THE

ONTARIO WATER RESOURCES

COMMISSION

THE ROLE OF NUTRIENTS AND THEIR BUDGETS in the BAY OF QUINTE, LAKE ONTARIO

August, 1970

The Role of Nutrients and their Budgets in the Bay of Quinte, Lake Ontario

M. G. Johnson[1]
Special Studies Branch, Division of Research

and

G. E. Owen
Biology Branch, Division of Laboratories

Ontario Water Resources Commission

August, 1970

[1] Present address: Department of Zoology, University of Guelph, Guelph, Ontario.

ABSTRACT

The Bay of Quinte shows symptoms of cultural eutrophication which are markedly similar to those of Lake Erie. Algal blooms are severe and prolonged, and macroinvertebrate and fish communities are composed of pollution-tolerant species.

The bay received about 9,700,000 pounds of nitrogen and 700,000 pounds of phosphorus in 1968. Of these total inputs 89% of the nitrogen and 60% of the phosphorus were attributable to land drainage and the remainder of each nutrient to municipal-industrial sources.

Comparison of absolute inputs is shown to be ecologically unsound because low-volume high concentration inputs are compared directly with high-volume, low-concentration river inputs. Comparisons based on "net inputs" are proposed; "net input" is defined as the amount of nutrient contained in an input in excess of the amount of nutrient in the equivalent volume of water displaced at the outlet. In the Bay of Quinte about 50% of the "net input" of nitrogen and 85% of phosphorus were contributed by municipal-industrial sources in 1968.

Phosphorus removal from high-concentration, low-volume inputs i.e. municipal-industrial sources, is recommended. The high turnover rate of water in the bay, five times annually, should contribute towards improved water quality by translocating re-suspended nutrients from sediments in shallow water of the inner bay to sediments in deeper waters of the outer bay and Lake Ontario. The estimated cost

of nutrient removal, 200,000 dollars per year, is apparently justified in view of the importance of the local tourist trade (about one million visitors in 1968 spent 7.8 millions of dollars) and its future viability in the face of deteriorating water quality conditions.

INTRODUCTION

Among the symptoms of so-called cultural eutrophication which sums the variety of human activities contributing to excessive enrichment of lake waters, are nuisance blooms of algae, increased turbidity, depletion of deep-water oxygen and changes in the composition of communities of algae, invertebrates and fishes. These symptoms are increasingly obvious in the Bay of Quinte of Lake Ontario, which is indeed unfortunate because this bay is one of the finest natural features of the St. Lawrence Great Lakes.

The purpose of this paper is to describe the severity of these symptoms, to associate these with the increased human activity on the Bay of Quinte which has led to increased input of nutrients, to describe the nutrient budget of the bay, and, finally, to clarify the respective significance of contributions from tributary rivers and from municipal-industrial sources.

THE BAY OF QUINTE AND ITS WATERSHED

The Bay of Quinte is a Z-shaped bay 87 mile^2 in area on the northeastern shore of Lake Ontario (Fig. 1). The inner bay, 22 miles long, consists of several connected basins, 12 to 25 feet deep, which vary in width between 1 and 3.5 miles. The greatest human development in extent and rate of growth is along the north shore of the inner

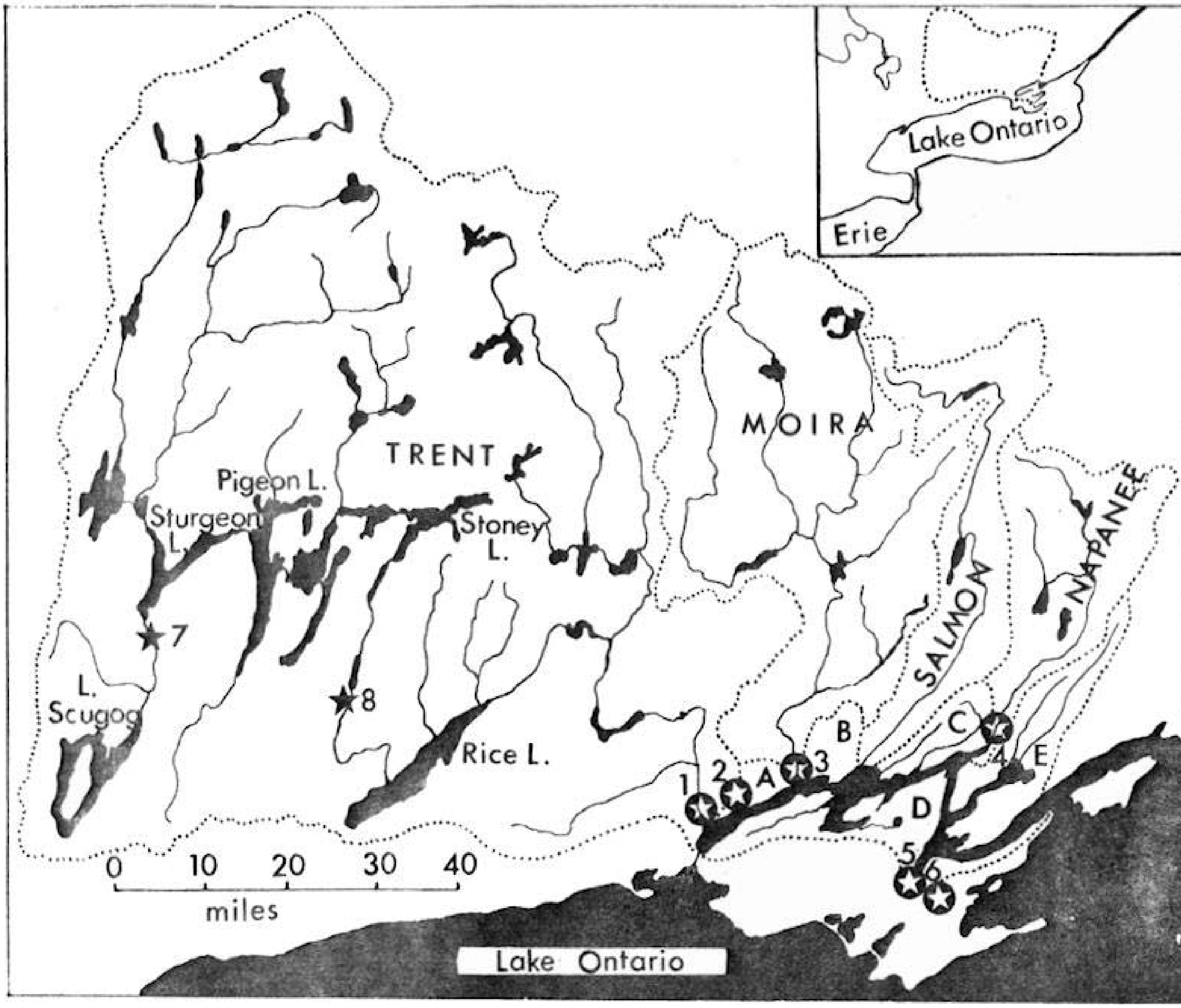

Fig. 1. Bay of Quinte watershed showing the major river systems, the larger lakes and major urban centers; 1, Trenton; 2, Department of National Defence (DND) at Trenton; 3, Belleville; 4, Napanee; 5, Picton; 6, DND Picton; 7, Lindsay and 8, Peterborough. Small watersheds where streams were not sampled are indicated as areas A to E.

bay, where the total 1968 population was about 75,000. The population in this area has increased from 50,000 since 1953. Also, the Trent River draining 4,870 $mile^2$, the Moira River draining 1,040 $mile^2$, and the Salmon and Napanee rivers together draining 640 $mile^2$ enter along the north shore of the inner bay. The middle bay is 8 miles long, about 0.5 mile wide at the north and 3.5 miles wide near Picton, and 19 to 56 feet in depth. The outer bay is 10 miles long, about 2 miles wide; the maximum depth increases from 56 feet to 170 feet towards the bay mouth. The watershed of the middle and outer bays is not extensive, but includes Hay Bay, 7 miles long, and its watershed. Only about 15,000 people reside in the towns and townships bordering the middle and outer bays.

Trenton, Belleville, Napanee and two bases of the Canada Department of National Defence near Trenton and Picton (the latter was closed in 1969) have conventional secondary or partial waste treatment (Fig. 1), but, to date, no special measures have been taken for nutrient removal from any of these waste effluents. Two municipalities, Belleville and Deseronto, take water from the bay for domestic and industrial use. Quality is often unsatisfactory and treatment to produce potable water is beset with many difficulties, attributable to the continuously high algal densities and the thick blooms of blue-green algae which develop every summer. The bay is used throughout its length for varied recreational activities, many of which are curtailed by unsatisfactory water quality. Water quality improves lakeward.

Two passages, one at each end of Amherst Island, join the lower bay and Lake Ontario. The western passage is 1.5 miles wide and 43 feet deep, and the eastern passage is of similar width but twice as deep. The inner arm of the bay is connected to Lake Ontario for navigation purposes near Trenton by the Murray Canal, which is only about 75 feet wide and 9 feet deep.

The watershed of the Bay of Quinte (Fig. 2), which totals 7,030 mile^2 at the bay mouth, consists of about one-half Precambrian Shield and one-half Palaeozoic limestones, which in many areas have little overburden. The Kawartha Lakes lie along the juncture of the rocky, forested hills of the Shield and till plains to the south, except for Rice and Scugog lakes near the kame moraine which forms the southern height of land of the Trent watershed. Extensive sand and clay plains occur throughout the southern half of the watershed, particularly in the lower Trent and Napanee watersheds.

The two important municipalities, Lindsay with a 1968 population of 11,800 and Peterborough with a population of 54,060, are at considerable distances upstream from the Bay of Quinte (Fig. 1), and exert their greatest influence on deteriorating water quality in Sturgeon Lake and Rice Lake respectively.

EFFECTS OF EXCESS NUTRIENTS

The earliest biological data on the Bay of Quinte are those on the fisheries (Hart 1930, 1931). The whitefish, *Coregonus clupeaformis* (Mitchill), once ascended in spawning migrations as far as Big Bay but this particular population is apparently now extinct. In addition, the prized sport fishery for walleye, *Stizostedion vitreum* (Mitchill),

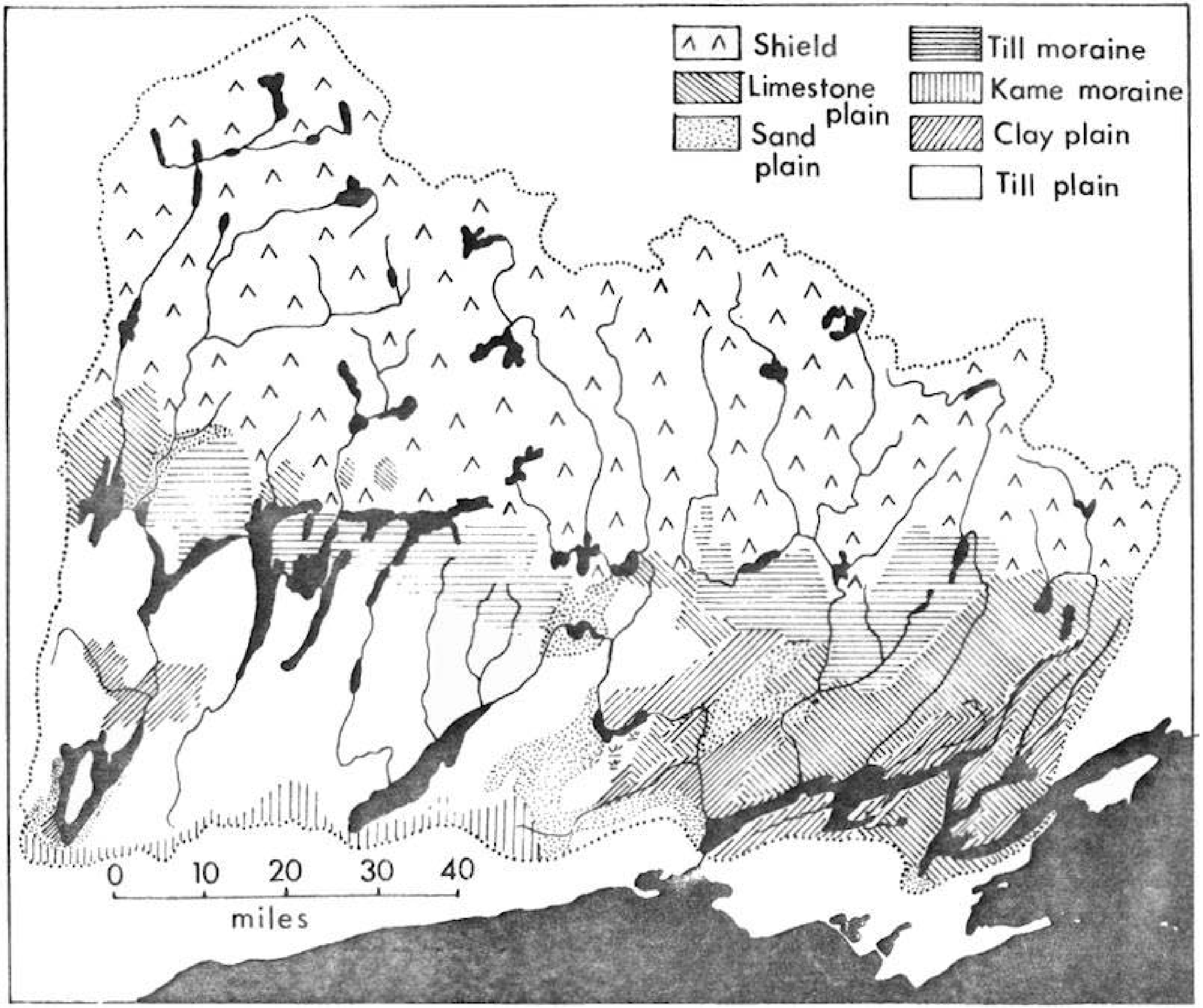

Fig. 2. Physiography of the Bay of Quinte watershed. Further interpretation is made in the text.

in the bay and the commercial whitefish fishery off the bay mouth in Prince Edward Bay have declined drastically in recent years. The smelt, *Osmerus mordax* (Mitchill), and the white perch, *Roccus americanus* (Gemlin), became abundant in the late 1940's and mid 1950's respectively. The relationships among these and other fish species and the general trend of eutrophication is not well understood (Christie, 1968).

There is evidence from Hart's studies that the mayfly *Hexagenia* was common in the inner bay in 1930, but not a single specimen was collected above lower Adolphus Reach in recent work. The chironomid *Chironomus plumosus* is the dominant species in the upper bay. In deeper waters *Chironomus attenuatus* and *Chironomus anthracinus,* both tolerant of organic enrichment, together with the tolerant tubificid *Limnodrilus hoffmeisteri* and *Tubifex tubifex*, are most abundant. The similarities in the benthic macroinvertebrate communities in Lake Erie from west to east and in the Bay of Quinte from the inner to outer bays (with consideration of depth) are striking (Johnson and Brinkhurst, in press).

McCombie (1967) reported that concentrations of algae in the inner bay were about 10 times those in the middle bay and 100 times those near the mouth. Although there was no definite evidence of an increase in algae at the bay mouth since 1945 when Tucker (1948) carried out his investigations, diatoms were relatively less abundant and blooms of the blue-green alga *Aphanizomenon* began one month earlier in 1963 and 1964 than in 1945. No earlier data on the algae in the inner bay are available, but residents, including the superintendent of the Belleville water filtration plant (Scriven, pers. comm.), indicated that the algal blooms have become more intensive and prolonged. Also, the attached alga *Cladophora* has become moderately abundant wherever suitable rocky substrates are present. This alga was stimulated by applications of phosphorus in field experiments in Lake Huron by Neil and Owen (1964).

Collections of algae were examined by Dr. A. E. Christie, Ontario Water Resources Commission. A summary of his data (Table 1) shows the decrease in mean and maximum standing stocks of algae from Big Bay (east of Belleville) , Glenora (near Picton), Conway (near the bay mouth) to a station 8 miles off the bay mouth in Lake Ontario. Changes in the relative dominance of blue-green algae and diatoms from Big Bay to Lake Ontario are evident.

Occasional extinction of dissolved oxygen was found in subsurface waters in summer in the inner bay near Belleville by McCombie (1966), and more recently in the middle bay near the confluence of Hay Bay by Dr. D. Hurley (pers. comm.). Super-saturation of surface waters with oxygen (to 150%) and minimal Secchi disc readings (sometimes less than 1 foot) in the inner and middle bays accompany the development of heavy stocks of algae. In contrast, Secchi disc readings averaged 8 feet in the outer bay and 11 feet in Lake Ontario off the bay mouth. Prince Edward Bay is affected by the influx of waters from the Bay of Quinte. Dobson (1967) gave 70% saturation with oxygen as the lowest concentration observed in open Lake Ontario, but he reported 40% at a single station in Prince Edward Bay in August, 1966. Subsequent unpublished OWRC data support Dobson's findings.

Table 1. Mean and maximum standing stocks of algae at four stations along the Bay 9f Quinte in 1967-68. Stocks are in areal standard units per ml (1 asu equals 400 μ^2). These data were provided by Dr. A. E. Christie, Ontario Water Resources Commission.

	BIG BAY			GLENORA			CONWAY			LAKE ONTARIO		
Algal group	Mean	Mean %	Max.*	Mean	Mean %	Max.*	Mean	Mean %	Max. *	Mean	Mean %	Max. *
Blue-greens	2,910	65.4	30,900	670	35.3	3,200	270	22.6	2,000	50	18.2	260
Diatoms	1,330	29.9	4,400	1,120	58.9	2,700	850	71.0	2,300	200	75.6	1,300
Others**	210	4.7	1,600	120	5.8	550	80	6.4	510	20	6.2	70
Total	4,450	100.0	31,800	1,910	100.0	4,500	1,200	100.0	2,500	270	100.0	1,300

* Maxima of the three groups are not additive because maxima were attained at different times.

** Included greens, yellow-greens, dinoflagellates.

Concentrations of most nutrients decreased in the Bay of Quinte from Napanee to Lake Ontario. Concentrations of total nitrogen averaged 0.83 ppm in the inner bay, 0.63 ppm at Glenora and 0.55 ppm at the bay mouth. Total phosphorus concentrations (as P) were 0.073 ppm in the inner bay, 0.039 ppm at Glenora and 0.034 ppm at the bay mouth. The severity of algal blooms is related to concentrations of these two nutrients. Although carbon has been known for many years to limit algal production in soft waters (Birge and Juday, 1911), recently attention has been focussed on carbon as a limiting factor in hard water (Lange, 1967; Kuentzel, 1969).

However, inorganic carbon in the Bay of Quinte remained at a high concentration of 24 ppm between the inner bay and bay mouth (calculated from methyl-orange alkalinity, i.e. titer between ambient pH of about 8.3 to pH of 4.5). Therefore, nitrogen and phosphorus, which decreased toward the bay mouth, appeared to be of greater potential importance than carbon in controlling algal production. The high C:N:P ratios, about 500:40:1, indicate that inorganic carbon is superabundant, considering also that a sizeable but unknown fraction of the total nitrogen and phosphorus is unavailable, that is, much is in particulate matter.

These limnological data demonstrate the trophic gradient which occurs between the inner bay and Lake Ontario, due to the concentration of nutrients in the inner bay and their removal and dilution lakeward. Although fewer basic limnological data are available from the Bay of Quinte than from Lake Erie, there is little doubt that the process of cultural eutrophication has taken much the same course in both waters in relation to increased inputs of nutrients from municipal-industrial wastes and land drainage.

NITROGEN AND PHOSPHORUS BUDGETS

River input

Water samples from the Trent, Moira, Salmon and Napanee rivers were collected on 26 days during 1968 and early 1969. Sampling effort was intensified during periods of high flow. Analyses were made according to standard methods (American Public Health Association, 1965) except that the nitrate ion was measured as nitrite following reduction with cadmium. Colorimetric analyses were made on a Technicon Automatic Analyzer ®. Hydrographic data were obtained from the Canada Department of Energy, Mines and Resources.

Inputs of total nitrogen and total phosphorus were calculated by developing nutrient-stream flow rating curves, $N=aQ^b$, where the daily input of a nutrient is a function of the volume of water passing the sampling point in 1 day. This model permits both linear and non-linear responses. A linear model would have served equally well with the four Quinte rivers. However, for broad application the non-linear model is preferable because some rivers have higher nutrient concentrations at high stream flows (b= 1.0), such as several streams with considerable streambank erosion draining agricultural lands north of Toronto (Owen and Johnson, 1966) where b had values of 1.3 to 1.5, and other rivers which are particularly well forested and protected would be expected to have lower concentrations of nutrients at times of snow melt and heavy spring discharge.

The equations used to estimate input of nitrogen were as follows, where N is in pounds, Q in thousands of $feet^3$ and S.E. of b is the standard error (P=0.05) of the regression coefficient.

River	Estimating equation	S.E. of b
Trent	$\log_e N = -5.114 + 1.152 \log_e Q$	0.093
Moira	$\log_e N = -4.343 + 1.093 \log_e Q$	0.071
Salmon	$\log_e N = -3.294 + 1.009 \log_e Q$	0.065
Napanee	$\log_e N = -2.595 + 0.961 \log_e Q$	0.055

None of the values of b were significantly different from 1.0 (P=0.05).

The estimating equations for total phosphorus were as follows:

River	Estimating equation	S.E. of b
Trent	$\log_e P = -4.246 + 0.861 \log_e Q$	0.143
Moira	$\log_e P = -4.083 + 0.806 \log_e Q$	0.078
Salmon	$\log_e P = -5.078 + 0.805 \log_e Q$	0.111
Napanee	$\log_e P = -4.648 + 0.867 \log_e Q$	0.079

In this set for phosphorus, b was significantly less than 1.0 only in the case of the Moira River. Concentrations of neither nitrogen nor phosphorus were related to flow and, in fact, concentrations did not vary widely through time and among rivers (Table 2).

Rating curves (Fig. 3 and 4) were used in calculating the daily nutrient inputs through 1968 which are summarized in monthly inputs of nitrogen (Fig. 5) and phosphorus (Fig. 6). The total inputs via the four rivers in 1968, which do not include the municipal-industrial sources on the bay, were as follows:

Table 2. Mean flows in 1968 and mean concentrations of total nitrogen and phosphorus (± 2 S.E.) in unfiltered samples in the four main rivers tributary to the Bay of Quinte. Each mean concentration is based on 21 to 26 observations.

River	Mean flow cfs	Nitrogen (N) ppm	Phosphorus (P) ppm
Trent	3,990	0.71 ± 0.12	0.050 ± 0.012
Moira	888	0.64 ± 0.12	0.037 ± 0.006
Salmon	357	0.68 ± 0.08	0.027 ± 0.006
Napanee	330	0.83 ± 0.10	0.043 ± 0.006

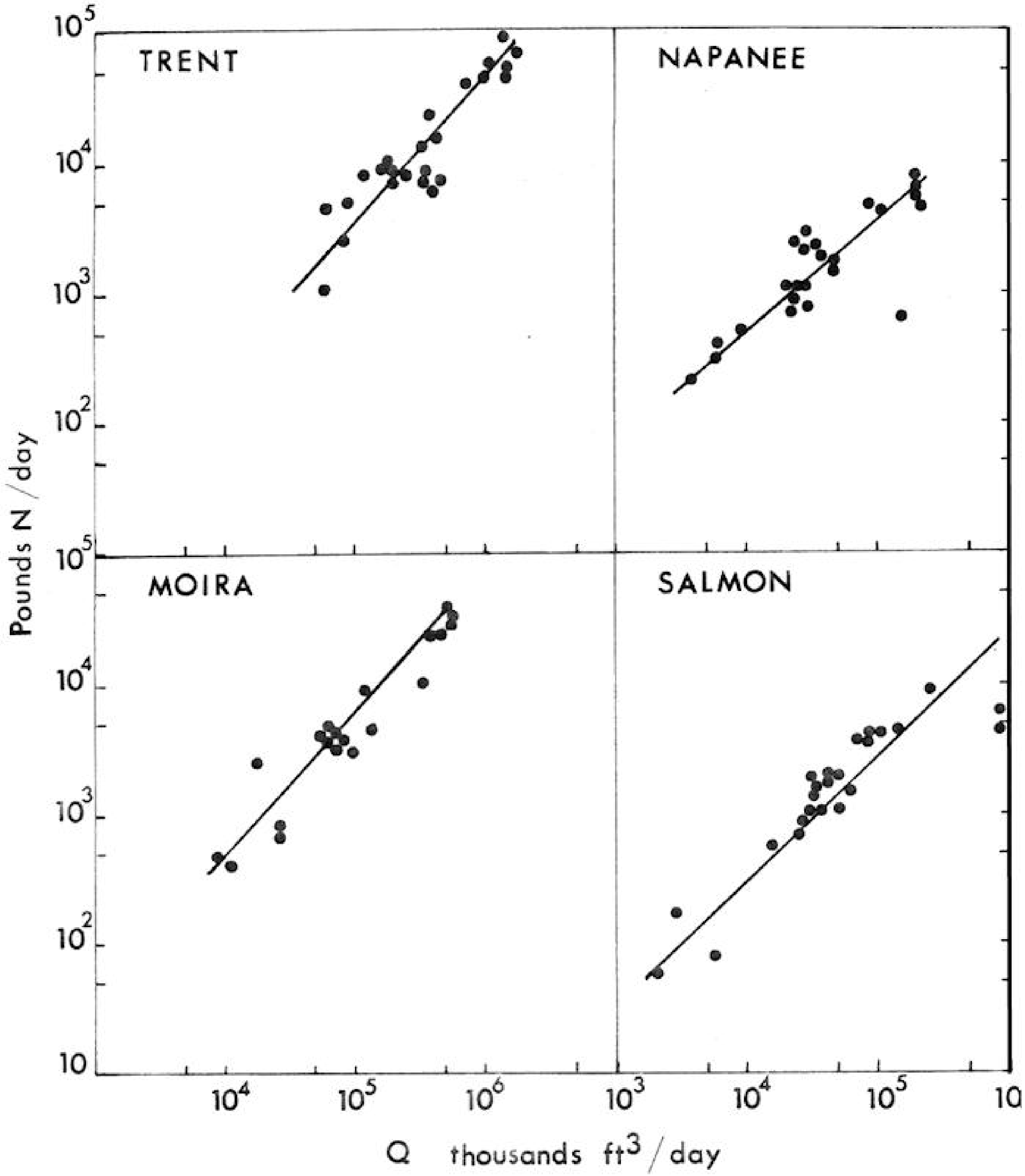

Fig. 3. Rating curves (daily discharge vs. daily nutrient input) for nitrogen for the four major rivers. Each point represents the nutrient in one water sample at the mean flow during that day.

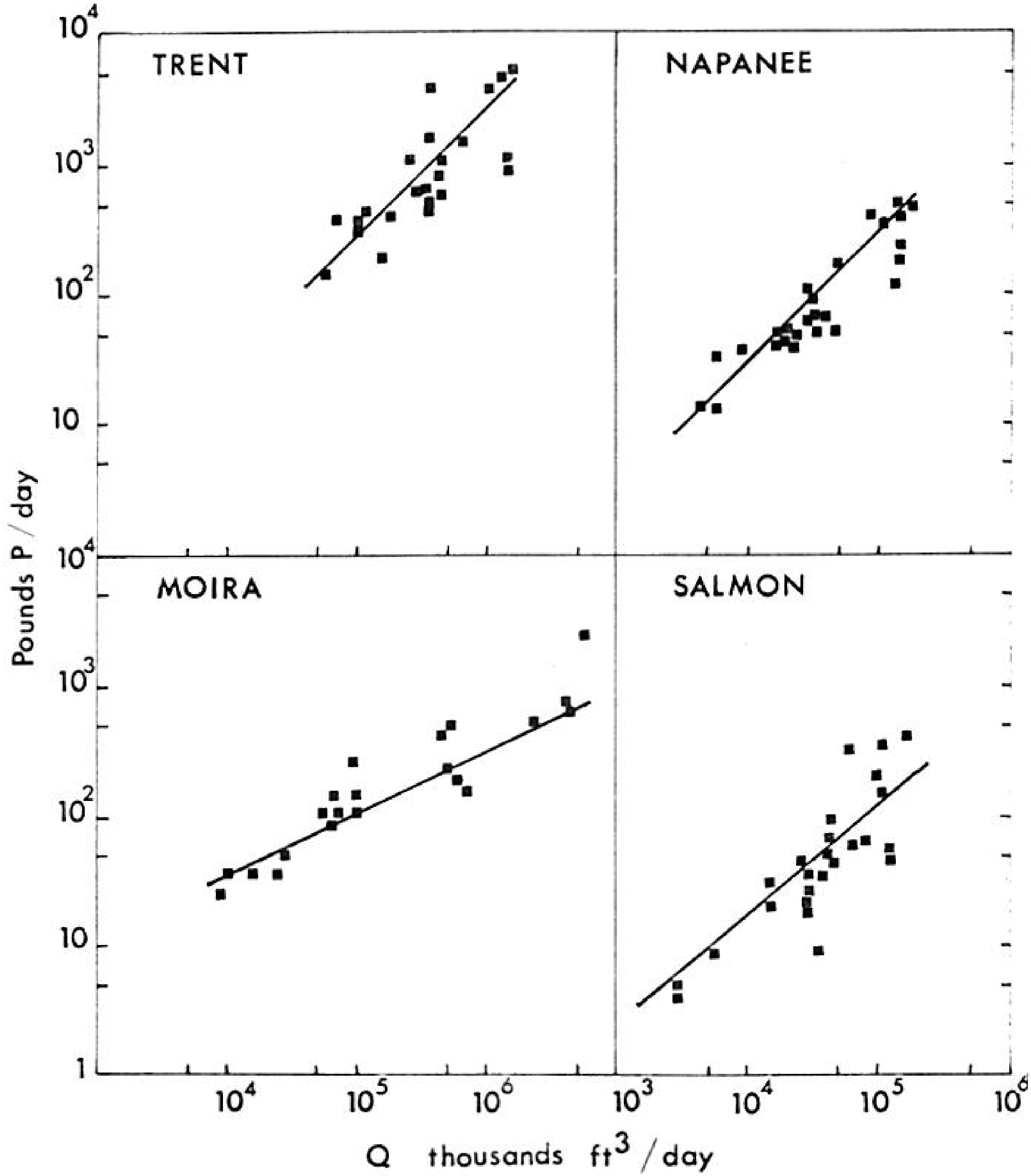

Fig. 4. Rating curves (daily discharge vs. daily nutrient input) for phosphorus for the four major rivers.

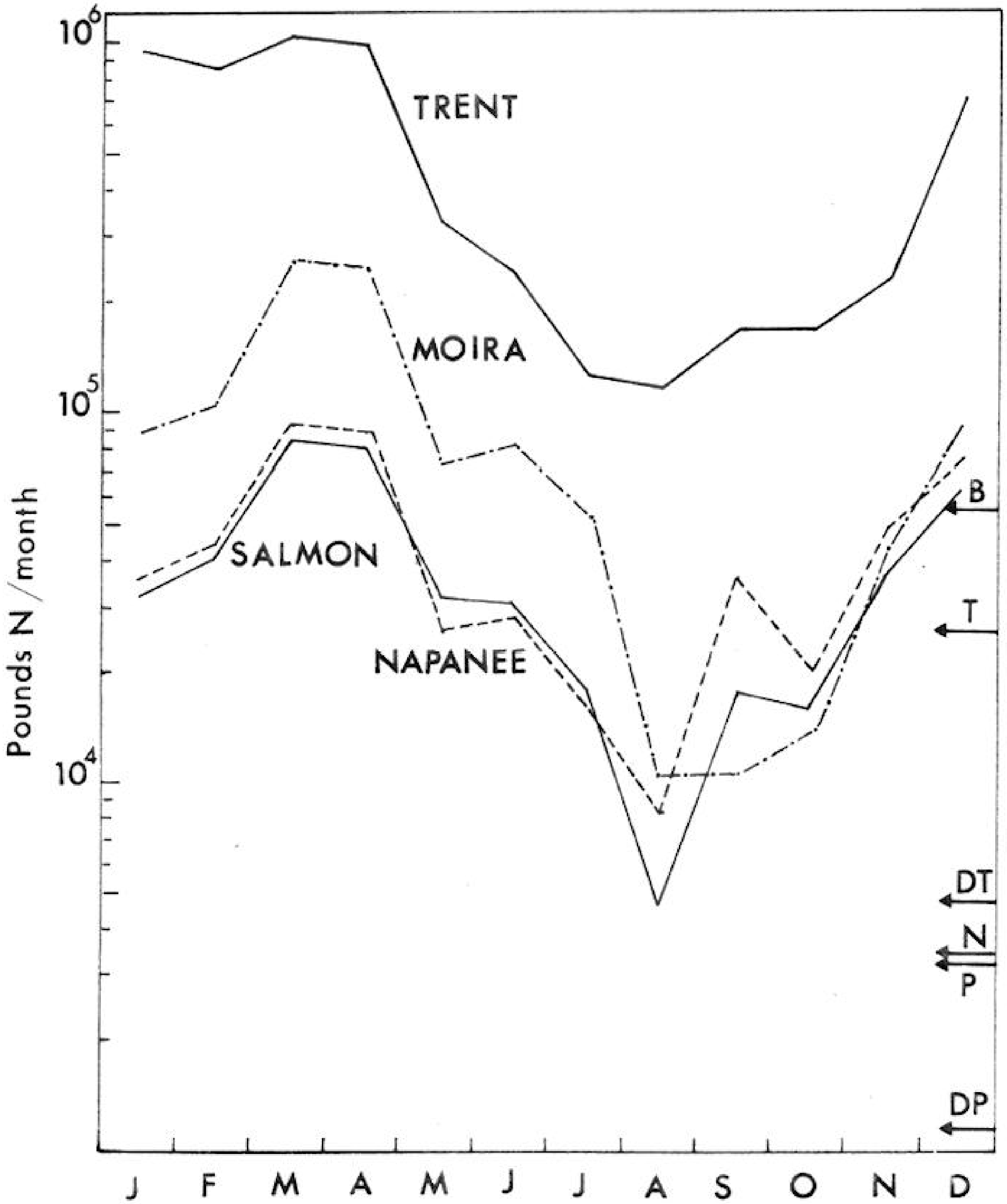

Fig. 5. Seasonal variation in river input of nitrogen from the four major rivers and the comparatively constant input from municipal-industrial sources: B, Belleville; T, Trenton; DT, DND Trenton; N, Napanee; P, Picton and DP, DND Picton.

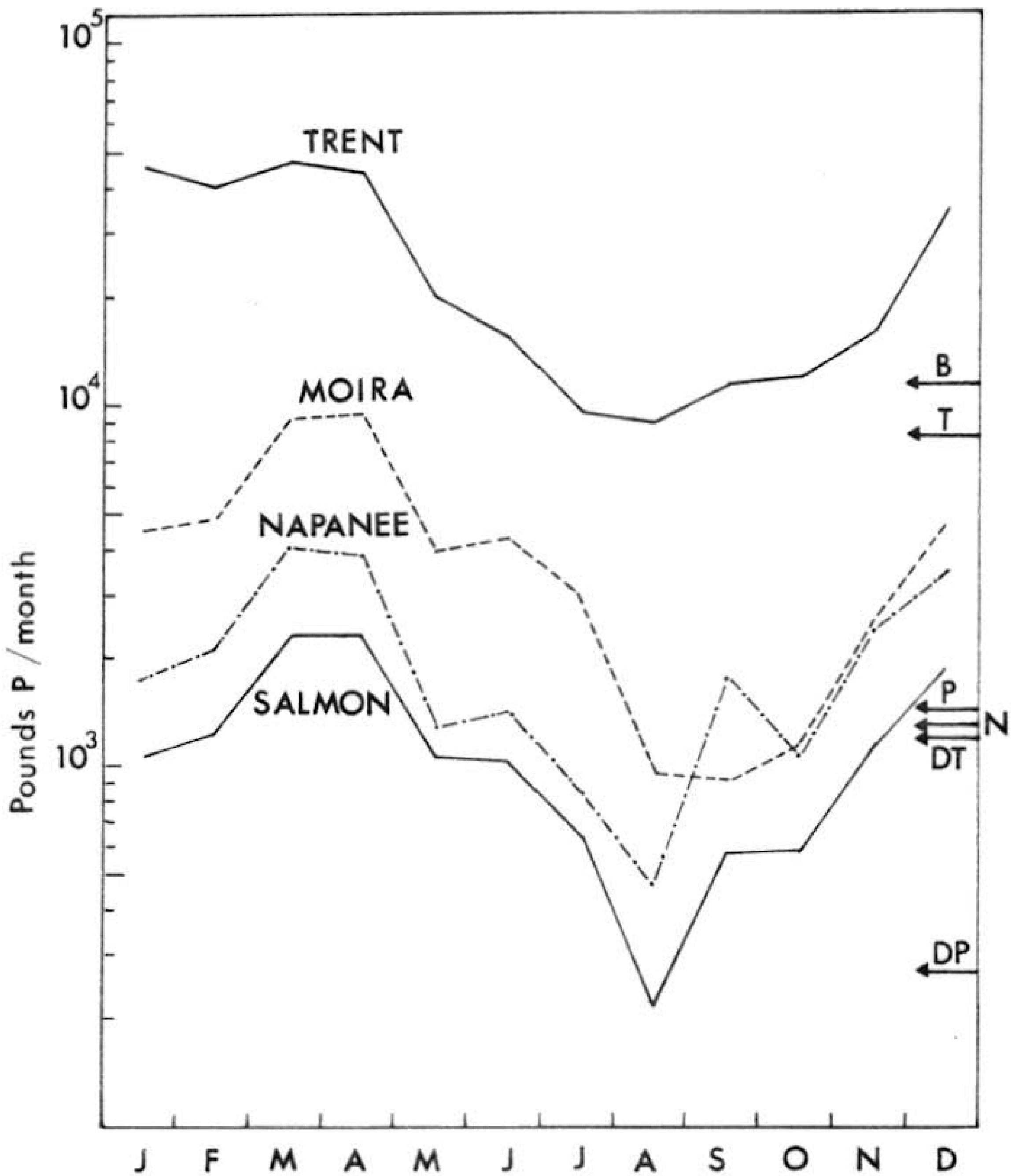

Fig. 6. Seasonal variation in river input of phosphorus from the four major rivers and the comparatively constant input from municipal-industrial sources *(see* Fig. 5).

River	Nitrogen (pounds)	Phosphorus (pounds)
Trent	5,890,000	309,000
Moira	1,091,000	50,000
Salmon	457,000	14,000
Napanee	515,000	25,000

About 9% of the drainage basin was not sampled (areas A to E in Fig. 1). These areas were assumed to contribute amounts per mile^2 of watershed similar to the Salmon and Napanee rivers. They may have contributed greater relative amounts because of their proximity to the Bay of Quinte, but, because of the small fraction of the total watershed which they comprise, rough estimates of input should not introduce any large error in the total nutrient budget.

Annual inputs per mile^2 were as follows:

River	Nitrogen (pounds)	Phosphorus (pounds)
Trent	1,220	64
Moira	1,050	48
Salmon	1,370	41
Napanee	1,720	82

The generally lower yields of nutrients from the Trent and Moira watersheds may have been the result of the greater proportions in Precambrian Shield and larger numbers of lakes (which trap nutrients). The Napanee watershed may have produced greater areal inputs because a clay plain is traversed in the lower reaches.

The above inputs are less than those of predominantly fertile, non-urbanized agricultural lands. For example annual total nitrogen and phosphorus yields per $mile^2$ from the West Humber River were 1,800 pounds N and 117 pounds P; from the Little Rouge River, 4,800 pounds N and 200 pounds P; and from Altona Creek, 2,300 pounds N and 97 pounds P (Owen and Johnson, 1966; Neil, Johnson and Owen 1967). Sawyer (1947) reported a mean annual yield of about 230 pounds P per $mile^2$ and 4,500 pounds N per $mile^2$ from agricultural drainage near Madison, Wisconsin. Sylvester (1961) reported 1,360 pounds N per $mile^2$ and 480 pounds P per $mile^2$ annually from forested areas in Oregon. Cooper (1969) found annual losses of 990 pounds N and 38 pounds P per $mile^2$ from four forested watersheds with many bogs and small lakes in northern Minnesota. The unweighted mean annual inputs in the major Quinte rivers, 1340 pounds N and 59 pounds P per $mile^2$ compare favourably with the foregoing, considering that about one-half of the area of these watersheds is moderately fertile agricultural land, while the remainder is forested land with many lakes and bogs.

Municipal-industrial input

The six water pollution control plants (Fig. 1) contributed approximately 300 million gallons (about 18 cfs) of treated wastewater per month to the Bay of Quinte in 1968. Although the volume was insignificant, the nutrient concentrations were high (Table 3). The unweighted mean concentrations of total nitrogen and phosphorus in these effluents were 16.3 and 5.4 ppm respectively, which were 23 and 138 times as great as the mean river concentrations of 0.71 and 0.039 ppm of nitrogen and phosphorus respectively.

Table 3. Mean monthly flows and concentrations of total nitrogen and phosphorus (± 2 S.E.) in unfiltered samples of the final effluents of the six Water Pollution Control Plants on the Bay of Quinte in 1968. Each mean is based on 10 to 15 individual composite collections.

WPC Plant	Mean flow MG/month *	Nitrogen (N) ppm	Phosphorus (P) ppm
Trenton	37.4	25.2 ± 7.0	10.1 ± 3.0
DND Trenton	24.1	16.4 ± 11.0	3.5 ± 0.8
Belleville	180.7	19.4 ± 3.2	5.6 ± 1.2
Napanee **	26.3	13.4 **	4.9 **
Picton	26.0	13.4 ± 3.8	4.9 ± 1.0
DND Picton	8.2	9.9 ± 4.0	3.1 ±1.2

* 1 Million gallons per month (MGP) equals 0.06 cfs approximately.

** Insufficient data on Napanee WPC Plant; therefore, Picton nutrient concentrations were substituted.

These inputs, together with all significant separate industrial effluents and other municipal wastes, including by-passed domestic wastewaters, contributed 1,105,000 pounds of nitrogen and 292,000 pounds of phosphorus annually. Inputs from the six main sources are shown with the major river inputs in Fig. 5 and 6.

The annual inputs per capita of these nutrients from municipalities (Table 4) averaged 14.0 pounds of nitrogen and 4.3 pounds of phosphorus, although considerable variation, apparently related to degree of industrialization, was evident. Richmond Hill and the Highland Creek watersheds of Metropolitan Toronto yielded respectively 13.6 and 7.0 pounds per capita of nitrogen annually and 2.6 and 2.2 pounds per capita of phosphorus. It is noteworthy that in 1947 Sawyer estimated an annual per-capita yield of 0.5 pounds of phosphorus in biologically treated domestic sewage from Madison, Wisconsin. The per-capita inputs found in the Quinte study indicate further that the widespread use of synthetic detergents and other high-phosphate materials has increased the levels of phosphorus in sewage several times (Sawyer, 1965).

Other inputs

Inputs in rainfall have not been included in the nutrient budget, but they were estimated as 5,000 pounds of nitrogen per mile^2 per year, assuming 1 ppm in rainwater, and 100 pounds of phosphorus, assuming 0.02 ppm in rainwater (American Water Works Association, 1967). These inputs account for only 4% and 1% of the total inputs of nitrogen and phosphorus respectively.

Table 4. Estimates of annual inputs per capita of nitrogen and phosphorus from the six major sources of domestic-industrial wastes on the Bay of Quinte.

Source	Nitrogen (N) lbs/capita/yr	Phosphorus (P) lbs/capita/yr
Trenton	23.4	6.9
DND Trenton	14.4	3.5
Belleville	19.0	4.4
Napanee	9.0	4.4
Picton	8.5	3.3
DND Picton	9.7	3.1

To some extent, particularly for phosphorus, losses via emerging insects offset rainfall inputs; about 1,000 pounds per $mile^2$ of nitrogen and about 100 pounds per $mile^2$ of phosphorus leave the bay in the form of emerging midges, but what proportion is returned as dead flies following over-water, egg-laying flights is not known but most likely it is a small proportion of the emergent population.

Nitrification and denitrification (to N_2) were not measured as an input and a loss respectively; however, these counteracting agencies were relatively minor components and nearly balanced in the nitrogen budget of Lake Mendota (Brezonik and Lee, 1968).

Comparison of major inputs

Tables 5 and 6 provide comparisons of absolute inputs of nitrogen and phosphorus. About 90% of nitrogen enters via rivers and about 10% from municipal-industrial sources (Table 5). About 60% of phosphorus is attributable to rivers and 40% to municipal-industrial sources (Table 6).

Superficially, these data offer dismal prospects for the usefulness of nutrient control because of the high relative inputs in rivers from which nutrient removal would be difficult. However, the relative concentrations and flows must be examined; that is, municipal-industrial wastes are high-concentration, low-volume inputs, which displace small amounts of nutrients froth the bay. In contrast, river flows displace large amounts of nutrients from the bay. Increases in municipal-industrial inputs have a

Table 5. Absolute and net inputs (in thousands of pounds per year and as percentages of the total) of nitrogen from river drainage and municipal-industrial sources on the Bay of Quinte in 1968. Net input will be defined in the text subsequently.

Source	Absolute input thousands lbs/yr	(%)	Net input thousands lbs/yr	(%)
Trent R.	5,890.2	(60.9)	827.0	(37.3)
Moira R.	1,090.5	(11.4)	42.0	(1.9)
Salmon R.	457.2	(4.7)	35.7	(1.6)
Napanee R.	515.3	(5.3)	125.6	(5.7)
Rest watershed	613.4	(6.3)	112.7	(5.1)
Subtotal Rivers	8,566.6	(88.6)	1,143.0	(51.6)
Trenton	320.9	(3.3)	315.0	(14.2)
DND Trenton	57.7	(0.6)	55.8	(2.5)
Belleville	626.2	(6.5)	605.6	(27.4)
Napanee	42.3	(0.4)	40.4	(1.8)
Picton	41.8	(0.4)	39.9	(1.8)
DND Picton	9.7	(0.1)	9.2	(0.4)
Misc. Industry	6.5	(0.1)	6.4	(0.3)
Subtotal Mun.-Ind.	1,105.1	(11.4)	1,072.5	(48.4)
Total	9,671.7	(100.0)	2,215.5	(100.0)

Table 6. Absolute and net inputs (in thousands of pounds per year and as percentages of the total) of phosphorus from river drainage and municipal-industrial sources on the Bay of Quinte in 1968. Percentage net input of river drainage is given only for the total of such drainage because of the occurrence of three negative net inputs.

	Absolute input		Net input	
Source	thousands lbs/yr	(%)	thousands lbs/yr	(%)
Trent R.	308.9	(43.3)	55.7	-
Moira R.	49.6	(7.0)	-2.8	-
Salmon R.	14.2	(2.0)	-6.9	-
Napanee R.	24.5	(3.4)	5.0	-
Rest Watershed	24.5	(3.4)	-0.6	-
Subtotal Rivers	421.6	(59.1)	50.4	(14.8)
Trenton	96.8	(13.4)	96.5	(28.1)
DND Trenton	14.3	(2.0)	14.2	(4.2)
Belleville	144.3	(20.3)	143.3	(42.3)
Napanee	15.5	(2.2)	15.4	(4.5)
Picton	16.4	(2.4)	16.3	(4.8)
DND Picton	3.1	(0.4)	3.0	(0.9)
Misc. Ind.	1.4	(0.2)	1.3	(0.4)
Subtotal Mun.-Ind.	291.6	(40.9)	290.0	(85.2)
Total	731.2	(100.0)	340.4	(100.0)

greater effect in increasing bay water concentrations, and, in general, cultural eutrophication is due to increased concentrations of nutrients. Furthermore, much of the contribution of nutrients from the Quinte rivers occurs in the winter months (Fig. 5 and 6). The hydrologic turnover time in the bay (above Glenora where the most serious deterioration in water quality has occurred) is about one month in the months December to April. That is, nutrients contributed in large amounts between December and March would be moved through the bay to Lake Ontario because there is minimal algal production and sedimentation of nutrients during the period of ice cover.

Nutrients added in April remain in the bay to support the spring increase in algae. Contributions from rivers during the summer months are lower in comparison with winter contributions. Municipal-industrial inputs are rather constant through the year. These two points, firstly the low-volume and high-concentration of municipal-industrial inputs and, secondly, their steady supply through the spring and summer make comparisons based on absolute input ecologically unsound. The latter point is well recognized, but the former has not been clarified, although Edmondson (1969) introduced the concept in comparing Lake Washington and Lake Sammamish.

> "A comparison of the nutrient income (of Sammamish) with that of Lake Washington is instructive. The annual nutrient income is 54,500 kg of inorganic nitrogen (nitrate and nitrite) and 22,800 kg of total phosphorus. On areal and volumetric bases, these amounts are well above the corresponding income of Lake Washington, and the question naturally arises: Why does Lake Sammamish not produce larger populations of algae than Lake Washington? It may be significant that the concentrations of the materials in the water entering the two lakes are very different because of larger proportion of the income entered directly into Lake Washington as very concentrated effluent. That is, sewage

effluent delivered directly into Lake Washington had mostly concentrations of phosphate phosphorus in the range of 5 to 10 mg per liter, and about half the phosphate was income of the lake delivered in this form. Lake Sammamish does not receive effluent directly but through Issawuah Creek. The most concentrated effluent entering Lake Sammamish had 0.23 mg per liter of total phosphorus, and the largest stream had 0.16 mg. Thus, even though on a relative basis the income of Sammamish is higher, the concentration is lower. This kind of information must be used in evaluating nutrient budgets, but exactly how is not yet clear."

One approach to this problem is as follows. "Net input" of the individual source was calculated as the amount of nutrient contained in that input in excess of the amount of nutrient displaced (to Lake Ontario) in the equivalent volume of water. A hypothetical example is meant to demonstrate this definition of "net input" (Fig. 7). Two sources, one a river and the other a municipality, input volumes V and V^1 at respective concentrations C and C^1. The relative proportions are realistic and the yields Y and Y^1 ($C \bullet V$ and $C^1 \bullet V^1$) are the same; that is each source contributes 50% of the absolute input. The concentration in the outflowing water, C_o, if all of the nutrients passed through the lake, is

$$(Y + Y^1) / (V + V^1)$$

But, in general, some nutrient removal occurs in lakes, hence the use of the parameter k. The high river input of V displaces an approximately equal volume from the lake at the nutrient concentration C_o. The "net input" of the river, according to the above definition, is $(V \bullet C) - (V \bullet C_o)$. Because of the substantial disparity in displacement

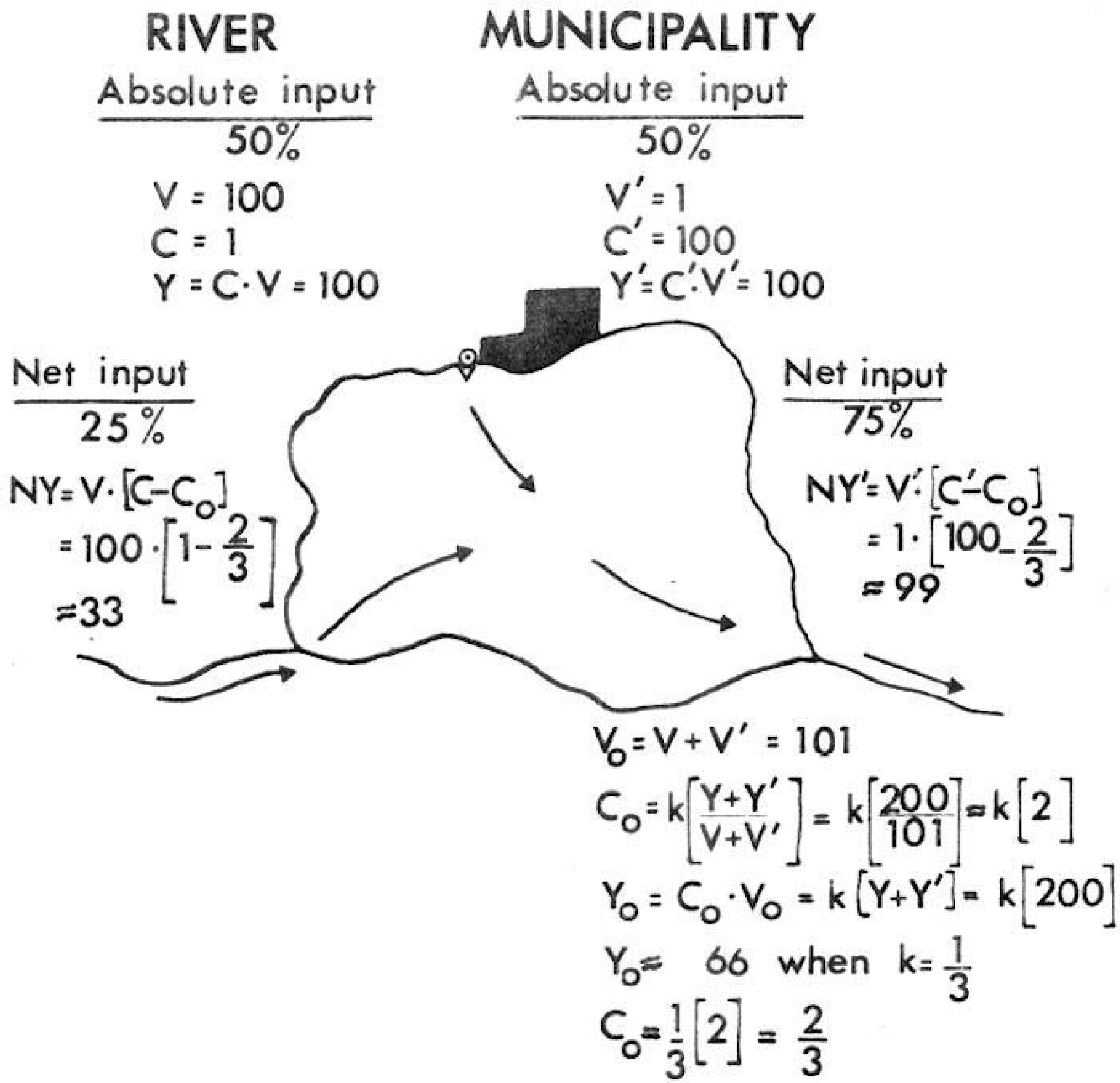

Fig. 7. Hypothetical, "two-source" nutrient-input system, one low-volume, high-concentration municipal input and one high-volume, low-concentration river input. Further explanation in text.

volumes of the two sources, the relative amounts of "net input" contributed are 75% from the municipality and 25% from the river. In this example k was given the value of one-third, only because lakes are well known traps of nutrients (that is, 1-k would be detained in the lake). With k <1 the river will have a positive "net input" in the absence of municipal inputs. However, together with low-volume, high-concentration inputs, the river "net input" may be negative because it has at that time a beneficial effect on the lake in counter-acting the temporal increase in nutrients, that is, it flushes the lake of excess nutrients. It should be clear that, as nutrients from municipal-industrial sources are controlled, net yields re-calculated for rivers would be substantial. If the desired concentration of nutrients at a point of control (i.e. the bay mouth in relation to water quality in Lake Ontario) is not achieved, then additional nutrient removal from land drainage would be required in spite of the probable higher cost.

This approach, although simply contrived, may provide for ecologically realistic comparisons of nutrient sources. For the Bay of Quinte, relative "net inputs" of the rivers and municipal-industrial sources (Tables 5 and 6) are about 50% each in the case of nitrogen and 15% for rivers and 85% for municipal-industrial sources in the case of phosphorus. These data tend to place the high-concentration, low-volume flows in proper perspective, aside from the obvious fact that nutrients may be more economically removed where they are most concentrated.

The "net inputs" from Belleville and Picton could have been taken as 100% of their absolute inputs because these two municipalities use Bay of Quinte water and, therefore, do not provide a flow of "new" water to the system.

However, the inputs of nutrients should then be adjusted according to the nutrient concentrations in the finished water supply (not concentrations in raw water, because these are reduced in filtration) which unfortunately, were not determined. The precision of estimates of nutrient inputs probably does not warrant such a detailed study of individual plants. Therefore, all inputs were treated alike in this analysis.

Detention of nutrients in the Bay of Quinte

The concentrations of total nitrogen and phosphorus in bay water discharged to Lake Ontario in 1968 were 0.55 ppm and 0.034 ppm respectively (Fig. 8). The amounts of nutrients which left the bay in 1968 were obtained from these average concentrations and total discharge to the bay. Discharge from unsampled watershed area was estimated from areal yields of water from the Napanee and Salmon watersheds. Rainfall and evaporation were taken as equal (see data compiled by Phillips, 1969). The back-and-forth flow through the Murray Canal was not considered to significantly alter the nutrient budget. The flow was out almost as often as in, without significant differences in concentration of nutrients in relation to direction. Furthermore, flow rate in the canal was low (0-600 cfs) in comparison with the Trent River (4,000 cfs). About 31% of the nitrogen input and 44% of the phosphorus were detained in the Bay of Quinte.

The locations within the bay where deposition of nutrients occurred was

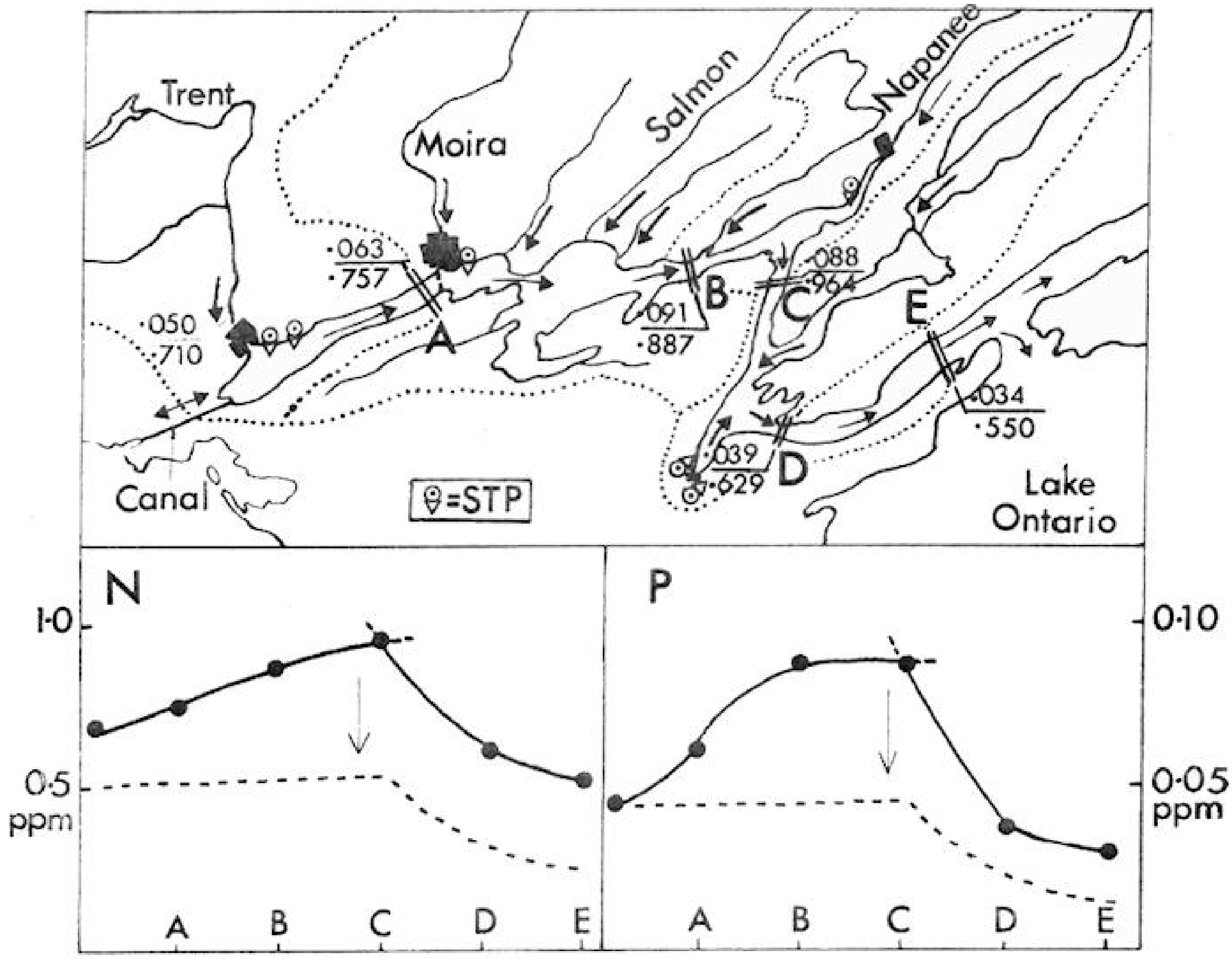

Fig. 8. Sections A to E of the Bay of Quinte selected for nutrient "routing" of total nitrogen and phosphorus. Average concentrations (ppm) of phosphorus (above) and nitrogen (below) in water entering and leaving each section are indicated. Below are the 1968 concentrations of nitrogen and phosphorus (solid line) and the projected nutrient concentrations (dashed line) subsequent to nutrient removal at all major municipal-industrial sources.

determined by comparing the input and estimated output in five sections of the bay (Fig. 8). Output was determined as the product of cumulative flow through the bay (addition of carried-over discharge plus new discharges to the bay from section to section) and average concentrations observed at the downstream end of each section (locations A to E in Fig. 8). Output from each section is "carried over" and added to "new input" in the next section (Table 7). Although error is compounded in this procedure, apparently both nitrogen and phosphorus were not detained in relatively large quantities in the first three sections. Most removal of both nitrogen and phosphorus apparently occurred in section C-D, and additional removal occurred in section D-E (Adolphus Reach).

The presence of sediments with a substantial content of nitrogen and phosphorus in sections A-B and B-C is not inconsistent with the preceding analysis because in these shallow areas the rate of accumulation is unknown and detention of sediments may be transitory over much of the inner bay.

The total amounts of nutrients retained in the bay obtained by addition in Table 7 are not as accurate as estimates of detention obtained as the difference between total input (sum of "new inputs") and calculated output from section D-E to Lake Ontario. This "nutrient routing" procedure serves only to indicate which areas of the Bay of Quinte detained nutrients in greatest relative amounts.

Table 7. Budgets of nitrogen and phosphorus in five sections of the Bay of Quinte, 1968. All data in thousands of pounds per year.

Nutrient	Budget item	Section 1	Section 2	Section 3	Section 4	Section 5
Total nitrogen	Carried over		5,995	9,552	11,037	7,374
	New input	6,319	2,467	582	253	31
	Total input	6,319	8,462	10,134	11,290	7,405
	Output	5,995	9,552	11,037	7,374	6,470
	Retained	323	nil	nil	3,916	934
Total phosphorus	Carried over		498	979	1,007	457
	New input	422	221	42	20	2
	Total input	422	719	1,021	1,027	459
	Output	498	979	1,007	457	400
	Retained	nil	nil	13	570	59

In the course of measuring energy import to the bottom muds by collection of detritus in sedimentation traps (Johnson and Brinkhurst, in press) the inputs to bottom muds of total nitrogen and phosphorus also were measured. Deposition and accumulation apparently occurs where water depth exceeds 25 feet in an area of about 17 $mile^2$. Average rates of sedimentation of nitrogen and phosphorus (sediment trap data) are compared with amounts retained as calculated indirectly in the nutrient budget.

Technique	Detention of N (pounds in 1968)	Detention of P (pounds in 1968)
Sediment traps	2,304,000	242,000
Nutrient budget	3,182,000	307,000

The two techniques gave similar estimates of retention, considering that substantial errors were to be expected in both methods.

Remedial measures

Cultural eutrophication is well advanced in the Bay of Quinte and nutrients from municipal-industrial wastes apparently have contributed substantially to the temporal increase in concentrations of nitrogen and phosphorus in the bay.

Nutrient inputs per unit area are similar to those in Lake Erie. The Bay of Quinte annually receives 112,000 pounds of nitrogen and 8,400 pounds of phosphorus per $mile^2$ and Lake Erie receives 39,000 pounds of nitrogen and 6,100 pounds of phosphorus per $mile^2$ (International Lake Erie and Lake Ontario - St. Lawrence River

Water Pollution Boards, 1969). In fact, the Bay of Quinte may be a useful area for the first large-scale attempt at nutrient control in the Great Lakes. What can and should be done to counteract deterioration of water quality? The well-founded proposal of Thomas (1969) and others is that nutrient control should be directed toward phosphorus for the following reasons. Bacteria and many blue-green algae are able to bind gaseous nitrogen organically, provided that adequate phosphorus is available (carbon is limiting probably only in soft-water lakes).

Many water-quality problems are directly proportional to the standing stocks of these blue-green algae. Nitrogen occurs in greater amounts in rainfall than does phosphorus. Also, inorganic nitrogen returns to the water in larger quantities than phosphate compounds in the biogeochemical cycle. Finally, phosphorus is more easily and economically removed from sewage than is nitrogen, and a greater proportion of total phosphorus than of nitrogen input passes through water pollution control plants where nutrients can be removed.

For example about 10% of the nitrogen and 40% of the phosphorus pass through waste-treatment facilities located on the Bay of Quinte. The careful use of natural and formulated fertilizers and control of land and streambank erosion is necessary, but removal of phosphorus from municipal-industrial wastes is urgently required.

Nutrient removal in the Quinte water-pollution control plants (activated-sludge plants) was not high; about 30% of nitrogen and 40% of phosphorus were removed. These results are similar to those obtained in earlier studies (Owen and Johnson, 1966; Hurwitz *et al.*, 1965; Owen, 1953).

Phosphorus removal of at least 95% should be possible. The methods have been discussed at length most recently by Rohlich (1969). The cost should not exceed $50 per million gallons. Malhotra in 1964 calculated a cost of $41 per million gallons, while, previously, Lea *et al.*, (1954) estimated from pilot-plant studies that the cost of phosphorus removal at Madison, Wisconsin would have been $20 per million gallons. Capital costs apparently are about 1 to 2% of the total costs of water pollution control plants (Thomas, 1969). Total annual cost of removing phosphorus in the 325 million gallons flow per month from treatment plants and unconnected industries which discharge to the Bay of Quinte would be about $200,000 and may be less in fact because of savings in secondary process operating costs and in other (BOD, solids) improvements in water quality predicted by Black and Lewandowski (1969).

An economic cost-benefit study has not been made, but it seems obvious that increased municipal and domestic water-treatment costs, loss in revenue at resorts which once catered to sport fishermen, and depreciation of cottage and resort values would exceed the cost of phosphorus removal. Such a study would be hampered by difficulties in determining intangible values and the area of benefits, which would include Lake Ontario and even the St. Lawrence River to some degree. Nevertheless, the value of the tourist trade is demonstrated by a survey (Ontario Department of

Tourism and Information, unpublished date) which showed that close to one million visitors spent 7.8 millions of dollars in the Bay of Quinte tourist region in 1968.

Will phosphorus removal be effective? Improvement in water quality in Lake Ontario would be expected, provided that programs for nutrient removal in the lower Great Lakes progress throughout their basins. Immediate, rapid improvement in the upper Bay of Quinte may not occur, but conditions will not deteriorate further. The upper bay is shallow, the total amounts of nitrogen and phosphorus in the sediments there are substantial (although probably not permanently deposited) and resuspension of bottom muds occurs during windy periods. The total amounts of nutrients in bottom muds (to a depth of 1 inch) are as follows, based on 156 samples collected throughout the Bay of Quinte.

Location	Nitrogen (Millions of pounds)	Phosphorus (Millions of pounds)
Inner bay (55 $mile^2$)	89	11
Middle bay (17 $mile^2$)	33	4
Outer bay (15 $mile^2$)	20	3
Total (87 $mile^2$)	142	18

The layer of physical-chemical interaction between water and mud is probably less than 1-inch in the mud, but the activities of macroinvertebrates expose mud to water at and from depths much greater than 1-inch (Brinkhurst *et al.*, 1969). The actual depth of interaction is not known precisely. Nonetheless, it is interesting that there is about 25 times more nitrogen in the upper 1-inch of bottom mud than the yearly (1968) input to the bay. The corresponding ratio for phosphorus is 15. Because only restricted sections of the bay detain significant amounts of these nutrients, much of the content of nutrients in bottom muds may be mixed with the water periodically. The real significance of this mechanism for regeneration of nutrients and clay in water quality improvement is not well understood.

Kemp and Mudrochova (1970) proposed that phosphorus regeneration from sediments would have minimal effect on concentrations in Lake Ontario and Lake Erie waters. However, Abbott (1957) proposed that planktonic algae may derive nutritive phosphorus directly from complex polyphosphates or organic phosphorus on suspended colloidal clay. Furthermore, ample data are available to show that disturbed mud-water systems release more phosphorus than undisturbed, aerobic systems (Hasler, 1957; Gahler, 1969), which may stimulate algal production directly or indirectly through mineralization of phosphorus by bacteria and zooplankton. As the concentrations of nutrients decline in the Bay of Quinte (following nutrient removal at water-pollution control plants) the amount of nutrients released from re-suspended sediments may increase in accordance with principles of adsorption kinetics. However, a new sediment-water equilibrium should be established over a few seasons. Concentrations such as those shown in Fig. 8 (dotted lines) should be approached and lower concentrations may be expected in time as remedial measures are carried out elsewhere in the Trent system. Considerable research is needed on the recovery process, particularly in shallow eutrophic waters like the Bay of Quinte. The turnover rate (annual discharge divided by the volume of the bay) is five times per year, and it is nine times per year above Glenora. This high turnover rate will act to collect and translocate the feedback of nutrients from sediments in shallow water to sediments in deeper sections lakeward as it probably always had done prior to the accelerated human development and subsequent deterioration in water quality in the Bay of Quinte.

ACKNOWLEDGEMENTS

Assistance was provided by many colleagues in the Ontario Water Resources Commission, and especially by Mr. Ronald Hunsinger. Data were made available by Mr. John Thon and Mr. John Vogt of the Divisions of Sanitary Engineering and Industrial Wastes, respectively.

The Ontario Department of Lands and Forests provided laboratory space and other assistance at the Glenora Fisheries Research Station. Finally, Dr. J. R. Vallentyne of the Fisheries Research Board of Canada, Professor L. R. Webber of the University of Guelph, Dr. T. G. Brydges of the Chemistry Branch, OWRC, and C. F. Schenk of the Biology Branch, OWRC, read the manuscript and made several suggestions for its improvement.

REFERENCES

Abbott, W. 1957. Unusual phosphorus source for plankton algae. Ecology, 30:152.

American Public Health Association. 1965. Standard methods for the examination of water and wastewater. 12th ed., APHA, New York, 769 pp.

American Water Works Association. 1967. Sources of nitrogen and phosphorus in water supplies (Task Group Report, P. L. McCarty, Chairman). J. Amer. Water Works Assoc., 59:344-366.

Birge, E. A. and C. Juday. 1911. The inland lakes of Wisconsin. The dissolved gases of the water and their biological significance. Bull. Wis. Geol. Nat. Hist. Surv., 22:1-259.

Black, S. A. and W. Lewandowski. 1969. Phosphorus removal by lime addition to a conventional activated sludge plant. Pub. Res. Div., Ontario Water Resources Comm., 36:1-49.

Brezonik, P. L. and G. F. Lee. 1968. Denitrification as a nitrogen sink in Lake Mendota, Wisconsin. Envir. Sci. Tech., 2:120-125.

Brinkhurst, R. O., K. I. Chua and E. Batoosingh. 1969. Modifications in sampling procedures as applied to studies on the bacteria and tubificid oligochaetes inhabiting aquatic sediments. J. Fish. Res. Bd. Can., 26:2581-2593.

Christie, W. J. 1968. Possible influences of fishing in the decline of Great Lakes fish stocks. Proc. Int. Assoc. Great Lakes Res., 11:31-38.

Cooper, C. F. 1969. Nutrient output from managed forests. p. 446-463. *In* Eutrophication: causes, consequences, correctives. National Academy of Sciences, Washington, D.C.

Dobson, H. H. 1967. Principle ions and dissolved oxygen in Lake Ontario. Pub. Great Lakes Res. Div., Univ. Michigan, 10:337-356.

Edmondson, W. T. 1969. Eutrophication in North America p. 124-149 *In* Eutrophication: causes, consequences, correctives. National Academy of Sciences, Washington, D.C.

Gahler, A. R. 1969. Sediment-water nutrient exchange. p. 243-257. Proc. Eutrophication-BiostimulationAssessment Workshop. Pacific North-west Water Laboratory, Corvallis, Oregon.

Hart, J. L. 1930. The spawning and early life history of the whitefish in the Bay of Quinte, Ontario. Can. Biol. Fish., 6:167-214.

Hart, J. L. 1931. The food of the whitefish in Ontario waters, with a note on the parasites. Can. Biol. Fish., 6:447-454.

Hasler, A. D. 1957. Naturally and artificially (air-ploughing) induced movement of radioactive phosphorus from the muds of lakes. UNESCO Int. Conf. Radioisotopes, 6:658-675.

Hurwitz, E., R. Beaudoin and W. Walters. 1965. Phosphates-their fate in a sewage treatment plant-waterway system. Water and Sewage Works, 112:84-89.

International Lake Erie and Lake Ontario - St. Lawrence River Water Pollution Boards. 1969. Report to the International Joint Commission on the pollution of Lake Erie, Lake Ontario and the international section of the St. Lawrence River, vol. 1:1-150.

Johnson, M. G. and R. 0. Brinkhurst. (in press). The benthos of the Bay of Quinte and Lake Ontario. I. Associations of macroinvertebrates and species diversity.

Johnson, M. G., and R. O. Brinkhurst. (in press). The benthos of the Bay of Quinte and Lake Ontario. III. Community metabolism.

Kemp, A. L. W. and A. Mudrochova. 1970. Extractable phosphates, nitrates and ammonia in Lake Ontario sediments. Paper presented at 13th Conf. on Great Lakes Research, Mar. 31-Apr. 3, Buffalo, New York.

Kuentzel, L. E. 1969. Bacteria, carbon dioxide and algal blooms. J. Water Poll. Cont. Fed., October, 1969:1737-1747.

Lange, W. 1967. Effect of carbohydrate on the symbiotic growth of planktonic blue-green algae with bacteria. Nature, 215 (5107):1277-1278.

Lea, W. L., G. A. Rohlich and W. J. Katz. 1954. Removal of phosphate from treated sewage. Sewage and Indust. Wastes, 26:261-275.

Malhotra, S. K., G. F. Lee and G. A. Rohlich. 1964. Nutrient removal from secondary effluent by alum flocculation and lime precipitation. Int. J. Air Water Poll., 8:487-500.

McCombie, A. M. 1966. Some physical and chemical characteristics of the Bay of Quinte. Res. Rep. Ontario Dept. Lands and Forests, 79:1-56.

McCombie, A. M. 1967. A recent study of phytoplankton of the Bay of Quinte 1963-64. Proc. Int. *Assoc.* Great Lakes Res., 10:37-62.

Neil, J. H. and G. E. Owen. 1964. Distribution, environmental requirements and significance of *Cladophora* in the Great Lakes. Pub. Great Lakes Res. Div., Univ. Michigan, 11:113-121.

Neil, J. H., M. G. Johnson and G. E. Owen. 1967. Yields and sources of nitrogen from several Lake Ontario watersheds. Pub. Great Lakes Res. Div., Univ. Michigan, 16:375-381.

Owen, G. E. and M. G. Johnson. 1966. Significance of some factors affecting yields of phosphorus from several Lake Ontario watersheds. Pub. Great Lakes Res. Div., Univ. Michigan, 15:400-410.

Owen, R. 1953. Removal of phosphorus from sewage plant effluent with lime. Sewage and Indust. Wastes, 25:548-556.

Phillips, D. W. 1969. A climatological summary of the Great Lakes basin. Appendix III In The Great Lakes as an Environment, D. V. Anderson (ed.) , Rep. PR 39 Great

Lakes Inst., Univ. Toronto.

Rohlich, G. A. 1969. Engineering aspects of nutrient removal. p. 371-382 In Eutrophication: causes, consequences, correctives. National Academy of Sciences, Washington, D. C.

Sawyer, C. N. 1947. Fertilization of lakes by agricultural and urban drainage. J. New Eng. Water Works Assoc., 61:109-127.

Sawyer, C. N. 1965. Problems of phosphorus in water supplies. J. Amer. Water Works Assoc., 57 :1431-1439.

Sylvester, R.O. 1961. Nutrient content of drainage water from forested, urban and agricultural areas. p. 80-87 In Algae and Metropolitan Wastes. Pub. U.S. Public Health Service W61-3.

Thomas, E. A. 1969. The process of eutrophication in central European lakes. p. 29-49 In Eutrophication: causes, consequences, correctives. National Academy of Sciences, Washington, D.C.

Tucker, A. 1948. The phytoplankton of the Bay of Quinte. Trans. Am. Microsc. Soc., 67:365-383.