Materials Balance

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1. Introduction

Under the Biology–Chemistry Program of IFYGL, studies were undertaken to determine the form and amount of materials entering, leaving, and residing in Lake Ontario and to measure the quantities of nutrients and toxic chemicals flowing into and out of the lake. Closely related to such a materials balance analysis is the water balance, which was analyzed by DeCooke and Witherspoon, with the results presented in an earlier chapter of this book.

The first step in assessing the materials balance consisted of identifying significant loadings to the lake, computing discharge rates, and establishing the change in storage. The second major task was to determine the whole lake content and the change in lake storage and thereby to define more clearly the relationship between the loadings, the discharge, the storage in the lake, and the storage in the sediments.

2. Tributary Loadings and Change in Storage

The monitoring of tributary discharge rates is an ongoing program in both the United States and Canada, and no further efforts in this regard were necessary during the Field Year. In the United States, flow data from gauging stations on the major tributaries (Niagara, Genesee, Oswego, and Black Rivers), as well as St. Lawrence outflow data, were obtained from the Water Resources Division of the U.S. Geological Survey, which maintains a gauging station near the mouth of each tributary. Input between the gauging station and the mouth of the river was found to represent less than 3 percent of the total stream discharge volume in all cases and was, therefore, considered to be negligible.

The gauging station for the St. Lawrence River is located at Cornwall, approximately 175-km downstream from the outlet of Lake Ontario at Wolfe Island. The discharge at the outlet of the lake was computed by applying an adjustment factor to allow for the increase in flow between Wolfe Island and Cornwall. For the purpose of monitoring the chemical concentrations in the outflow from Lake Ontario, two transects were sampled, one from the Canadian shore to Wolfe Island, the other from Wolfe Island to the U.S. shore. The north and south side flows around Wolfe Island were computed by the U.S. Army Corps of Engineers to be 40 and 60 percent, respectively. The increase in flow between Wolfe Island and the St. Lawrence River gauge at Cornwall was estimated at 142 m^3 s^{-1} (5,000 ft^3 s^{-1}). Therefore, a simple calculation of (0.4) $\times$ (flow at Cornwall $-$ 142 m^3 s^{-1})

yielded the outflow discharge for the north channel of Wolfe Island, and, similarly, a factor of (0.6) yielded the south channel discharge (Casey and Salbach, 1974). For the smaller tributaries on the Canadian side, lake flow rates were provided by the Water Survey of Canada, Environment Canada. Discharge rates for direct municipal and industrial sources were obtained from the individual treatment plants and industries within the basin.

Responsibility for the chemical sampling and analysis of the major and minor tributaries to Lake Ontario on the U.S. side rested with the Environmental Protection Agency and the New York State Department of Environmental Conservation. On the Canadian side, all tributary sampling and analysis was conducted by the Ontario Ministry of the Environment. From the beginning of April 1972 until the end of May 1973, the major tributaries were sampled at 2- to 3-day intervals. The minor tributaries, located primarily in Canada, were sampled from 12 to 18 times by a schedule determined from the flow characteristics of the stream under study. The sampling techniques and analysis procedures are discussed in detail in a report by the U.S. Environmental Protection Agency (1971).

Because of the differences in procedures used by the United States in sampling the major streams and by Canada, which sampled primarily minor tributaries, separate equations were adopted for calculating loadings. The equation used for the loadings from the United States tributaries was

$$\overline{M} = \frac{\sum_{i=1}^{n} Q_i C_i K}{n}, \qquad (1)$$

where

$\overline{M}$ = average daily mass loading,
Q = flow volume,
C = parameter concentration,
n = number of days on which samples were taken, and
K = conversion factor for appropriate units.

The computation was based on daily flow data obtained from the U.S. Geological Survey and nondaily concentrations, which were linearly interpolated to yield daily values. Results were compiled into monthly values to facilitate identification of seasonality over the assessment period.

The equation used for the loadings from the Canadian tributaries was

$$\overline{M} = \frac{\sum_{i=1}^{n_1} Q_i}{n} \cdot \frac{\sum_{i=1}^{n_2} C_i}{n} \cdot K, \qquad (2)$$

where the notation is the same as in eq. (1).

Loadings by precipitation were computed for samples collected and analyzed by the Canada Centre for Inland Waters (Shiomi and Kuntz, 1973) and by EPA. These calculations were made by multiplying the average monthly rainfall by the concentration of each variable under study. Chemical data for municipal and industrial loadings were provided by the Ontario Ministry of the Environment and the New York State Department of Environmental Conservation.

The results of the loading computations are presented in tables 1 and 2.

The following chemical lake budget equation, similar to the hydrologic equation used in the Terrestrial Water Balance Chapter, but without consideration of evaporation, was used to calculate the change in storage (Casey and Salbach, 1974):

$$\Delta S = I + P + G - O, \qquad (3)$$

where

ΔS = change in storage (net load),
I = inflow loading,
P = precipitation loading,
G = groundwater loading, and
O = outflow loading.

The calculated change in storage for total nitrogen, total phosphorus, and chloride are tabulated in table 3, expressed as mean metric tons per day. With respect to the conservative chloride ion, the net inflow loading ($I + P + G$) in table 3 balances the outflow loading to 8 percent and to 4 percent when account is taken of the greater inflow vs. outflow that occurred during the Field Year. With respect to the change in storage of total phosphorus and total nitrogen, the results indicate that 51 and 33 percent, respectively, of the loadings were stored in the lake-sediment system during IFYGL. In their study, Casey and Salbach (1974) concluded that the computed balance can be considered reasonably accurate.

3. Whole–Lake Balance — United States Data

Eleven major lakewide cruises (seven by United States ships, four by Canadian) were undertaken to

TABLE 1. — *Lake loadings – United States data (Casey and Salbach, 1974)*

Substance	Niagara River $\bar{X}$ metric tons day⁻¹	Confidence level % (95%)	Lake loadings g m⁻² day⁻¹ 10⁻³	Genesee River $\bar{X}$ metric tons day⁻¹	Confidence level % (95%)	Oswego River $\bar{X}$ metric tons day⁻¹	Confidence level % (95%)	Black River $\bar{X}$ metric tons day⁻¹	Confidence level % (95%)	X metric tons day⁻¹ Minor tribs.	Ground water	Precipitation	Municipal	Total $\bar{X}$ metric tons day⁻¹	Lake loadings g m⁻¹ day⁻¹ 10⁻³	St. Lawrence River $\bar{X}$ metric tons day⁻¹	Conf. level % (95%)
Total phosphorus	20.84	12	1.05	1.77	21	2.86	14	0.50	18	0.56	0.11	4.51	1.66	28.23	1.44	21.56	9
Organic phosphorus	2.43	20	0.12	0.34	19	0.92	15	0.08	22					3.75	0.19	5.12	23
Ammonia	19.72	26	1.00	3.73	41	6.66	13	1.51	19					31.63	1.61	21.35	16
Nitrate . .	110.91	19	5.64	10.82	23	17.46	14	6.20	19					145.38	7.39	143.65	17
Total Kjeldahl nitrogen	107.91	6	5.49	3.28	11	11.62	10	2.04	19					124.86	6.35	149.82	10
Total nitrogen .	218.82		11.12	14.09		29.09		8.25		3.76	0.94	62.21	4.22	278.22	14.14	293.47	
Total organic carbon	1683.27	18	85.55	54.50	20	167.77	11	94.94	22					2000.41	101.67	1852.88	17
Silicon dioxide . . .	370.61	22	18.84	34.94	25	68.73	24	54.07	10					528.33	26.85	459.94	13
Sulphate . . .	10730.72	14	545.41	509.89	19	1559.01	10	102.09	25					17491.13	655.76	18567.34	4
Chloride .	15183.67	3	771.71	319.34	21	4032.83	9	1.41	11		23.47	67.05		19563.88	995.75	77.26	10
Sodium	9117.73	10	463.41	279.16	10	1754.25	8	28.54	18					11190.26	568.77	19102.55	3
Magnesium .	4663.52	2	237.02	146.63	17	468.37	9	39.41	10					5303.98	269.58	9390.39	5
Potassium .	976.04	3	49.60	39.83	18	104.39	8	25.61	23					1134.40	57.66	5329.30	3
Calcium	20232.20	3	1028.31	471.92	11	2352.32	7	0.74	16					24244.18	1179.96	4.07	19

TABLE 2.—*Lake loadings (metric tons per day) – Canadian data (Casey and Salbach, 1974)*

Substance	Tributaries (excluding Niagara River)	Municipal	Industrial	Niagara River	St. Lawrence River
Total phosphorus	3.54	7.84	0.22	23.18	15.91
Soluble phosphorus	0.94	5.41	0.01	*	*
Nitrogen					
Ammonia	3.97	26.96	*	13.64	13.73
Total Kjeldahl	32.12	35.86	*	*	*
Nitrite	0.08	0.35	*	*	*
Nitrate	13.89	1.88	*	*	*
Total	46.8	38.1	9.2	200.5	250.5
Chloride	985	223	14	14,091	18,182
Total organic carbon	537	45	1	4,091	5,000
Total carbon	1,610	*	5	13,636	16,818
Total dissolved solids	9,746	53	83	*	*
Suspended solids	1,063	1,011	72	*	*
BOD_5	117.9	45.6	37.4	*	*
Sulphate	1,326	143	18	11,818	13,636
Iron	33.93	*	13.45	86.36	40.91
Phenol	0.306	*	0.090	2.273	0.909

*Insufficient data.

TABLE 3.—*Loadings of total nitrogen, total phosphorus and chloride, and change in storage (metric tons per day) during IFYGL (after Casey and Salbach, 1974)*

Component		Total nitrogen	Total phosphorus	Chloride
Niagara River		219	20.8	15184
Tributaries		102	9.2	5364
Municipal	(*I*)	42	9.5	233
Industrial		9	0.2	14
Precipitation	(*P*)	62	4.5	67
Groundwater	(*G*)	1	0.1	23
Total		435	44.4	20877
(Minus) St. Lawrence River	(*O*)	293	21.6	19103
Change in storage	(Δ*S*)	142	22.8	1774

TABLE 4.—*Material balance cruises*

Cruise No.	Date	Vessel
1	May 1-5, 1972	*Researcher*
2	May 15–19, 1972	*Researcher*
3	June 12-16, 1972	*Researcher*
4	July 10-14, 1972	*Researcher*
5	Aug. 21–25, 1972	*Researcher*
6	Oct. 30–Nov. 3, 1972	*Researcher*
7	Nov. 27–Dec. 3, 1972	*Researcher*
8	Feb. 5-9, 1973	*Limnos*
9	Mar. 18-23, 1973	*Limnos*
10	Apr. 24–30, 1973	*Martin Karlsen*
11	June 11-15, 1973	*Limnos*

collect samples at 105 stations at depths of 5, 10, 15, 20, 25, 30, 40, 50, 100, 150, and 200 m, depending on the bathymetry at each station. Station locations are shown in figure 1, and the cruise schedule is listed in table 4. Sampling and analysis procedures were the same on all cruises (American Public Health Association, 1971; U.S. Environmental Protection Agency, 1971).

Data on tributary loadings were obtained from the study by Casey and Salbach (1974) via eqs. (1) and (2). Additional information was gathered, however, to include 26 parameters, among them precipitation, direct land runoff, and shore erosion.

Rates of precipitation were computed from data recorded by 23 stations surrounding the lake, and the overwater precipitation was then estimated using the Thiessen polygon technique (Bolsenga and Hagman, 1975). Contributions from direct land runoff and groundwater inflows were considered negligible in comparison with both the large and small tributaries and therefore were not included in the loading computations (Ostry, 1971; Singer, 1974). Loadings from

shore erosion during the Field Year were not evaluated for chemical composition, and, as a result, no data were available to include this factor in the balance. Recent studies indicate, however, that, with respect to clay and silt particles, all but 0.93 metric tons year^{-1} of eroded material is either sedimented immediately, transported to reside in the eastern basin sediments of the lake, or is flushed from the system in the outflow waters (Kemp and Harper, 1976).

Results of the loading computations are given in a materials balance report by Casey et al. (1977), which includes discussions of the statistical variance and seasonality of the loading data, as well as comparisons of the interrelationship between streamflow and load. With respect to tributaries, it is clear from the distributions that parameters behave reasonably independently of one another and vary in relation to streamflow by parameter type and streamflow characteristics. The loading summary for total phosphorus is shown in table 5; for the numerous further findings, the reader is referred to the report by Casey et al. (1977).

Data from the 11 cruises were used in computing lake content by means of an interpolative and integrative routine, "SPLOTCH" (Boyce, 1973). The results for nine major substances is given in table 6. Boyd and Eadie (1977) have shown, however, that many of the

analytical values on which these results are based are of questionable quality, and caution must be used in their interpretation.

For calculation of the materials balance, monthly changes in storage, resulting from biological-chemical transformation processes, sediment exchanges, and loading rate variations, were determined for the nine substances identified in table 6. The following equations relate the accumulation rate for a parameter with the rate of change of the lake content for that parameter relative to the net loading to the system:
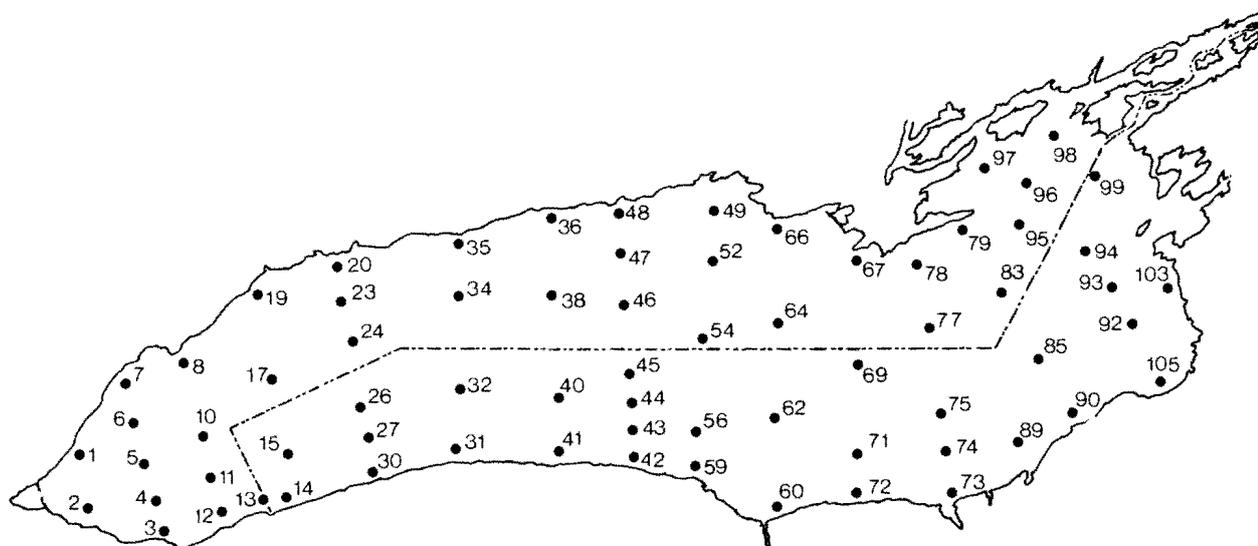
$$\int_V dV \, \frac{\partial \rho_i}{\partial t} = \int_S \rho_i \vec{v} \cdot \vec{n} dS + \int_V \&_i \, dV, \qquad (4)$$

which is the integral form of the equation for the conservation of mass (Batchelor, 1967),

where

ρ_i = concentration of parameter i,
$\vec{v}$ = flow velocity,
$\&_i$ = net rate of production of parameter i per unit volume,
V = volume of lake,
S = surface area of lake, and
$\vec{n}$ = unit vector normal to surface.

The term on the left side of eq. (4) can be rewritten

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FIGURE 1. — Materials balance cruise stations.

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$$\int_V dV \frac{\partial \rho_i}{\partial t} = \frac{d}{dt} \int_V dV\rho_i - \int_V \rho_i d \frac{\partial V}{\partial t} = \frac{dM_i}{dt} + C_i, \quad (5)$$

where M_i = the total mass content for parameter i at time t.

TABLE 5.—*Mean monthly loadings (mean metric tons per day) of total phosphorus (Casey et al., 1977)*

Month	Niagara River	Genesee River	Oswego River	Black River	St. Lawrence River	Canadian tributaries	Canadian municipal and industrial sources	United States municipal sources	United States minor tributaries	Precipitation	Net loading
(1972)											
Apr.	18.9	1.6	4.4	1.2	20.7	6.5	8.3	0.2	11.2	4.9	36.5
May	12.2	1.6	2.9	1.0	19.8	3.9	7.2	0.1	7.0	6.0	22.3
June	24.0	2.1	2.6	0.5	21.7	3.5	7.1	0.1	5.9	7.9	32.1
July	20.4	2.9	4.7	0.5	27.1	2.4	7.7	0.1	4.5	4.8	21.0
Aug.	22.1	0.4	2.0	0.2	33.6	1.0	6.7	0.1	1.9	6.4	7.2
Sept.	17.8	0.5	1.2	0.1	22.3	0.5	8.2	0.2	1.1	5.3	11.5
Oct.	15.4	0.7	1.8	0.3	16.9	1.0	7.3	0.1	2.0	5.7	17.6
Nov.	19.3	1.0	1.4	0.7	15.8	3.5	7.3	0.1	5.7	7.9	31.2
Dec.	31.4	4.3	1.9	0.5	13.3	4.9	9.1	0.2	8.2	8.2	55.5
(1973)											
Jan.	18.6	1.8	3.1	0.4	12.9	4.4	9.6	0.2	7.3	2.8	35.2
Feb.	23.5	0.7	2.3	0.6	20.4	3.2	9.9	0.2	5.3	4.0	29.3
Mar.	28.9	3.1	3.0	1.9	25.4	6.3	9.0	0.2	10.7	7.5	45.3
Apr.	17.8	2.3	1.8	1.4	27.0	5.0	8.3	0.2	8.7	7.7	26.2
May	19.5	1.6	2.0	0.5	28.0	2.4	7.9	0.1	4.0	5.7	15.8
Mean	20.7	1.7	2.5	0.7	21.8	3.5	8.1	0.2	6.0	6.1	27.6
Percent of total input	42	4	5	1		7	16	<1	12	12	+56

Total mean input = 49.5 metric tons day⁻¹

TABLE 6.—*Total substance masses (metric tons) in Lake Ontario (after Casey et al., 1977)*

Substance	Cruise no.										
	1 May 1-5	2 May 15-19	3 June 12-16	4 July 10-14	5 Aug. 21-25	6 Oct. 30-Nov. 3	7 Nov. 27-Dec. 3	8 Feb. 5-9	9 Mar. 18-23	10 Apr. 24-30	11 June 11-15
Total phosphorus	1.68E4	2.69E4	2.80E4	2.78E4	2.94E4	3.52E4	2.38E4	2.38E4	2.64E4	3.49E4	2.79E4
Dissolved organic phosphorus	2.60E3	7.04E3	3.50E3	5.35E3	5.47E3	7.01E3	6.00E4	1.08E4	8.07E3	1.13E4	5.99E3
Total nitrogen		9.04E5	7.04E5	1.05E6		6.33E5	4.86E5		7.35E5	5.31E5	4.67E5
Nitrate plus nitrite	8.57E5	5.94E5	4.26E5	7.01E5	4.45E5	3.70E5	3.22E5	4.41E5	5.51E5	4.09E5	3.02E5
Ammonia	8.85E5	8.77E3	2.04E4	3.59E4	3.04E4	3.37E4	1.61E4	8.27E3	1.04E4	1.76E4	1.87E4
Total Kjeldahl nitrogen		3.10E5	2.77E5	3.57E5		2.63E5	1.64E5		1.83E5	1.21E5	1.65E5
Organic nitrogen		3.01E5	2.55E5	3.21E5		2.29E5	1.48E5		1.73E5	1.04E5	1.46E5
Total organic carbon	4.14E6	4.27E6	5.69E6	7.57E6		7.24E6		2.91E6	4.28E6	4.28E6	5.43E6
Sulphate						4.27E7	3.77E7	4.36E7	4.33E7	4.38E7	3.67E7

Note exponential notation, e.g., 1.68E4 = 1.68 × 10⁴.

The component C_i represents the second term on the right side of eq. (5) and can be neglected whenever $(\Delta\rho \; \rho^{-1}) >> (\Delta V \; V^{-1})$. During 1972 a lake-level change of approximately 1 m was measured, which represents about 20 km³. Hence, $(\Delta V \; V^{-1}) \simeq 0.012$. Since total phosphorus, with the smallest concentration change of the major parameters shows $(\Delta\rho \; \rho^{-1}) = 0.20$, it may be considered that $(\Delta\rho \; \rho^{-1}) >> (\Delta V \; V^{-1})$ for all parameters studied.

From eq. (4), the second term, representing the loading rate, can be expressed as

$$\int_S \rho_i \vec{v} \cdot n \, dS = L_{iT} + L_{iR} + L_{iS}, \tag{6}$$

where

$\quad L_{iT}$ = net loading rate from tributaries,
$\quad L_{iR}$ = loading rate from rainfall, and
$\quad L_{iS}$ = net loading rate from sediment exchange.

(The processes of dry fallout and gaseous exchange are not included. Although they were not measured, they are believed to be small in Lake Ontario for the materials analyzed.)

The third term in eq. (4) represents the net rate of production of parameter i, and can be expressed as

$$\int_V \&_i dV = T_i, \tag{7}$$

where T_i is a function of time.

Substituting eqs. (5), (6), and (7) into eq. (4) yields

$$\frac{dM_i}{dt} = L_{iT} + L_{iR} + L_{iS} + T_i, \tag{8}$$

where the terms L_{iT} and L_{iR} were measured during IFYGL. The terms L_{iS} and T_i were not measured, but were computed as residuals by rewriting eq. (8) as

$$\frac{dM_i}{dt} = L_{iT} + L_{iR} + S_i, \tag{9}$$

where

$$S_i = L_{iS} + T_i. \tag{10}$$

The term S_i represents the volume rate of production and sediment exchange of parameter i, its importance depending upon the particular parameter under evaluation. The changes in storage, dM_i/dt, were computed from monthly lake content values obtained with "SPLOTCH"; the measured loadings, L_{iT} and L_{iR}, were computed; and the monthly values of S_i were computed as a residual from eq. (9) for each parameter under study. The results for total phosphorus are given in table 7 and are plotted in figure 2, which also shows the computed content values from table 6. From these results, certain conclusions regarding the lake/loading balance for total phosphorus can be drawn. The average deviation from the mean content is approximately 9.5 percent, with a maximum deviation of 19 percent in the spring of both 1972 and 1973, which is indicative of the seasonal cycling of total phosphorus in Lake Ontario and appears to be consistent with the occurrence of the maximum loading rate observed in December 1972. The term S indicates a net phosphorus rate of production and loading to the sediments during the study period.

For a full evaluation of the other major balance parameters, the reader is referred to the study by Casey et al. (1977).

4. Whole-Lake Balance — Canadian Data

To clarify some of the more distinctive characteristics of the whole-lake materials balance and to examine the major parameters by a different method, a study incorporating data from IFYGL cruises oriented toward dynamic processes was prepared (Fraser, 1978). Eleven such cruises were undertaken, following the schedule shown in table 8. Nine consisted of four detailed transects across the lake; on the other two, observations were made at 95 stations distributed evenly across the lake. The chemical analysis procedures used have been fully documented by
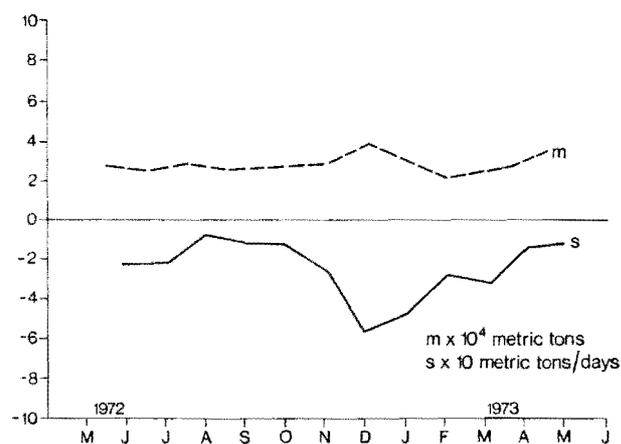

FIGURE 2. — Mass content (m) and production rate (s) of total phosphorus during IFYGL.

Traversy (1971) and Philbert and Traversy (1973) and therefore will not be elaborated on further here.

TABLE 7. — *Mass balance terms for total phosphorus (metric tons per day)*

Month	dM/dt	L	S
(1972)			
June	8.8	32.1	−23.3
July	3.3	21.0	−21.1
Aug.	1.3	7.2	−6.9
Sept.	1.9	11.5	−11.1
Oct.	6.5	17.6	−11.5
Nov.	5.5	31.2	−24.5
Dec.	0.2	55.5	−55.2
(1973)			
Jan.	−12.5	35.2	−46.5
Feb.	0.7	29.3	−28.0
Mar.	11.9	45.3	−32.1
Apr.	9.2	26.2	−15.9
May	0.8	15.8	−10.0
Mean	3.9	27.6	−23.8

The data and the method for the loading computations were the same as previously described and discussed by Casey et al. (1977). The resulting monthly net loadings from all sources for nine major substances are shown in table 9.

The mass contents within the lake for the major parameters were obtained by use of a numerical integration routine, "ALDAR", developed at the Canada Centre for Inland Waters, which computes linearly

TABLE 8. — *Schedule of process-oriented cruises*

Cruise No.	Date	Vessel
10	Apr. 10-22, 1972	*Martin Karlsen*
24	May 23-27, 1972	*Martin Karlsen*
32	June 19-July 1, 1972	*Martin Karlsen*
42	July 19-29, 1972	*Martin Karlsen*
55	Sept.5-16, 1972	*Martin Karlsen*
60	Sept. 19-23, 1972	*Martin Karlsen*
69	Oct. 17-28, 1972	*Martin Karlsen*
75	Nov. 20-Dec. 2, 1972	*Martin Karlsen*
04	Jan. 9-19, 1973	*Martin Karlsen*
15	Mar. 6-17, 1973	*Martin Karlsen*
20	Mar. 19-24, 1973	*Martin Karlsen*

TABLE 9. — *Monthly net loadings (metric tons) to Lake Ontario*

Substance	1972									1973				
	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Total phosphorus (P)	1,095	691	963	651	223	345	546	936	1,721	1,091	820	1,404	786	490
Soluble reactive phosphorus (P)		326	318	143	198	252	307	390	533	388	235	307		
Total nitrogen (N)	8,595	8,227	12,189	3,605	3,965	2,379	2,198	9,639	12,493	9,536	5,558	9,002	10,269	8,692
Nitrate + nitrite (N)	5,208	2,737	7,875	1,070	338	1,833	1,767	4,284	5,428	4,703	1,954	3,016	3,636	3,072
Ammonia (N)	3,333	2,833	3,969	2,310	2,046	1,950	2,352	4,785	3,525	2,427	1,588	2,787	2,691	2,334
Total Kjeldahl nitrogen (N)	6,387	5,490	6,696	2,536	3,627	546	431	5,355	7,065	4,802	3,604	5,986	6,609	5,620
Total organic nitrogen (N)	3,057	2,657	2,730	266	1,581	−1,401	−1,913	570	3,540	2,378	2,016	3,199	3,921	3,286
Total organic carbon (C)	60,201	63,023	9,837	37,733	48,307	−3,066	−8,841	50,664	101,785	74,902	51,694	99,764	70,839	57,592
Sulphate (SO_4)							−233,616	−6,870	160,518	109,089	30,884	88,598	11,070	−8,959

interpolated concentrations for a 2-km reference grid over Lake Ontario, taking into account the basin bathymetry and the inshore-offshore differentiation that is characteristic of the lake. The total lake content is obtained by summing the contents computed for each 2-km grid column.

For conservative substances, i.e., those with no chemical-biological interactions ($T_i = 0$), the following expanded version of eq. (3) was used (Fraser, 1978):

$$\triangle M = L_T + L_M + L_I + L_A + L_G + L_R + L_S - \phi - S - E, \quad (11)$$

where

$\triangle M$ = change in mass,
L_T = tributary loading,
L_M = municipal loading,
L_I = industrial loading,
L_A = atmospheric loading,
L_G = groundwater loading,
L_R = loading from resuspension,
L_S = loading from shore erosion,
ϕ = output from lake,
S = sedimentation, and
E = evaporation.

The units are mass per unit time. Evaporation, E, is not considered, since either the materials studied are not subject to evaporation or evaporation would have minimal effect on the balance in the context discussed. The groundwater term, L_G, is assumed to be negligible in comparison with the tributary component, L_T, and is, therefore, deleted. The shore erosion term, L_S, is also ignored, because of the lack of data on the chemical composition of eroded material and because the majority of such material is directly sedimented or rapidly flushed from the system. Thus,

$$\triangle M = L_T + L_M + L_I + L_A + L_R - \phi - S. \quad (12)$$

The computed net change in content over a period of time for a given parameter can be expressed as follows:

$$\triangle M = L_T + L_M + L_I + L_A - \phi + N, \quad (13)$$

where

$$N = L_R - S + E_R,$$

with N = net sediment storage plus error and

E_R = error.

The net load, $L_N(= L_T + L_M + L_I + L_A - \phi)$, was measured for each month of the field year. The measured lake content, M, was calculated for each ship cruise using the computer routing "ALDAR". The monthly change in mass was obtained as a time difference between the values of M for the last day of each month obtained by linear interpolation from the cruise value. (See tables 10 and 11 for total phosphorus and total nitrogen, respectively.) The term N was not measured, but was calculated as a residual from equation (13).

Results of the monthly balance calculations for total phosphorus in Lake Ontario are shown in table 12, and for total nitrogen in table 13. These results for one year, beginning with the first lake cruise on April 10, are summarized in table 14 where an indication of the net sedimentation over the 11 months may be inferred from the term N if the net error term is assumed small.

Of particular importance to biological systems in Lake Ontario is the concentration of total phosphorus in the water column. Large-scale remedial programs for phosphorus loading abatement are underway in the Great Lakes basins for the purpose of controlling the excessive development of phytoplankton. Over the period from May 1, 1972, to March 31, 1973, the measured content of total phosphorus increased by 4,730 metric tons. Over this 11-month period the net sedimentation of total phosphorus was estimated as 4,680 metric tons, approximately 10 percent of a mean

TABLE 10.—*Total phosphorus for Lake Ontario* *(metric tons X 10^3)*

Cruise date	Measured content[1]	Date	Interpolated content
(1972)		(1972)	
Apr. 10	35.47	Apr. 30	35.34
May 23	35.18	May 31	34.90
June 19	34.23	June 30	33.39
July 17	32.09	July 31	32.15
Sept. 5	32.31	Aug. 31	32.29
Sept. 19	33.46	Sep. 30	32.40
Oct. 17	30.77	Oct. 31	32.05
Nov. 20	33.88	Nov. 30	34.49
		Dec. 31	36.36
(1973)		(1973)	
Jan. 9	36.91	Jan. 31	37.89
Mar. 6	39.41	Feb. 28	39.14
Mar. 19	39.24	Mar. 31	40.07
Apr. 24	41.72		

[1]Derived with "ALDAR" routine.

measured content in table 10. Worthy of note is the increase in measured content, ΔM, in table 12 from November 1972 to February 1973, with a source of total phosphorus from both the rivers and the sediment.

The nitrogen cycle in Lake Ontario is extremely dynamic and deserves much attention since it also plays a major role in the trophic development of the lake. The seasonal pattern for total nitrogen is similar

to that of total phosphorus, although the results vary somewhat more and include a questionable measured content value for the cruise on October 17 (table 11). Over the period from May 1, 1972, through March 31, 1973, the measured content of total nitrogen, ΔM, decreased by 86,900 metric tons (table 14). Over the 11-month period the net sedimentation of total nitrogen, N, assuming the error term is small, was 165,700 metric tons, approximately 30 percent of the mean measured content in table 11.

TABLE 11.—Total nitrogen for Lake Ontario (metric tons X 10^3)

Cruise date	Measured content[1]	Date	Interpolated content
(1972)		(1972)	
Apr. 10	608.5	Apr. 30	634.6
May 23	664.5	May 31	658.7
June 19	644.9	June 30	660.0
July 17	683.2	July 31	665.0
Sept. 5	518.2	Aug. 31	534.7
Sept. 19	532.0	Sept. 30	600.7
Oct. 17	706.8	Oct. 31	621.8
Nov. 20	500.3	Nov. 30	520.0
		Dec. 31	580.9
(1973)		(1973)	
Jan. 9	598.6	Jan. 31	598.6
Mar. 6	598.6	Feb. 28	598.6
Mar. 19	505.9	Mar. 31	547.7
Apr. 24	631.2		

[1]Derived with "ALDAR" routine.

TABLE 12.—Total phosphorus balance (metric tons X 10^3)

Month	ΔM	L_N	N
(1972)			
May	−0.44	0.69	−1.13
June	−1.51	0.96	−2.47
July	−1.24	0.65	−1.89
Aug.	0.14	0.22	−0.08
Sept.	0.11	0.35	−0.24
Oct.	−0.35	0.55	−0.90
Nov.	2.44	0.96	1.48
Dec.	1.87	1.72	0.15
(1973)			
Jan.	1.53	1.09	0.44
Feb.	1.25	0.82	0.43
Mar.	0.93	1.40	−0.47

TABLE 13.—Total nitrogen balance (metric tons X 10^3)

Month	ΔM	L_N	N
(1972)			
May	24.1	8.2	15.9
June	1.3	12.2	−10.9
July	5.0	3.6	1.4
Aug.	−130.3	4.0	−44.3
Sept.	66.0	2.4	−26.4
Oct.	21.1	2.2	18.9
Nov.	−101.8	9.6	−111.4
Dec.	60.9	12.5	48.4
(1973)			
Jan.	17.7	9.5	8.2
Feb.	0.0	5.6	−5.6
Mar.	−50.9	9.0	−59.9

TABLE 14.—Balance of total phosphorus and total nitrogen, May 1, 1972, through March 31, 1973, (metric tons x 10^3)

	ΔM	L_N	N
Total phosphorus	4.73	9.41	−4.68
Total nitrogen	−86.9	78.8	−165.7

5. Carbon Budget

As a special study, the carbon system of Lake Ontario was examined in some detail to identify the sources and sinks of the various forms of carbon in the system (Eadie and Robertson, 1976; Robertson and Eadie, 1975). Inflow and outflow were calculated, and a monthly carbon budget for the lake was derived (table 15).

This budget shows the addition of inorganic carbon in tributary streams, especially the Niagara River, and the fixation of CO_2 in organic matter by primary pro-

duction to be the two major carbon sources. The major sinks are shown to be inorganic carbon outflow with the St. Lawrence River and net CO_2 exchange between the atmosphere and the dissolved inorganic carbon pool in the lake. The monthly values in table 15 indicate a distinct seasonal pattern, with net carbon inflow to the lake during the warm months and net outflow during the cold months. This cycle is driven by the seasonality in primary production. During the warm season, high rates of primary production result in the fixation of large amounts of carbon, which, in turn, cause a depletion in the dissolved CO_2 in the lake and hence a net influx of CO_2 from the atmosphere. During the cold months, decomposition of organic matter predominates, resulting in a large flux of CO_2 from the lake to the atmosphere.

Charlton (1977) has raised some substantive questions concerning this budget. He objects to the inclusion of primary production as a budget term because, as he points out, this process only moves carbon from the dissolved inorganic form to the particulate organic form and does not lead to a direct movement of carbon into or out of the lake. Unfortunately, however, this problem is not straightforward. Again as Charlton points out, there were no direct measurements of CO_2

exchange with the atmosphere during IFYGL; this exchange term in the budget was calculated by using measure concentrations of alkalinity (primarily bicarbonate plus carbonate) to compute partial pressures of dissolved CO_2 and then using the difference between this value and the partial pressure of CO_2 in the atmosphere to calculate the direction and magnitude of the driving force for CO_2 exchange. This procedure carries the assumption that the concentration of bicarbonate plus carbonate is in equilibrium with dissolved CO_2, which is, in turn, in equilibrium with atmospheric CO_2. However, there is evidence that this is not true, and that, instead, the dissolved CO_2 is taken up rapidly during times of primary production by the phytoplankton and that this process may well be kinetically more rapid than the exchange between dissolved CO_2 and bicarbonate plus carbonate. To take this phenomenon into consideration, the assumption was made in the budget calculations that the method used for computing atmospheric exchange really only accounted for the amount of CO_2 moving into the inorganic pool and that a term for CO_2 uptake by primary production needed to be included in the budget to account for the CO_2 that moved from the atmosphere (and also from decomposing inorganic mat-

TABLE 15.—*Carbon balance ($X\ 10^8$ g) for 1972 (Eadie and Robertson, 1976)*

	Inflow			Outflow					
	Inorganic	Organic		Inorganic			Organic		
Month	Tribu-taries	Tribu-taries	Primary production	St. Lawrence	Exchange with inorganic carbon pool	Precipi-tation of $CaCO_3$	St. Lawrence	Sedimen-tary deposition	Net
Jan.	5.0	0.5	0.4	4.4	9.1	0.13	0.3	0.03	−8.1
Feb.	4.0	0.4	0.8	4.7	4.8	−0.13	0.3	0.02	−4.5
Mar.	4.9	0.4	1.4	5.0	2.1	−0.11	0.3	0.04	−0.6
Apr.	4.0	0.6	1.9	4.2	0.6	0.16	0.6	0.08	0.9
May	4.3	0.7	2.3	4.8	−0.1	0.17	0.6	0.11	1.7
June	4.4	0.7	2.7	4.0	−0.6	0.19	0.6	0.13	3.5
July	4.7	0.6	5.7	4.3	−0.8	0.17	0.6	0.15	6.6
Aug.	4.8	0.3	7.7	4.4	−0.6	−0.13	0.7	0.32	8.1
Sept.	4.9	0.5	7.1	4.0	−0.1	−0.14	0.7	0.43	7.6
Oct.	5.5	0.7	2.6	3.8	0.9	−0.13	0.2	0.40	3.6
Nov.	5.5	0.4	1.0	4.4	5.2	0.12	0.2	0.15	−3.2
Dec.	5.3	0.6	0.5	4.7	8.7	0.12	0.3	0.06	−7.5
Subtotal	57.3	6.4	34.1	52.7	29.2	0.4	5.4	1.9	
Total		97.8				89.6			8.2

ter) to dissolved CO_2 and then directly to phytoplankton without ever showing up in the measurement of alkalinity. Whether this assumption is correct or whether Charlton's approach is closer to fact is not at all clear at this point. More research on the kinetics of the bicarbonate-carbonate-dissolved CO_2-atmospheric CO_2-phytoplankton system is needed before the question can be resolved. The budget is in approximate balance when the primary production term is included. but, as pointed out by Charlton, is grossly out of balance when this term is omitted.

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