et al.* (1998) for the Middle River, which drains Triassic-Carboniferous land emptying into St. Patrick's Channel, was 68 μM; for the

Framboise River, which drains Cambrian-Devonian terrain adjacent to East Bay but actually discharges into the Atlantic, it was 1.1 μM.

Sewage inputs of nitrogen and phosphate are both very small compared to the natural fluxes into and out of the Lakes, and while these inputs may cause locally eutrophic conditions if the water circulation is restricted, they will have little impact on the Lakes as a whole. However, the faecal coliform organisms associated with sewage discharges do cause local closures of shellfish harvesting and may make some areas unsuitable for contact recreation. Nutrient inputs from finfish aquaculture are similar in size to those from sewage, but will be concentrated near the few farm sites. Inputs from aquaculture may also lead to local increases in nutrient levels, but do not pose the human health risks associated with domestic sewage.

Implications for Productivity. Phytoplankton growth requires nitrogen and phosphorus in a 16:1 ratio (in molar units), known as the Redfield ratio. N:P ratios in the inputs to the Lakes are 5.4, 4.6 and 2.7 in spring, summer and fall, strongly suggesting that nitrogen is the limiting nutrient in the Lakes. Nitrogen is also in short supply in the waters of Sydney Bight. N:P ratios through most of the year vary from 2 to 10; only in February do N:P ratios approach the Redfield ratio (Petrie *et al.*, 1999).

Since phytoplankton require carbon and nitrogen in a fixed ratio, and nitrogen is the limiting nutrient, the amount of 'new' primary production that could be supported by these net nitrogen inputs to the Lakes can be calculated. New production is that fraction of the total primary production that is due to external inputs, as opposed to production supported by the internal recycling of nutrients within the surface layer. The highest net input of nitrogen, 390 μmoles m^{-2} d^{-1} (this is the total nitrogen flux in Fig 2, corrected for the nitrogen exported through the mouth of the Great Bras d'Or Channel to Sydney Bight), occurs in the spring, and corresponds to a primary productivity of 2.6 mg carbon m^{-2} h^{-1} (average value for 12 h of growth each day). Similarly estimated production rates in summer and fall are 1.0 and 0.6 mg carbon m^{-2} h^{-1}, respectively. Another source of nitrogen for new production is the nitrate and ammonia stored in deep waters inside the Lakes, which are brought to the surface layer by vertical mixing processes. The water fluxes from Gurbutt and Petrie's model (1995) and nutrient data from Strain *et al.* (2001) can be used to estimate these vertical fluxes, and the production that they could support. The potential productivity due to this nitrogen source varies from 4.1 mg carbon m^{-2} h^{-1} in the spring to 4.3 and 5.7 mg carbon m^{-2} h^{-1} in the summer and fall. St. Andrew's Channel is the most important location for this supply, accounting for between 50 and 70 % of the total, despite the fact that the area of St. Andrew's Channel is only 12 % of the total area of the Lakes. Taken together, the external and deepwater sources can account for between 5.3 and 6.7 mg carbon m^{-2} h^{-1} of new production. Geen and Hargrave (1966) reported direct measurements of total primary production in the Lakes, over the late spring and summer, between 20 and 40 mg carbon m^{-2} h^{-1}. These estimates are equivalent if new production represents 15 to 30 % of the total production. These ratios are typical of those found in coastal waters at this time of year (Harrison, 2001).

The above estimates are appropriate for late spring, summer and fall production rates, but an additional source of nitrate is important during the spring bloom. Nutrients accumulate in the surface waters of the Lakes in the winter when light levels and temperatures are too low for the growth of phytoplankton. These nutrients are derived both from inflowing water from Sydney Bight (nitrate levels peak in Sydney Bight in January and February, and are 2-5 times greater than in April and May, Petrie *et al.*, 1999) and mixing between surface and deeper waters of the Lakes caused by winter cooling and storms. These accumulated nutrients both fuel, and are quickly removed by, the increased production rates that occur in the bloom. Although no direct observations of nutrient distributions in the Lakes are available for the winter period, it is possible to use the water circulation from Gurbutt and Petrie's model (1995) to estimate the winter build-up of nitrate. This estimate is an approximation, since the circulation model is based on spring to fall data. Using the same box structure as Gurbutt and Petrie (1995), and starting with observed fall nitrogen concentrations (Strain *et al.,* 2001), we simulated pre-bloom conditions by estimating the nitrate concentrations in the Lakes after 90 days without biological uptake. These calculations predict that the mean surface nitrate concentration would increase from 0.3 to 4.9 μM, similar to the few reported winter measurements. Wright (1976) reported maximum nitrate levels of 6.5 and 5.4 μM for Baddeck and Nyanza Bays, respectively. For a bloom that spans a two week period, the nitrogen inventory predicted by the model for the top 20 m would support an average new production rate of 27 mg carbon m^{-2} h^{-1}. Overall, these calculations indicate that new production during the spring bloom could be supported mostly by nutrients accumulated in the surface layer over the winter, but that nutrients from deep waters within the Lakes dominate later in the growing season, when the rate of new production is much lower.

Almost all of the nitrogen available for new production in the Lakes is supplied from marine sources, either Sydney Bight or the deep waters of the Lakes. An even higher percentage of the phosphorus supply is derived from these sources. Only for silicate are land based sources significant. Silicate supply will not affect the overall potential for new production, but it will determine the abundance of diatoms, which are an important group of phytoplankton which require silicate for growth. Since silicate inputs from land sources are spatially variable around the Lakes, there may also be variations in the relative abundance of diatoms in different lake basins.

Table I External sources of inorganic nitrogen (nitrate + nitrite + ammonia) to inlets in Maritime Canada (μmoles m^{-2} d^{-1}).

	Bras d'Or	**Ship Hbr[1]**	**Halifax Hbr[2]**	**Kouchibouguac[1]**	**Letang[3]**
Precipitation	50	50	50	50	50
River Inputs	26	530	230	140	92
Marine Exchange					
In	245	2130	318	~ 3330[4]	~ 48000[4]
Out	125	1710		~ 2040[4]	~ 48000[4]
Net In	120	420		~ 1290[4]	???
Sewage	8	< 1	1780	< 1	32
Industrial					
Fish processing					520
Finfish Aquaculture	9				4130
Pulp & Paper					12

[1] Strain, unpublished data.
[2] Petrie and Yeats (1990).
[3] Strain et al. (1995).
[4] Marine exchange difficult to quantify with existing data.

Comparison of Inputs with those for Other Maritime Coastal Waters. Table I compares the average annual nitrogen inputs to the Bras d'Or Lakes with those to other inlets of various types in the Maritime provinces. As in Fig 2, the data are reported in terms of daily delivery of nitrogen, normalized to the area of the inlets. Ship Harbour is a relatively pristine inlet on the Atlantic coast of Nova Scotia. Halifax is the largest population centre in the Maritimes: raw sewage from approximately 350,000 residents, as well as industrial wastes, are discharged into its harbour. Kouchibouguac is a barrier beach inlet in a National Park on the New Brunswick Gulf of St. Lawrence shore. The Letang is an inlet on the New Brunswick Bay of Fundy coast whose industries include intensive Atlantic salmon aquaculture, fish processing and pulp and paper.

Although these calculations are approximate, they do suggest that the Bras d'Or Lakes are quite different from these other inlets in several ways. River inputs of nitrogen to the Bras d'Or are the lowest of any of these locations, due to both the relatively small freshwater discharges and the low concentrations of nitrogen in those discharges. With the relatively small size of the river and marine inputs, precipitation to the Bras d'Or is relatively more important than in the other systems. Although the net marine exchange is an important fraction of the total external nitrogen input to the Lakes (as it is for some of the other inlets), it is the smallest value found in this group of inlets. The total nitrogen inputs are very much smaller than to any of the other inlets, which may explain why the Lakes have been described as a 'relatively unproductive body of water' (Geen and Hargrave, 1966).

Nutrient and Chlorophyll *a* Distributions in the Bras d'Or Lakes

The nutrient distributions in the Bras d'Or Lakes, as in all water bodies, are determined by inputs, biological processes and water circulation. Strain *et al.* (2001) report measurements from all of the lake basins; Fig 3 is a composite map of station locations they sampled from 1995 to 1997.

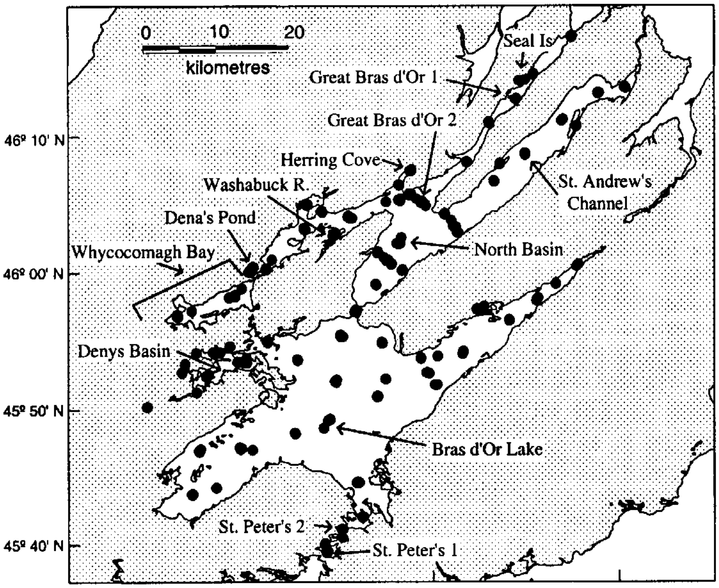

Fig 3 Stations sampled from 1995-1997 (Strain *et al.*, 2001).

Surface Distributions. The histograms in Fig 4, 5 and 6 show the range of values for the nutrients, chlorophyll *a* and dissolved oxygen in the Lakes during the spring (April 25 – May 1), summer (July 7-11) and fall (Sept. 22-27) of 1996 for the top 15 m of the water column. This depth range is used to illustrate conditions in the surface layer without introducing data from bottom waters of some of the shallower basins in the Lakes which might obscure surface processes.

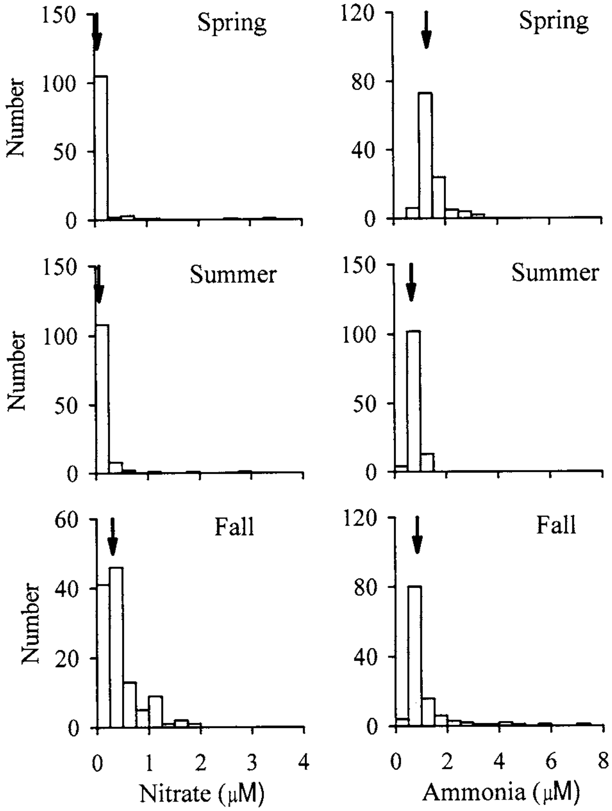

Fig 4 Seasonal distribution of nitrate and ammonia concentrations in the 0-15 m layer of the Bras d'Or Lakes, in 1996 (Strain *et al.*, 2001). Median values are shown by arrows.

Surface nitrate+nitrite (subsequently referred to as nitrate) levels were very low throughout the Lakes in the spring (Fig 4). Ninety-eight of 114 measurements were less than the detection limit of 0.14 μM. Only 2 samples had concentrations greater than 2 μM: a station in St. Patrick's Channel near Nyanza Bay and a station in Herring Cove at the head of Baddeck Bay (the latter site is a very small embayment, 30 m deep, isolated from the rest of Baddeck Bay by a sill with a depth of less than 10 m; see Fig 3). These very low surface concentrations of nitrate are typical of conditions in inlets on the Atlantic coast of Nova Scotia after the growth of phytoplankton during the spring bloom has converted all the available oxidized nitrogen to organic nitrogen or ammonia (Keizer *et al.*, 1996). The very low nitrate concentrations typically persist through the summer. In the summer survey of 1996, 91 out 121 nitrate measurements in the Lakes from the top 15 m were below the detection limit. By the fall survey, only 22 of 119 nitrate measurements were below detection limit; 30 samples had levels greater than 0.5 μM, indicating that nitrate was being added to the surface layer faster than it was being consumed by production. The deepening of the surface mixed layer by fall winds is one mechanism that would contribute to the higher surface nitrate concentrations. Earlier studies (Geen and Hargrave, 1966; Young, 1976) also reported low concentrations of nitrate in the late spring and summer.

Surface ammonia concentrations in the spring were higher than those of the oxidized nitrogen, with a median value of 1.3 μM (Fig 4). This is typical of behaviour for inlets on the Atlantic coast of Nova Scotia (e.g. Strain, 2002), in which the dominant inorganic form of nitrogen after the spring bloom is ammonia. By July (Fig 4) the median ammonia concentration decreased to 0.67 μM, as demand for inorganic nitrogen continued to exceed its supply. In the fall survey, most ammonia concentrations were still less than 1 μM, but there were a number of higher values as well. All samples in Denys Basin were above 4 μM, with a maximum value of 7.2. Higher than median values were also found at the west end of Whycocomagh Bay, the Washabuck River, Nyanza Bay, and in the cove behind Seal Island in the Great Bras d'Or Channel (Fig 3). Since these higher ammonia levels were found in places with restricted circulation, they are probably due to organic matter decomposition in underlying waters and sediments. Land sources or direct sewage inputs might be another possibility, but there are no indications of ammonia levels this high in the rivers flowing into the Lakes, in either the data reported by Dalziel *et al.* (1998) or measurements made on streams flowing into Denys Basin by Strain *et al.* (2001) in the spring and fall of 1997. The ammonia levels reported by Geen and Hargrave (1966) are very similar to those from Strain *et al.* (2001), ranging from 2 to 3 μM.

In sharp contrast to nitrate, all of the spring dissolved phosphate concentrations are greater than the phosphate detection limit (0.038 μM), with a median value of 0.20 μM (Fig 5). Even using the sum of the median concentrations for nitrate, nitrite and ammonia (1.36 μM), the N:P ratio is only 6.8. The phosphate concentrations are clearly in excess of the total inorganic nitrogen available for phytoplankton growth. Based on the NOAA National Estuarine Eutrophication program definitions of low, medium and high nutrient concentration (Bricker *et al.*, 1999), total nitrogen concentrations fell into the low category for 446 of 450 surface samples (medium concentrations were found for 4 samples from Dena's Pond (Fig 3), Denys Basin and the southern end of St. Peter's Inlet), while ~10% of surface phosphate concentrations were in the medium range with a single sample (Dena's Pond) in the high range. This is further evidence that primary production in the Lakes is nitrogen limited. Surface layer phosphate concentrations observed in the summer and fall surveys are very similar to those seen in the spring survey. Phosphate levels determined by Geen and Hargrave (1966), 0.1 to 0.2 μM, are consistent with the more recent observations.

Like nitrate, the spring distribution of silicate is skewed to very low values, with 70 out of 114 measurements less than 1.0 μM in the spring (24 were at or below the detection limit of 0.19 μM; Fig 5). However, there are a number of high silicate concentrations in samples from the top of the surface layer (depth = 1 m). These high values are all found in or near Whycocomagh Bay, St. Patrick's Channel, Baddeck Bay and Denys Basin. This pattern is consistent with the presence of high silicate levels in freshwaters flowing into these parts of the Lakes. Dalziel *et al.* (1998) found high concentrations in the Middle River (mean = 41 μM), Baddeck River (73 μM), both of which flow into Nyanza Bay, and River Denys (42 μM), which flows into Denys Basin.

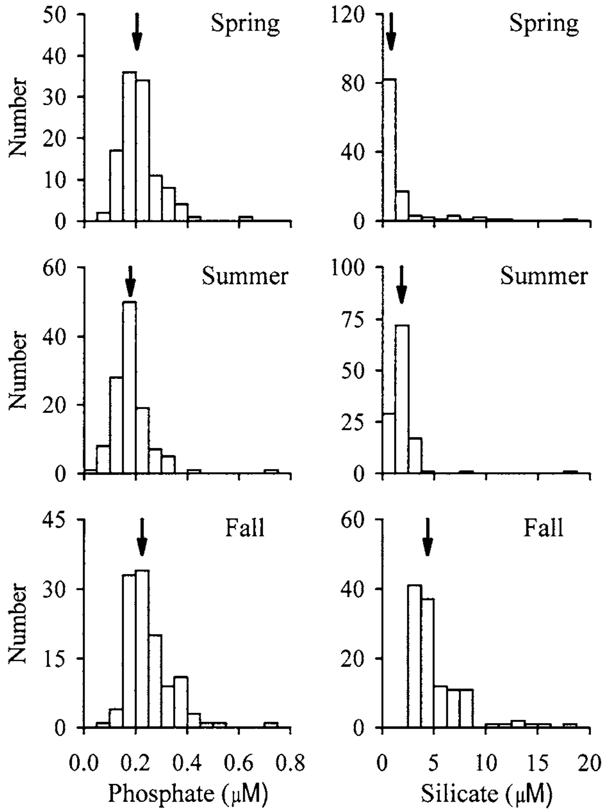

Fig 5 Seasonal distribution of phosphate and silicate concentrations in the 0-15 m layer of the Bras d'Or Lakes, in 1996 (Strain *et al.*, 2001). Median values are shown by arrows.

By summer, the median silicate value had increased from 0.81 to 1.82 μM. Approximately half of the silicate values fell between 1 and 2 μM; no measurements were below the detection limit. There were fewer high levels of silicate: in the spring, 10 samples had concentrations greater than 5 μM; in the summer, only one sample contained more than 5 μM. The summer concentrations reflect the balance between silicate delivery by the rivers (which may have been lower due to a drought in early summer, 1996) and diatom production. By the fall, the median value of silicate had increased even more, to 4.4 μM. Similar to the spring survey, high values were found in St. Patrick's Channel, Whycocomagh Bay, Denys Basin (all samples in Denys Basin were > 10 μM), and at a single station at the northeast end of East Bay. At this time of year, silicate supply exceeded the demand from diatom growth.

The chlorophyll *a* concentrations were very low throughout the Lakes during the spring of 1996: 95 out of 106 samples had chlorophyll *a* levels at or below 0.5 μg L^{-1} (Fig 6). No sign of an active bloom was indicated by these samples. By summer,

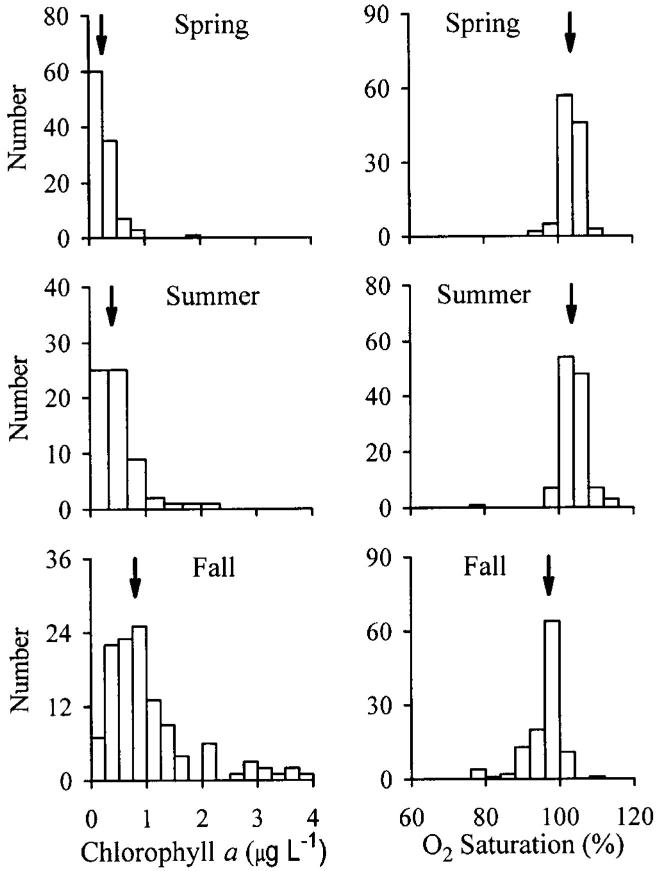

Fig 6 Distribution of chlorophyll *a* and dissolved O_2 saturation in the 0-15 m layer of the Bras d'Or Lakes, in 1996 (Strain *et al.*, 2001). Median values are shown by arrows.

the median chlorophyll *a* level had increased marginally, from 0.24 to 0.40 μg L^{-1}, but overall phytoplankton biomass remained very low. The chlorophyll and phaeophytin (a degradation product of chlorophyll, which was also present in very low concentrations) concentrations for the fall survey show that some additional algal growth had occurred: the median concentration for chlorophyll was 0.80 μg L^{-1}. The highest chlorophyll values (> 2 μg L^{-1}) were found in Whycocomagh Bay, St. Patrick's Channel, Denys Basin, St. Peter's Inlet and at a single station at the southeast end of St. Andrew's Channel. Geen and Hargrave (1966) measured similar chlorophyll concentrations in waters of the open Lakes (1 to 3 μg L^{-1}), and cautioned that inshore estimates of chlorophyll were often biased by the chlorophyll present in organic detritus. Detrital chlorophyll might also explain higher near-bottom concentrations of chlorophyll seen in nearshore samples by Young (1973a). Young's data from more open areas of the Lakes (0.4 - 1.9 μg L^{-1}) are similar to the data from the other studies.

As expected, the surface layer oxygen concentrations were always close to saturation (Fig 6). The distribution observed by Strain *et al.* (2001) is narrow, with a median value of 104 % in the spring and summer surveys. The slight supersaturation could be due to production exceeding respiration in the surface layer, or to warming of the layer occurring faster than equilibration with the atmosphere. Dissolved oxygen concentrations were slightly lower on the fall survey, with a median value of 97 % saturation. This may be a further indication of decomposition processes, or it could be due to physical processes: the surface layer could have been cooling faster than air-sea exchange could re-establish equilibrium conditions.

The low spring concentrations of the inorganic nitrogen species in 1996, together with the very low values of chlorophyll and phaeophytin, suggest that a spring bloom had already occurred in the Lakes prior to these surveys. The generally low concentrations of silicate, despite the abundant silicate in some of the rivers feeding the Lakes, suggests that diatoms were a significant part of the bloom and were responsible for removing most of the silicate from the surface layer.

By the time of the fall survey in 1996 (Sept. 22-27), many of the distributions had changed from those observed in spring and summer. The changes in properties seen in the fall data are consistent with a modest bloom fuelled by an increase of nutrients in the surface layer. This re-supply was due to a combination of regeneration and vertical mixing caused by fall wind conditions and the reduction in stratification due to fall cooling. However, there is no such evidence for a bloom in the data for the other two fall surveys (1995 and 1997) reported by Strain *et al.* (2001), although the absence of pigment data for these other surveys makes this conclusion tentative. The nitrate and ammonia distributions in these two surveys were more similar to those observed on the spring and summer surveys in 1996 than the distribution in the fall of 1996. The more restricted spatial coverage of the 1995 and 1997 data should not affect this conclusion, since both of these surveys covered some of the areas with the highest chlorophyll concentrations found in 1996. It is not known whether the evidence of a bloom in late September 1996 and the apparent absence of a fall bloom in 1995 and 1997 indicate that blooms may occur in some years and not others, or simply that the timing of the bloom was different in different years (the three fall surveys were conducted on almost identical dates). Regardless, these observations further illustrate the variations in seasonal cycles that occur between different years.

Nutrient Distributions in Deep Waters. Nutrient concentrations in deeper waters also influence the potential productivity of marine ecosystems. Dead organisms and other organic detritus sink into the deep water, where they decompose, either in the water or in the bottom sediments, and release inorganic nutrients back into the water column. Physical mixing processes, such as diffusion and upwelling, can then resupply the photic zone (the layer in which light levels are high enough to support photosynthesis) with the nutrients needed for phytoplankton growth. In temperate latitudes, this resupply typically occurs in the fall and winter when cold temperatures and storm winds break down the stratification of the water column and mix regenerated nutrients from the deep water into the surface layer.

Fig 7 shows the nitrate levels observed in the 1996 surveys (Strain *et al.*, 2001) at stations representative of the deep basins in the Lakes. At Great Bras d'Or 1 (Fig 3), nitrate levels are very low and uniform throughout the water column in spring, summer and fall. These low levels are a reflection of the intense mixing that occurs in the northeastern section of the Great Bras d'Or Channel which prevents the accumulation of both organic detritus and regenerated nutrients. This behaviour contrasts to the southwestern end of the Channel (Great Bras d'Or 2), where concentrations of nitrate

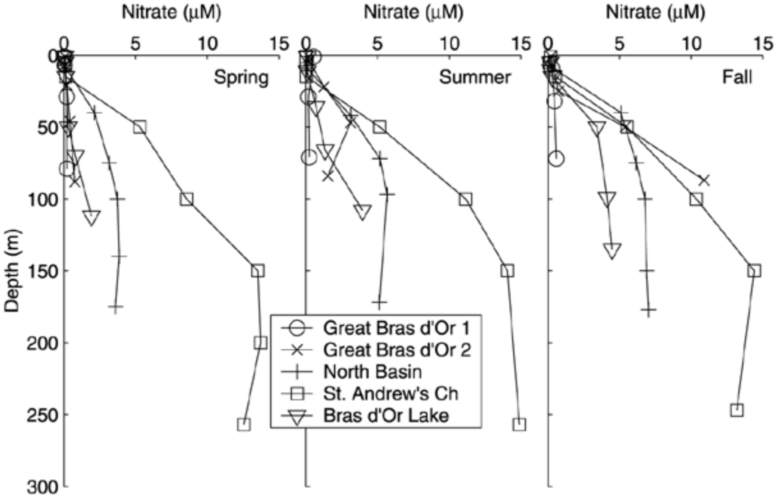

Fig 7 Nitrate at 5 deep stations in the Bras d'Or Lakes in 1996 (Strain *et al.*, 2001).

at depth increase from spring to fall, to levels that are higher than the concentrations in the inflowing water from Sydney Bight, illustrating the importance of the regeneration processes described above. Similar nitrate increases from spring to fall also occur in the deep waters of St. Andrew's Channel, North Basin, and Bras d'Or Lake (we will use Bras d'Or Lake, singular, to refer to the Lake basin south of Barra Strait). The concentrations of nitrate at similar depths in these 3 areas, however, are markedly different. Levels are highest, and vary the least from season to season, in St. Andrew's Channel. The high fall concentrations at the southwestern end of the Great Bras d'Or Channel suggest that some St. Andrew's Channel deep water may mix with water outside the channel. The lower concentrations found in the North Basin, however, show that this mixing does not reach the North Basin and may be quite limited.

Nitrate levels in Bras d'Or Lake south of Barra Strait are lower than the levels in both St. Andrew's Channel and the North Basin north of Barra Strait. Barra Strait, and the shallow sill north of the Strait (depths < 30 m), are effective barriers to nitrate supply from Sydney Bight or from the deep reservoir in St. Andrew's Channel. These concentration differences combined with estimates of vertical mixing (Gurbett and Petrie, 1995) suggest that the flux of nitrate into the surface layer is 5-10 times greater north of Barra Strait than in the Bras d'Or Lake. The lower availability of nitrogen in the Lakes south of Barra Strait probably makes the total production there significantly lower than north of Barra Strait.

The vertical profiles for phosphate (Fig 8) and silicate (Fig 9) are generally similar to those for nitrate, except for the previously noted differences in the surface layer. A significant difference between the silicate profiles and those for nitrate and phosphate is that the difference between silicate levels north and south of Barra Strait that were observed in spring and summer had disappeared by the fall. In addition, the contrast between the deep water concentrations inside the Lakes and those in the Sydney Bight input is greater for silicate than it is for nitrate or phosphate. These observations show

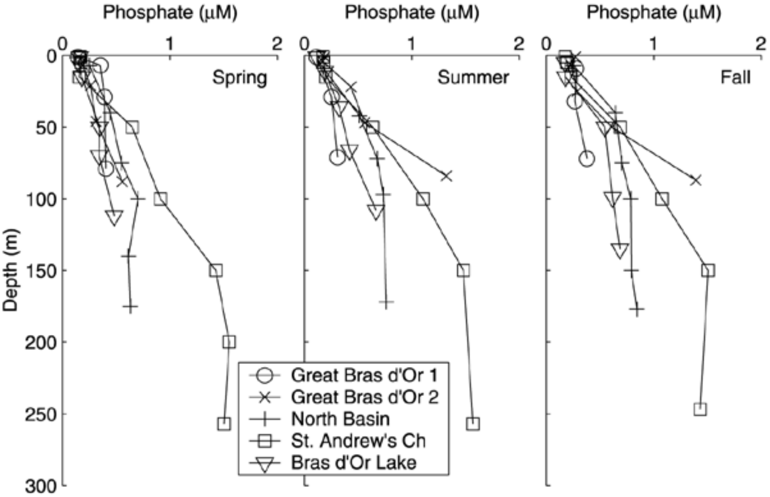

Fig 8 Phosphate at 5 deep stations in the Bras d'Or Lakes in 1996 (Strain *et al.*, 2001).

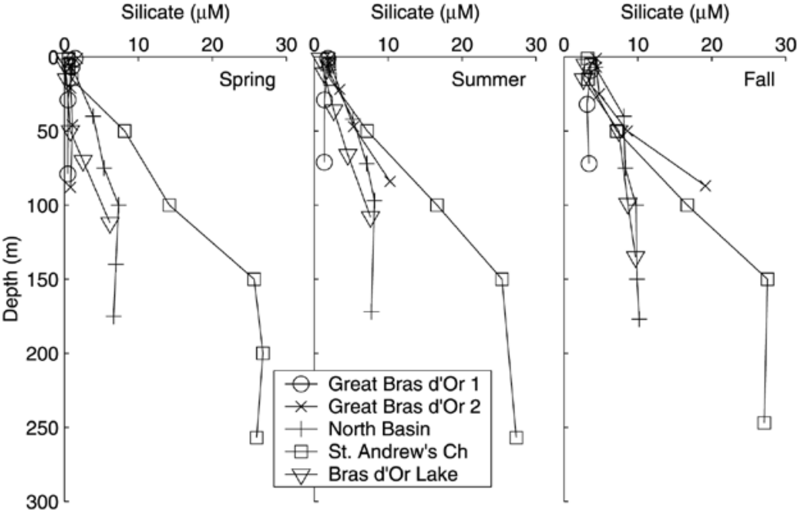

Fig 9 Silicate at 5 deep stations in the Bras d'Or Lakes in 1996 (Strain *et al.*, 2001).

that internal sources and internal recycling processes are more important, and advective transport is less important, for silicate than for nitrate or phosphate.

Dissolved oxygen saturation levels (Fig 10) are almost mirror images of the nitrate profiles (Fig 7); this is expected for the aerobic decomposition of organic matter which consumes oxygen in a constant proportion to the nitrate produced. Dissolved oxygen levels decreased in the southwestern end of the Great Bras d'Or Channel, the North Basin and Bras d'Or Lake from spring to fall, as the decomposition proceeded. However, the dissolved oxygen levels in the deepest samples from St. Andrew's Channel were very consistent, at 57, 55 and 55 % for the spring, summer and fall, respectively. These constant values suggest that the oxygen consumed by regeneration and the oxygen supplied by advection of new water into the basin were approximately in balance during this period. Over longer times, however, the oxygen levels in St. Andrew's Channel do vary: in July, 1974 the oxygen saturation in the deep water was 78 % (Krauel, 1975).

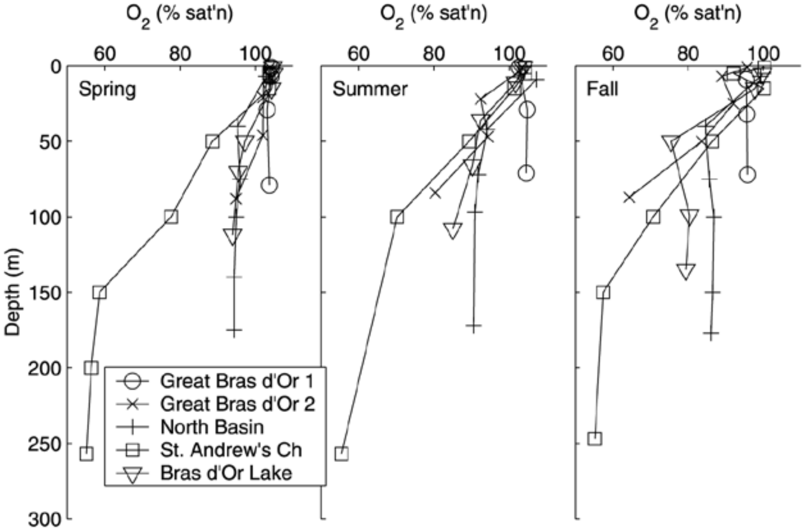

Fig 10 Oxygen saturation at 5 stations in the Bras d'Or Lakes in 1996 (Strain *et al.*, 2001).

Nutrient Conditions in Embayments of the Bras d'Or Lakes

So far the discussion has focussed on nutrient dynamics in the Lakes as a whole, or the major basins within the Lakes. However, the degree of isolation of many of the smaller basins and inlets around the Lakes can lead to conditions that are very different than the average conditions in the Lakes.

Whycocomagh Bay. Fig 11 shows the distribution of nutrients and dissolved oxygen in Whycocomagh Bay for the fall, 1995, and illustrates a number of the processes that occur in many of the smaller embayments in the Lake system. Whycocomagh Bay contains two deep basins separated by a broad, shallow sill (~7 m deep): the western one is narrow and steep-sided with a maximum depth of ~48 m; the eastern one is comparatively wide and gently sloped with a maximum depth of ~38 m. Whycocomagh Bay as a whole has a very restricted connection to the rest of the Lakes through Little Narrows, which is only 100 m wide and ~12 m deep. Gurbutt *et al.* (1993) estimated that the flushing time for the deep waters of the two basins in

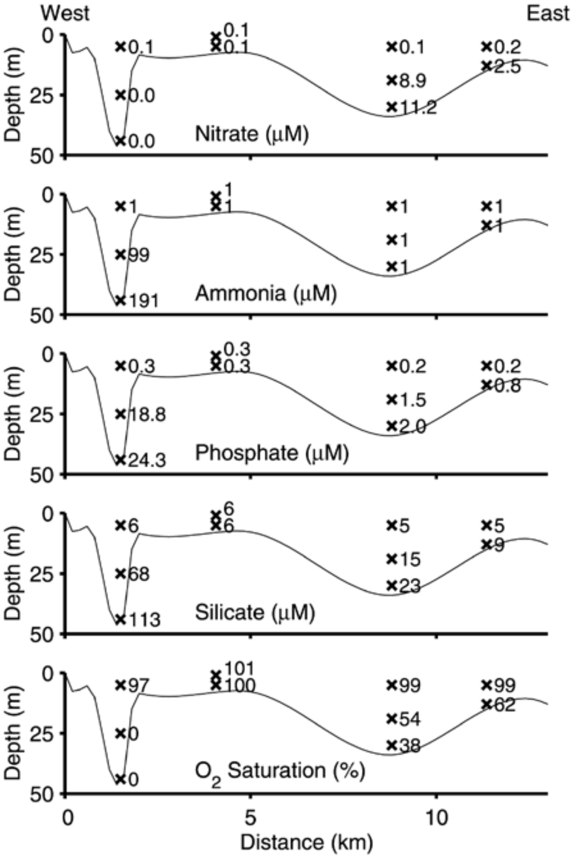

Fig 11 Cross-section of nutrient concentrations and % oxygen saturation in Whycocomagh Bay in the fall of 1995 (Strain *et al.*, 2001). Sample locations are indicated by X's and values for each measurement are given. The depth of the Bay is shown as a continuous line.

Whycocomagh Bay is approximately 2 y. But the nutrient and oxygen data show that the regeneration processes in the two basins are quite different. In the bottom water of the eastern basin, the dissolved oxygen levels were relatively high (38 % saturation), and significantly elevated levels of nitrate (11.2 μM), phosphate (2.0 μM), and silicate (23 μM) were observed. The presence of residual oxygen, high levels of nitrate, and low levels of ammonia all indicate that the organic matter decomposition had occurred aerobically. In the western basin, in contrast, there was no nitrate or oxygen in the deep water, and the ammonia concentration was 191 μM near the bottom. Profiles obtained with a profiling oxygen sensor from 1995-1997 (Strain, unpublished data) show that dissolved oxygen consistently falls to zero at depths between 10 and 15 m in the western basin. Similar results were reported by Krauel (1975) for July 1974, when dissolved oxygen was at 47 % saturation at 15 m, and anoxic by 25 m. Furthermore, sulfide, which does not normally co-exist with oxygen, has been measured in the deep water of the western basin at concentrations of 30-60 μM (Strain *et al.*, 2001). All of these observations indicate that anaerobic decomposition of organic matter (i.e. decomposition in the absence of oxygen) occurs in the western basin. The very high values of phosphate (24 μM) and silicate (113 μM) show that more decomposition products have accumulated in the western basin than in the eastern basin. The most likely reason for the differences between the two basins is that the flushing time of the western basin is significantly longer than that of the eastern basin.

Denys Basin. Denys Basin is a small (~25 km^2) basin of some economic and cultural significance because of its oyster population and the local harvesting of oyster spat. In recent years some of the shellfish areas in Denys Basin have been closed because of unacceptable faecal coliform levels. Possible sources of the contamination are inadequate treatment of domestic sewage and inputs from farms in the River Denys drainage basin. Although there is no sill separating Denys Basin from the rest of the Lakes, the only connection to the Lakes is a narrow winding channel ~7 km long. This isolation raises the possibility that the basin may accumulate inputs; however the average nutrient, dissolved oxygen, and chlorophyll concentrations (Table II) are very similar to those in other areas of the Lakes (Fig 4-6). Denys Basin did show some small differences from the rest of the Lakes. Ammonia levels in the fall were higher in 1996 than in other parts of the Lakes, reaching a maximum value of 7.2 μM, despite the fact that the maximum ammonia level observed in the inflowing rivers in falls from 1993-1997 was only 1.0 μM (Dalziel *et al.*, 1998; Strain *et al.*, 2001). Two observations of oxygen levels between 75 and 80 % saturation were made at 5 m depths in the fall of 1996. These values are not extreme, but even this reduction in O_2 is unusual at such a shallow depth for exposed waters. Even anoxic conditions can occur at depths as shallow as 5 m in protected barachois ponds (Smith and Rushton, 1964).

Table II Concentrations of chlorophyll, nutrients, and dissolved O_2 in Denys Basin (data from Strain *et al.*, 2001). Mean ± 1 σ(n)

	Spring	**Summer**	**Fall**
Nitrate (μM)	0.07 ± 0.14 (12)	0.06 ± 0.04 (6)	0.42 ± 0.60 (20)
Ammonia (μM)	0.97 ± 0.44 (11)	0.68 ± 0.10 (6)	2.08 ± 2.09 (20)
O_2 saturation (%)	102.2 ± 1.9 (6)	108.2 ± 4.7 (6)	92.9 ± 6.9 (16)
Phosphate (μM)	0.15 ± 0.06 (12)	0.18 ± 0.07 (6)	0.23 ± 0.09 (20)
Silicate (μM)	3.94 ± 2.74 (12)	1.44 ± 0.31 (6)	6.19 ± 4.61 (20)
Chlorophyll (μg L^{-1})	0.45 ± 0.28 (6)	0.40 ± 0.08 (5)	1.48 ± 1.30 (6)

Other Small Inlets. Growth and decomposition processes have different impacts in the various small embayments around the Bras d'Or Lakes. Fig 12 shows nitrate, dissolved O_2, ammonia and phosphate profiles for 5 such sites (Fig 3). Herring Cove is a small bay (about ~300 m across) separated from the rest of Baddeck Bay by a sill less than 10 m deep. The Washabuck River site is in a small bay connected to St. Patrick's Channel by a very narrow channel (~20 m wide) over a shallow sill (<5 m deep). St. Peter's 1, another silled basin, is adjacent to the town of St. Peters at the south end of St. Peter's Inlet. It has been the site of finfish aquaculture. St. Peter's 2, also in St. Peter's Inlet, is approximately 4 km from the open Lake, but is not separated from it by a sill. Dena's Pond is a small bay (~0.5 x 1.5 km) that has supported rainbow trout aquaculture for many years and is almost totally isolated from the rest of the Lakes: at its narrowest, the mouth of the pond is approximately 150 m wide, and less than 1 m deep; the maximum depth in the pond is ~25 m. Aerobic decomposition apparently dominates at these sites, given that nitrate concentrations in the bottom water generally increase from spring to fall. The highest nitrate values occur in Herring Cove, Dena's Pond and St. Peter's 1, the 3 bays with significant sills separating them from the open Lakes. Strain and Yeats (1999) showed that the presence/absence of sills is the dominant factor that determines the sensitivity of Nova Scotia inlets to eutrophication (i.e. the build-up of nutrients). Herring Cove also shows a number of differences from the other sites. High levels of ammonia are present in the deep water at all times of year, despite significant levels of dissolved O_2 in spring and summer. It is possible that some anaerobic decomposition also occurs in Herring Cove, especially since dissolved O_2 levels are close to zero in the fall. But another possibility is that there are local inputs of ammonia to Herring Cove. Herring Cove is also one of the few sites in the Lakes that shows high surface concentrations of nitrate in spring and summer, perhaps due to local sources of nitrate. The high summer nitrate level at the surface, together with the low phosphate value, may indicate that primary production in Herring Cove is briefly phosphate limited in the summer. In contrast, Dena's Pond shows very high levels of phosphate, which might be due to extreme isolation of this Pond from the Lakes and the accumulation of wastes from aquaculture operations and other sources.

Organic Contaminants And Heavy Metals

Very few measurements have been made of organic contaminants in the Bras d'Or Lakes. Bailey and Howell (1983) reported 0.104 μg/g of total PAHs in sediment and 0.006 μg/L in water at a station in St. Patrick's Channel off Kidston Island. The Willis (1999) study included measurement of individual PCB and PAH compounds in sediments from 5 sites in the Lakes (Whycocomagh Bay, Baddeck Bay, East Bay, Denys Basin and Nyanza Bay). None of the PCB compounds were present at concentrations above the detection limit of 0.2 ng/g, and none of the PAHs were above the detection limit of 8 ng/g, except for 8.5 ng/g of fluoranthene and 9.3 ng/g of benzo(b)fluoranthene in the sample from Baddeck Bay. None of these concentrations approach any of the Canadian Council of Ministers of the Environment sediment or water quality guidelines for the protection of aquatic life (CCME, 1999).

Young (1973b, c) and Creamer *et al.* (1973) reported concentrations of 9 metals in oysters, mussels and sediments from a number of inlets and bays around the periphery of the Bras d'Or Lakes. Chou *et al.* (1999) have reported concentrations of 21 metals from liver and kidney tissues of winter flounder and sediments from Whycocomagh Bay, Baddeck Bay, East Bay, Denys Basin and Nyanza Bay. Average concentrations determined in these 2 studies conducted 25 years apart and using very different techniques are listed in Table III. The spatial variability that was found during the investigations is discussed in the original papers, but no consistent patterns that showed elevated levels of several metals in any one area were seen. With the exception of the Cd concentration reported by Creamer *et al.* (1973), all the average sediment concentrations are below Probable Effects Levels quoted in the CCME (1999) quality guidelines. Cd levels measured in 1972 should probably be considered unreliable because of limitations of the analytical techniques that were generally used for Cd at that time. The more recent results (Chou *et al.*, 1999) show Cd levels are well below the guideline. Biota levels are also low except for the Zn value reported for oysters. Oysters are known to bioaccumulate Zn, even in the absence of elevated environmental concentrations, and the levels found in the Lakes are not high compared to those found elsewhere (Young, 1976).

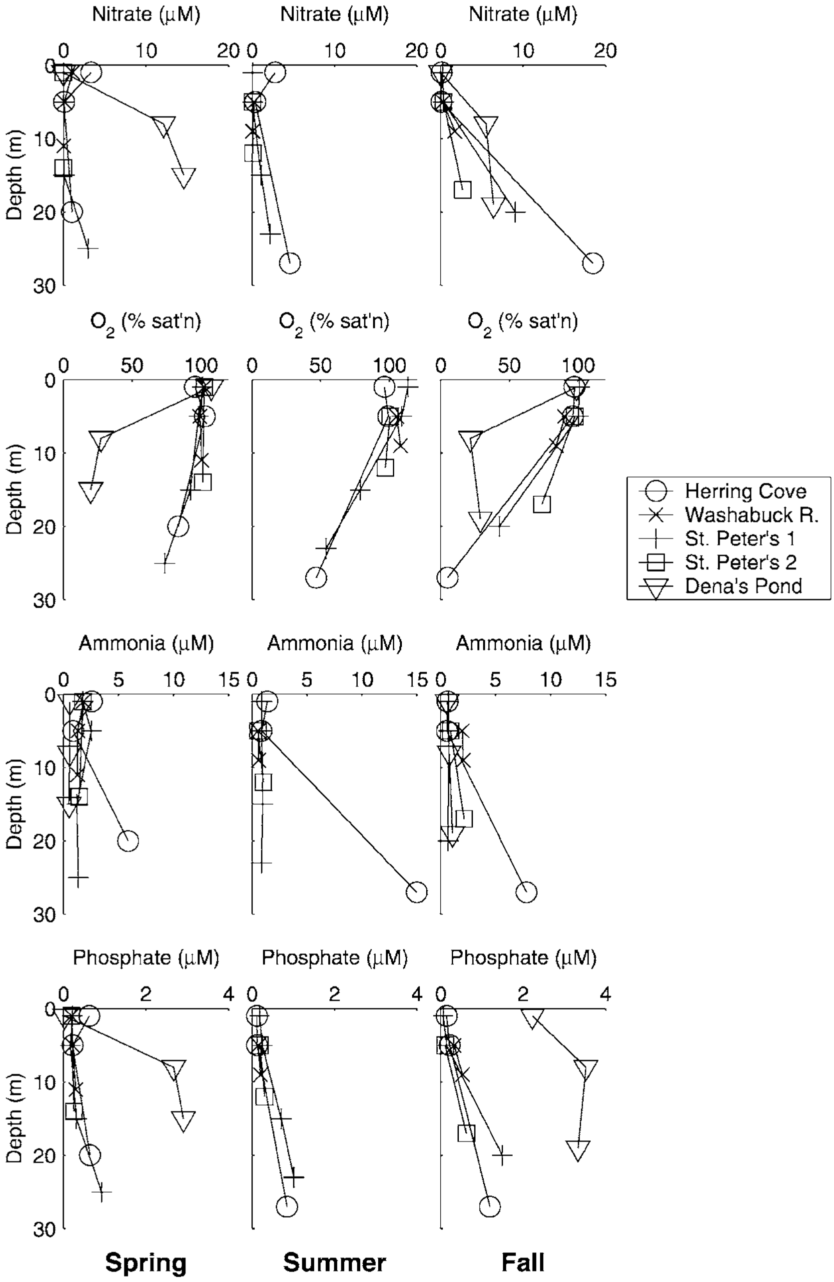

Fig 12 Nitrate, ammonia, and phosphate (μM) and % oxygen saturation in 5 embayments around the Bras d'Or Lakes (Strain *et al.*, 2001). See Fig 3 for locations.

Table III Average metal levels in biota and sediments from the Bras d'Or Lakes (biota, μg/g wet, and sediments μg/g dry).

Metal	Oyster[1]	Mussel[2]	Sediment[3]	Flounder kidney[4]	Flounder liver[4]	Sediment[4]
Al	19.7	15				
Ag					0.36	0.069
As				1.27	13.6	6.37
Cd	1.28	0.6	18	0.13	0.66	0.15
Co				0.16	0.41	5.62
Cr	0.086	0.18	79	0.62	0.67	31.9
Cu	20.9	2.0	58	0.77	11.1	10.5
Fe	43.7	35	27000			
Hg	0.037					
Li				0.09	0.06	32.6
Mn	8.3	11	720	1.07	1.71	136
Mo				0.07	0.17	1.71
Ni				0.78	0.72	72.6
Pb	0.90	2.0	95	0.05	0.07	5.42
Se				2.92	2.46	4.61
Sr	1.36	1.5		0.86	0.51	13.7
Ti				0.34	0.29	1445
Tl				0.003	0.003	0.27
U				0.022	0.015	2.12
V				0.97	0.99	51.4
Zn	931	26	97	30.9	41.6	47.0

[1] Young, 1973b

[2] Young, 1973c

[3] Creamer et al., 1973

[4] Chou et al., 1999

Table IV Comparison of dissolved metal concentrations in the Bras d'Or Lakes waters with those in other areas (mean ± standard deviation).

Bras d'Or [1] 13 samples	Halifax Hbr [2] 63 samples	Pictou Hbr [3] 19 samples	Ship Hbr [4] 42 samples	SydneyHbr[4] 32 samples	
Cd (μg L^{-1})	0.021±0.010	0.036±0.011	0.033±0.010	0.022±0.006	
0.023±0.006	Cu (μg L^{-1})	0.29±0.03	0.42±0.15	0.60±0.24	
0.22±0.04	0.46±0.11	Fe (μg L^{-1})	1.2±0.9	2.3±1.2	
6.9±4.4	2.7±1.6	3.3±3.3	Mn (μg L^{-1})	1.5±1.1	
1.8±1.0	2.7±1.8	2.9±1.8	7.1±3.9	Ni (μg L^{-1})	
0.22±0.04	0.47±0.17	0.36±0.06	0.30±0.11	0.43±0.19	Pb (μg L^{-1})
0.011±0.008	0.057±0.064	0.046±0.023	0.015±0.010	0.028±0.013	Zn (μg L^{-1})
0.83±0.69	3.1±1.9	1.2±0.6	1.0±0.9	1.0±1.0	
Hg (ng L^{-1})	0.80±0.19	1.01±0.67			

[1] Survey 95908, Strain et al., 2001.

[2] Dalziel et al, 1991.

[3] Dalziel et al., 1993.

[4] Yeats, unpublished data.

Early studies of dissolved metal concentrations in Lake waters (Young *et al.*, 1959; Young, 1976) are of little value because of limitations of the analytical techniques. More recently, a small number of dissolved metal concentrations in the Bras d'Or Lakes were measured on two surveys (Strain *et al.*, 2001). The first survey (BIO cruise 95908, Sept 1995) showed that concentrations at 11 stations throughout the Lakes (Table IV) were consistently lower than those found in the more industrialized Halifax, Pictou and Sydney Harbours (Dalziel *et al.*, 1991, 1993; and Yeats, unpublished data) and more comparable to those in relatively pristine Ship Harbour (Yeats, unpublished data) despite the fact that salinities in the Lakes are only 20-25. We would expect lower salinities to result in higher concentrations because freshwater concentrations of these metals are generally higher than those in seawater. Metal concentrations in the Cape Breton rivers, however, are generally relatively low (Dalziel *et al.*, 1998).

In the second survey, only near bottom samples from basins with restricted water exchange were collected. Several of these had depleted oxygen concentrations (one was anaerobic). Dissolved iron and manganese concentrations were much higher (by a factor of approximately 500) in these oxygen depleted waters than elsewhere in the Lakes. Cd, Ni, Pb and Zn concentrations were unaffected and Cu was higher in only one sample (Dena's Pond). These measurements were part of a larger dataset used in a study of eutrophic bottom waters in Nova Scotia inlets (Strain and Yeats, 1999) that showed that Fe and Mn concentrations, but not those of Cd, Cu, Ni, Pb or Zn, are affected by the reduced oxygen concentrations that accompany eutrophication. The elevated concentrations of Fe and Mn result from their natural redox chemistry (the lower oxidation state compounds of Fe and Mn are more soluble than the higher oxidation state ones), not from pollution.

Metal Inputs. The main source of heavy metals in the Lakes is inflowing water from Sydney Bight through the Great Bras d'Or Channel. This source is greater by approximately an order of magnitude than inputs from either atmospheric precipitation or river runoff. Calculated inputs from rivers, offshore exchange, precipitation and sewage are shown in Table V. River inputs are based on the concentration data in Dalziel *et al.* (1998), the offshore inputs on data for metal concentrations in Sydney Bight (Yeats *et al.*, 1998 and unpublished data from surveys of Sydney Harbour), and precipitation and sewage concentrations from generic assessments of concentrations in these two inputs (Bond and Straub, 1974; GESAMP, 1989; Petrie and Yeats, 1990; MacNeil and Hurlbut, 2000). There were enough data to generate seasonal values only for the river inputs, all the rest are annual averages. Water transports are the same as those used for calculating nutrient inputs. The dominance of the Sydney Bight inputs in Table V is somewhat artificial because the exchange through the Great Bras d'Or Channel will have the greatest impact on the parts of the Lake closest to it, while inputs from precipitation, rivers and sewage will be distributed throughout the Lakes.

Table V Inputs of metals to the Bras d'Or Lakes.

	Units	Precip	Rivers			Sewage	Sydney Bight
			Spring	Summer	Fall		
SPM	mg m^{-2} d^{-1}	11.0	12.3	4.7	8.9	0.67	145
Al	μg m^{-2} d^{-1}	880	1100	240	840	0.58	12600
As	μg m^{-2} d^{-1}	0.18	2.5	2.3	2.4	0.20	105
Cd	ng m^{-2} d^{-1}	102	113	97	99	0.003	2600
Cu	μg m^{-2} d^{-1}	1.10	5.2	7.1	3.8	0.20	36
Fe	μg m^{-2} d^{-1}	380	1100	310	980	3.6	7800
Mn	μg m^{-2} d^{-1}	1.21	73	62	140	1.05	350
Ni	μg m^{-2} d^{-1}	0.79	3.2	2.9	3.6	0.036	40
Pb	ng m^{-2} d^{-1}	2800	1300	560	920	0.024	9500
Zn	μg m^{-2} d^{-1}	4.4	11.9	6.2	11.0	0.38	59

Seasonal average metal concentrations in Bras d'Or waters can be estimated using a geochemical model similar to that developed by Petrie and Yeats (1990) for Halifax Harbour with additional terms for particle reactivity of the metals. Water transports for the model are taken from Gurbutt and Petrie (1995) and input data from various sources identified above. The model uses partition coefficients (K_d's) to estimate the fractionation of metals between dissolved and particulate forms, and estimates of particle settling velocities to estimate the flux of metals to the sediments. In the absence of extensive measurements of contaminant concentrations in Lake waters, results from models such as this give some estimate of concentrations that may be expected. Model results for dissolved and particulate Al, Cd, Cu, Fe, Pb, Ni and Zn concentrations in the 20 boxes of the Gurbutt and Petrie water circulation model are shown in Table VI. Arsenic was entirely in solution and varied from 1.0 to 1.2 μgL^{-1}. For Cd, Cu, Pb, Ni and Zn, the agreement between the model results and the very few observations that have been made is good (results generally agree within a factor of 2). The model seriously overestimates dissolved Fe in the North Basin but underestimates concentrations in Whycocomagh Bay. There are no observations for Al and As available for comparison with model predictions. The model can also be used to estimate metal concentrations in material settling out of the water column (Table VII). The predicted concentrations in sedimenting material are within the ranges for sediments in the Lakes listed in Table III or those for Nova Scotia embayments (Loring *et al.*, 1996), except for Cd which is high by a factor of approximately 2-4. The model is very much dependant on the metal concentrations in water flowing into the Lakes through the Great Bras d'Or Channel (see Table V for the relative importance of various input terms). For suspended particulate material (SPM) and the particulate dominated metals Al and Fe, this input is not well constrained. The limited data suggest that these inflowing waters have rather high (1.8 mgL^{-1}) concentrations for predominantly inorganic SPM. Lower SPM concentrations or SPM with a more biogenic character would reduce the inputs substantially and provide a better agreement with observations for Fe.

Table VI Model predictions of summer dissolved and particulate water column concentrations of trace metals for each box of the Gurbutt & Petrie (1995) model. All concentrations in μg L^{-1}. (diss = dissolved, part = particulate, Btm = bottom)

Location		**Al**	**Cd**	**Cu**	**Fe**	**Pb**	**Ni**	**Zn**
Whycocomagh W								
0-10 m	diss	0.19	0.022	0.39	0.25	0.0079	0.29	0.50
	part	3.4	0.0005	0.018	2.7	0.0072	0.013	0.023
10-Btm	diss	0.18	0.021	0.38	0.24	0.0076	0.28	0.48
	part	3.4	0.0005	0.018	2.7	0.0072	0.013	0.023
Whycocomagh E								
0-10 m	diss	0.23	0.022	0.39	0.30	0.0084	0.30	0.50
	part	4.1	0.0005	0.018	3.2	0.0077	0.014	0.023
10-Btm	diss	0.21	0.020	0.36	0.27	0.0078	0.28	0.47
	part	4.1	0.0005	0.018	3.2	0.0077	0.014	0.023
West Bay								
0-10 m	diss	0.1	0.021	0.26	0.10	0.0046	0.24	0.41
	part	1.7	0.0005	0.011	1.1	0.0041	0.011	0.018
10-Btm	diss	0.16	0.023	0.27	0.16	0.0056	0.26	0.43
	part	3.0	0.0005	0.013	1.9	0.0054	0.013	0.021
East Bay								
0-10 m	diss	0.06	0.019	0.21	0.06	0.0037	0.19	0.34
	part	1.1	0.0004	0.009	0.6	0.0032	0.008	0.015
10-Btm	diss	0.10	0.022	0.25	0.10	0.0044	0.25	0.41
	part	1.9	0.0005	0.012	1.1	0.0042	0.012	0.020
St. Andrew's Channel								
0-10 m	diss	0.11	0.021	0.23	0.10	0.0046	0.23	0.38
	part	1.9	0.0005	0.010	1.1	0.0041	0.010	0.017
10-50 m	diss	0.35	0.023	0.28	0.35	0.0077	0.28	0.45
	part	7.3	0.0006	0.014	4.4	0.0080	0.015	0.023
50-Btm	diss	0.33	0.023	0.28	0.33	0.0073	0.28	0.45
	part	6.8	0.0006	0.014	4.1	0.0076	0.014	0.023
St. Patrick's Channel								
0-10 m	diss	0.28	0.022	0.38	0.35	0.0090	0.30	0.50
	part	5.1	0.0005	0.018	3.9	0.0083	0.014	0.023
10-Btm	diss	0.55	0.024	0.33	0.60	0.011	0.31	0.50
	part	13	0.0007	0.019	8.3	0.013	0.018	0.029
Bras d'Or Lake								
0-10 m	diss	0.14	0.022	0.25	0.14	0.0052	0.24	0.41
	part	2.5	0.0005	0.011	1.5	0.0047	0.011	0.018
10-Btm	diss	0.42	0.023	0.28	0.43	0.0086	0.29	0.46
	part	8.9	0.0006	0.015	5.4	0.0091	0.015	0.024
North Basin								
0-15 m	diss	0.56	0.023	0.29	0.58	0.0094	0.27	0.45
	part	12	0.0006	0.015	7.4	0.010	0.015	0.024
15-30	diss	1.2	0.025	0.31	1.2	0.016	0.32	0.50
	part	39	0.0010	0.025	24	0.025	0.025	0.040
30-Btm	diss	1.2	0.025	0.31	1.2	0.016	0.32	0.50
	part	39	0.0010	0.025	24	0.025	0.025	0.040
Great Bras d'Or Channel								
0-15 m	diss	0.83	0.023	0.29	0.84	0.012	0.29	0.46
	part	20	0.0007	0.018	12	0.014	0.018	0.028
15-Btm	diss	1.4	0.025	0.32	1.5	0.018	0.33	0.51
	part	52	0.0011	0.029	32	0.031	0.029	0.046

Table VII Model predictions of metal concentrations in settling particulate matter (μg/g).

Location	Al	As	Cd	Cu	Fe	Pb	Ni	Zn
Whycocomagh W	7100	3.0	1.0	38	5700	15	28	48
Whycocomagh E	8300	3.0	1.0	36	6500	16	28	47
West Bay	6200	3.5	1.1	27	3900	11	26	43
East Bay	4000	3.6	1.1	25	2400	9	25	41
St. Andrew's Ch	13100	3.5	1.2	28	7900	15	28	45
St. Patrick's Ch	21800	3.6	1.2	33	14400	22	31	50
Bras d'Or Lake	16800	3.6	1.2	28	10300	17	29	46
North Basin	49200	3.6	1.2	31	30000	32	32	50
Great Bras d'Or	58100	3.6	1.3	32	35300	35	33	51

Summary

The isolation of the Bras d'Or Lakes from shelf waters, the relatively small watershed, the variations in basin size and depth, and the size of connections between different basins are all factors that lead to the creation of a number of different chemical environments within the Lakes. For the Lakes as a whole, the relatively small amounts of nutrients delivered by rivers and the small inputs of nutrients from the shelf that can be brought in through the Great Bras d'Or Channel only support a relatively low level of natural biological productivity. Nutrient distributions at the end of winter before the onset of the spring bloom are unknown. Collection of winter data will provide actual measurements of nutrient concentrations prior to the spring bloom and allow a better understanding of the factors that control the concentrations and variability of nutrients in the deep basins of the Lakes. The Lakes as a whole should be relatively unaffected by new inputs of nutrients from human activities and are at low risk for eutrophication. However, localized build-ups of nutrients, including inputs from sewage, agriculture and aquaculture, have already affected the water quality of some microenvironments in the Lakes. Sites like the west end of Whycocomagh Bay and the many barachois ponds are most susceptible to such eutrophication, which is evident in reduced oxygen concentrations or even anoxia, and which may be accompanied by bacterial contamination that results in closures to shellfish areas and restrictions on recreational use. The available data on persistent organic and heavy metal contaminants are limited. A more comprehensive picture of contaminants in the Lakes will require a large sampling program that gives better spatial and temporal coverage including analyses for more contaminants (especially organic ones). However, based on the data now available, there is no indication that any persistent organic or heavy metal contaminants are a concern within the Lakes at present concentrations in water, sediments or biota. Overall, the environmental quality is very good. This status is a result of the small population density and the very limited industrial development around the Lakes. However, this relatively pristine character of the Lakes does not imply that they are immune to environmental degradation: any management decision must consider potential impacts for both the entire Lake system and the particular microenvironments that may be involved. Maintaining or improving the environmental quality of the Lakes will require careful management of current and future activities in the Lakes and their watershed.

References

Arseneau, D.F., Arseneau, A.J. and **Rogers, C.** 1977. The waters of East Bay, Cape Breton Island. Bras d'Or Institute of the College of Cape Breton. Technical Bulletin No. 2, 78 pp.

Bailey, H.S. and **Howell**, **G.D.** 1983. Survey of toxic organic constituents in the Atlantic Regions aquatic environment (1979-1981). *Env. Can. Rep.* IWD-AR-WQB-83-48, 61 pp.

Bond, R.G. and **Straub, C.P.** 1974. *CRC Handbook of Environmental Control*, Vol. IV: *Wastewater treatment and disposal*, pp. 62-67. CRC Press, Cleveland, Ohio.

Bricker, S.B., Clement, C.G., Pirhalla, D.E., Orlando, S.P and **Farrow, D.R.G.** 1999. National Estuarine Eutrophication Assessment: Effects of nutrient enrichment in the nation's estuaries. NOAA, National Ocean Service, Special Projects Office and the National Center for Coastal Ocean Science. Silver Spring, MD, 71 pp.

CCME (Canadian Council of Ministers of the Environment). 1999. Environment Canada, Canadian Environmental Quality Guidelines website: www.ec.gc.ca/ceqg-rcge.

Chandler, A. 2001. (Nova Scotia Department of Agriculture and Fisheries, Halifax, N. S.) Personal Communication.

Chou, C.L., Zwicker, B.M, Moffatt, J.D. and **Paon, L.** 1999. Elemental concentrations in the livers and kidneys of winter flounder (*Pseudopleuronectes americanus*) and associated sediments from various locations in the Bras d'Or Lakes, Nova Scotia, Canada. *Can. Tech. Rep. Fish. Aquat. Sci.* 2284: ix + 116 pp.

Creamer, R., Giles, M., MacDonald, J.H. and **Young, J.C.O'C.** 1973. Metals contents of silt samples from Bras d'Or Lake and influent rivers. St. Mary's University ESG Rep. 73-04. *In Silt, water and miscellaneous molluscs*. Environmental Studies Group, St. Mary's University, Halifax, Nova Scotia.

Dalziel, J.A., Amirault, B.P. and **Rantala, R.T.T.** 1991. The distribution of nutrients, suspended solids, dissolved and particulate metals in Halifax Harbour. *Can. Tech. Rep. Fish. Aquat. Sci.* 1826, iii + 60 p.

Dalziel, J.A., Yeats, P.A. and **Amirault, B.P.** 1998. Inorganic chemical analyses of major rivers flowing into the Bay of Fundy, the Scotian Shelf and the Bras d'Or Lakes. *Can. Tech. Rep. Fish. Aquat. Sci.* 2226: vii + 140 pp.

Dalziel, J.A., Yeats, P.A. and **Loring, D.H.** 1993. Water chemistry and sediment core data from Pictou Harbour and the East River estuary. *Can. Tech. Rep. Fish. Aquat. Sci.* 1917, iv + 78 pp.

Geen, G.H. 1965. Primary Production in Bras d'Or Lakes and other inland waters of Cape Breton Island, Nova Scotia. Ph.D. thesis, Dalhousie University, Halifax, N.S. 187 pp.

Geen, G.H. and **Hargrave, B.T.** 1966. Primary and secondary production in Bras d'Or Lake, Nova Scotia, Canada. *Int. Ver. Theor. Angew. Limnol. Verh.* 16: 333-340.

GESAMP 1989. The atmospheric input of trace species to the world ocean. IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution, *Rep. Stud. GESAMP* 38, World Meteorological Organization, 111 pp.

Gurbutt, P.A., Petrie, B. and **Jordan, F.** 1993. The physical oceanography of the Bras d'Or Lakes: Data analysis and modelling. *Can. Tech. Rep. Hydrogr. Ocean Sci.* 147: vii + 61 pp.

Gurbutt, P.A. and **Petrie, B.** 1995. Circulation in the Bras d'Or Lakes. *Est. Coast. Shelf Sci.* 41: 611-630.

Harrison, G. 2001. (Biological Ocean Sciences, Bedford Institute of Oceanography, Dartmouth, N. S.) Personal communication.

Keizer, P.D., Bugden, G., Subba Rao, D.V. and **Strain, P.M.** 1996. Long-term monitoring program: Indian Point and Sambro, Nova Scotia, for the period July 1992 to December 1994. *Can. Data Rep. Fish. Aquat. Sci.* 980: v + 20 pp.

Kirk, J.T.O. 1983. *Light and photosynthesis in aquatic ecosystems.* Cambridge University Press, Cambridge, U.K. xi + 401 pp.

Krauel, D.P. 1975. The physical oceanography of the Bras d'Or Lakes 1972-1974. Bedford Institute of Oceanography, *Fish. Mar. Sci. Serv. Tech. Rep.* 570: 357 pp.

Loring, D.H., Rantala, R.T.T. and **Milligan, T.G.** 1996. Metallic contaminants in the sediments of coastal embayments of Nova Scotia. *Can. Tech. Rep. Fish. Aquat. Sci.* 2111, viii + 268 pp.

Loring, D.H. and **Nota, D.J.G.** 1973. Morphology and sediments of the Gulf of St. Lawrence. *Bull. Fish. Res. Board Can*. 182, 147 pp.

MacNeil, M. and **Hurlbut, S.** 2000. Oceanographic modelling and assimilative capacity study project # 99-096, prepared for Halifax Harbour Solutions Project. Coastal Ocean Associates, Dartmouth, N.S., iii + 85 pp.

Mucci, A. and **Pagé, P.** 1987. The water chemistry of cruise 85-036 on Bras d'Or Lake, Cape Breton Island, Nova Scotia. *Geol. Surv. Can. Paper* 87-1A, Current Research Part A, p. 17-24 (vol. 1).

Mueller, J.A. and **Anderson, A.R.** 1983. Municipal sewage systems. In *Ocean disposal of municipal wastewater: impacts on the coastal environment.* (Eds. E.P Myers and E.T. Harding). *Mass. Inst. Tech. Sea Grant College Program Pub*. 83-33, Cambridge, Mass. Vol. 1, pp. 37-92.

O'Neill, H.J. 1988. An assessment of Atlantic Region Water Quality Branch toxic chemical data. Env. Can. Rep. IW/L-AR-WQB-88-140, 80 pp.

O'Neill, H.J. and **Kieley, K.M.** 1992. Polynuclear aromatic hydrocarbons: Atlantic Region data summary and review. *Env. Can., C&P Atlantic Region Tech. Rep. Ser.* 92-01, 64 pp.

Petrie, B. and **Bugden, G.** 2002. The physical oceanography of the Bras d'Or Lakes. *Proc. N.S. Inst. Sci.* 42: 9-36.

Petrie, B. and **Yeats, P.** 1990. Simple models of the circulation, dissolved metals, suspended solids and nutrients in Halifax Harbour. *Water Poll. Res. J. Can*. 25: 325-349.

Petrie, B., Yeats, P. and **Strain, P.** 1999. Nitrate, silicate and phosphate atlas for the Scotian Shelf and Gulf of Maine. *Can. Tech. Rep. Hydrog. Ocean Sci.* 203: vii + 96 pp.

Ruohonen, K., Vielma, J. and **Grove, D.J.** 1998. Comparison of nutrient losses into the water from rainbow trout based on fresh Baltic herring, moist and dry diets. *Aquaculture Int*. 6: 441-450.

Smith, M.W. and **Rushton, D.K.** 1964. A study of the barachois ponds in the Bras d'Or Lake area of Cape Breton, Nova Scotia. *Proc. Nova Scotian Inst. Sci*. 26: 3-17.

Strain, P.M. 2002. Nutrient dynamics in Ship Harbour, Nova Scotia. *Atmosphere-Ocean* 40 : 45-58.

Strain, P.M, Bugden, G., Brylinsky, M. and **Denny, S.** 2001. Nutrient, dissolved oxygen, trace metal and related measurements in the Bras d'Or Lakes, 1995 – 1997. *Can. Data Rep. Fish Aquat. Sci.* 1073: iv + 52 pp.

Strain, P.M., Wildish, D.J. and **Yeats, P.A.** 1995. The application of simple models of nutrient loading and oxygen demand to the management of a marine tidal inlet. *Mar. Poll. Bull.* 30: 253 - 261.

Strain, P.M. and **Yeats, P.A.** 1999. The relationships between chemical measures and potential predictors of the eutrophication status of inlets. *Mar. Poll. Bull.* 38: 1163-1170.

Willis, D. 1999. Biological Assessment of Pollution. *Presented at:* Bras d'Or Lakes Ecosystem Workshop, Westmount, Nova Scotia, Oct. 22-24. Workshop Report by T. Lambert, Department of Fisheries and Oceans, Canada, iii + 47 pp.

Wright, R.A. 1976. Some production parameters at select Bras d'Or sites. In *The proceedings of the Bras d'Or Lakes aquaculture conference*. (ed. G.W. McKay), College of Cape Breton Press, pp. 54-66.

Yeats, P.A., Dalziel, J.A. and **Milligan, T.G.** 1998. Water chemistry measurements associated with mine water discharge into coastal waters off Nova Scotia. *Can. Tech. Rep. Fish. Aquat. Sci.* 2242, vi + 28 pp.

Young, E.G., Smith, D.G. and **Langille, W.M.** 1959. Chemical composition of sea water in the vicinity of the Atlantic Provinces of Canada. *J. Fish. Res. Bd. Can.* 16: 7-12.

Young, J.C.O'C. 1973a. Exploratory studies of phytoplankton chlorophyll levels and oyster growth in Cape Breton Island waters. St. Mary's University ESG Rep. 73-02. In *Rocks, phytoplankton and oysters.* Environmental Studies Group, St. Mary's University, Halifax, Nova Scotia.

Young, J.C.O'C. 1973b. Metal content of oysters found in Cape Breton Island waters. St. Mary's University ESG Rep. 73-03. In *Rocks, phytoplankton and oysters.* Environmental Studies Group, St. Mary's University, Halifax, Nova Scotia.

Young, J.C.O'C. 1973c. Metal content of miscellaneous molluscs found in Cape Breton Island waters. St. Mary's University ESG Rep. 73-06. In *Silt, water and miscellaneous molluscs.* Environmental Studies Group, St. Mary's University, Halifax, Nova Scotia.

Young, J.C.O'C. 1976. Aquaculture and chemistry of Bras d'Or. In *The proceedings of the Bras d'Or Lakes aquaculture conference*. (ed. G.W. McKay), College of Cape Breton, Press, pp. 17-28.

(Received 1 March 2002)