Nutrient loads and budgets in the Bay of Quinte, Lake Ontario, 1972 to 2001

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by

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ABSTRACT

Minns, C.K., J.E. Moore, and K.E. Seifried. 2004. Nutrient loads and budgets in the Bay of Quinte, Lake Ontario, 1972 to 2001: 2694

The Bay of Quinte became highly eutrophic in the 1960s and 1970s. In the late 1970s a long-term program began to replace and upgrade sewage treatment facilities releasing effluents directly into the bay. This report describes the assembly and analysis of data for nutrient loads and budgets for the Bay of Quinte covering the period 1972 to 2001. The methods closely follow those used by Minns et al (1986b) in an earlier study of the Bay covering the period 1965 to 1981. Changes in the frequency and spatial cover of sampling made some simplifications of the methods necessary. Loads and budgets were estimated by month and by bay section (upper, middle, and lower) for total phosphorus (P), total nitrogen (N), and chloride (Cl). Point source loading of P have declined dramatically with decreases continuing to the present. Point source N loads are unchanged while Cl loads have increased. Analyses of whole Bay and sectional budgets showed there have been shifts in retention and estimated sediment P reflux in line with expectated declines in reflux after point source load reductions were implemented. The colonization of dreissenid mussels in the mid-1990s and the associated increases in macrophyte cover and density have altered the nutrient budgets thereby increasing upper bay concentrations. Recommendations for the future include more rigorous collection of nutrient and flow data for the major rivers and point sources, allowing refinement of certain components of the Bay of Quinte nutrient budgets. The budget results provide a basis for future development of a model simulating P dynamics over the period 1972 to 2001 and predicting future conditions under alternate hydrologic regimes, ecosystem conditions, and P management in the Bay of Quinte.

RÉSUMÉ

Minns, C.K., J.E. Moore et K.E. Seifried. 2004. Charges et bilans des matières nutritives dans la baie de Quinte, lac Ontario, de 1972 à 2001 : 2694

La baie de Quinte s'est fortement eutrophisée dans les années 1960 et 1970. À la fin des années 1970, un programme à long terme a été mis en place pour remplacer et moderniser les stations de traitement des eaux usées qui rejetaient des effluents directement dans la baie. Ce rapport décrit la collecte et l'analyse des données sur les charges et les bilans des matières nutritives dans la baie de Quinte pour la période allant de 1972 à 2001. Les méthodes suivent de près celles qu'avaient utilisées Minns *et al.* (1986b) dans une étude antérieure de la baie couvrant la période allant de 1965 à 1981. Pour modifier la fréquence et la couverture spatiale de l'échantillonnage, il a fallu simplifier certains aspects des méthodes. Les charges et les bilans ont été calculés par mois et par section de la baie (supérieure, moyenne et inférieure) pour le phosphore total (P), l'azote total (N) et les chlorures (Cl). Les charges de P de source ponctuelle ont baissé considérablement, et cette diminution se poursuit jusqu'à nos jours. Les charges de N de source ponctuelle n'ont pas changé, alors que les charges de Cl ont augmenté. L'analyse des bilans pour l'ensemble de la baie et par section montre des changements dans la rétention et le reflux estimé du P des sédiments, changements qui concordent avec les baisses prévues du reflux après la mise en œuvre des réductions des charges dues aux sources ponctuelles. La colonisation de la baie par les moules de la famille des dreissénidés au milieu des années 1990, et les augmentations concomitantes de la couverture et de la densité des macrophytes, ont modifié le bilan des matières nutritives, ce qui a causé une hausse des concentrations dans la section supérieure de la baie. Pour l'avenir, les recommandations visent notamment une collecte plus rigoureuse de données sur les matières nutritives et les écoulements pour les principales rivières et sources ponctuelles, ce qui permettra de raffiner certaines composantes des bilans des matières nutritives de la baie de Quinte. Les résultats des bilans serviront de base à l'élaboration d'un modèle simulant la dynamique de P pendant la période allant de 1972 à 2001 et prédisant les conditions futures sous divers régimes hydrologiques, dans diverses conditions écosystémiques, et selon divers modes de gestion de P dans la baie de Quinte.

INTRODUCTION

The Bay of Quinte, an embayment at the northeastern end of Lake Ontario had undergone major eutrophication in the 1950s and 1960s. In the early 1970s, the Bay of Quinte became one of many targets for point source phosphorus control around the Great Lakes. In 1972, a multi-agency group initiated Project Quinte, a long-term study of phosphorus load management and associated consequences for major biotic components in the Bay of Quinte. Phosphorus removal at sewage treatment plants discharging treated effluent to the Bay of Quinte was instituted in the winter of 1977-78. In 1986, the Project Quinte group published a collection of papers documenting ecosystem changes in the period 1972 to 1981 (Minns et al. 1986a). Included in that publication were estimates and analysis of nutrient budgets for the Bay of Quinte covering the period 1965-81 (Minns et al. (1986b). Since the major reductions in point source phosphorus inputs of 1977-78, significant further reductions in point source loading have been achieved through refinement of STP operations. The work of the Project Quinte group has continued, and in recent years has expanded its focus as dreissenid mussels became established mid-1990s. The purpose of this paper is to present an updated analysis of nutrient loadings and their effects on *in situ* nutrient concentrations in the Bay, covering the period 1972 to 2001.

For consistency with the earlier study, the methodology used by Minns et al. (1986b) has been used wherever possible. Any changes are noted. A more comprehensive analysis of Lake Ontario backflows and sediment P reflux rates has been undertaken in an effort to develop more predictive capability. Where possible, we have attempted to assess the impact of zebra mussels on the P budgets.

The results and analyses in this report and in a companion report on modelling future conditions (Minns and Moore 2004) will provide the Bay of Quinte Restoration Council, and its associated local, provincial and federal agencies (Environment Canada, through their Sustainability Fund, and Ontario Ministry of Environment, under the Canada-Ontario Agreement, funded this work), with the basis for an overall P management strategy for the Bay of Quinte.

MATERIALS AND METHODS

MORPHOMETRY AND DRAINAGE

Bay section areas

The section areas employed were fixed and defined as in Minns et al. 1986b, shown here with the precision actually employed in all calculations where applicable: upper bay,136.388 km^2; middle bay, 49.179 km^2; lower bay, 71.835 km^2. These areas were used throughout the budget calculations described below to convert quantities measured as distances to volumes, e.g., precipitation, evaporation, and water level changes.

WATER BUDGET

All nominal water budget calculations were done as per Minns et al. (1986b), and consisted of estimating monthly average values of the terms on the right-hand side of the following expression:

Outflow = River inflow (+ above section outflow) + Precipitation - Evaporation - Volume change

These estimates were obtained as follows:

River inflow. River inflow was calculated on a daily basis and then summed for each month. Daily inflows were based on daily discharge data obtained from Environment Canada (Water Survey Division, Burlington) for gauging stations on five rivers (Table A1).

Flows for the Trent River were based on the 02HK004 station, missing values being estimated from the 02HK002 data using a relationship developed from overlapping portions of the two time series:

$$02HK004 = -1.324 + 1.457 * 02HK002; n = 8557, r^2 = 0.95.$$

Flows for the Napanee River from 1974 to 2001 were based on the 02HM007 station. A lack of overlap with the other gauging station on the Napanee River (02HM001) precluded development of a relationship between these two stations. Instead, the missing data in 1972 and 1973 for the 02HM007 station were estimated using a regression between the existing data for that station and those for the 02HM003 station on the Salmon River, covering the period 1974 to 2001:

$$002HM007 = 1.046 + 0.694 * 02HM003; n = 10227, r^2 = 0.90$$

Flows for the other rivers were used unchanged. All river flows were prorated to account for those areas between the gauging station and the corresponding river mouth, using the areas as reported in Minns and Johnson (1979) (Table A2). Daily section river inflows were obtained from these five river inflows plus that from miscellaneous other drainages not included in the above. The latter were accounted for by calculating Wilton Creek equivalents (WCE) as per (Minns et. al. 1986b), where one WCE is the daily inflow from Wilton Creek. The inflow to the upper bay was thus calculated as the sum of the inflows from the Trent, Moira, Salmon, and Napanee Rivers plus 5.8 WCE. The middle bay river inflow was 3.1 WCE, and the lower bay received 0.7 WCE.

Daily Precipitation. Daily precipitation data were summed to provide monthly data and multiplied by each bay section area to get the precipitation input for that section. The precipitation data used were obtained from Environment Canada (Environmental Services Branch, Burlington) for the weather station at Trenton, consisting of rain and total precipitation in tenths of millimeters. Amounts recorded as trace values were treated as zeroes, and the water equivalent of snow was taken as the difference between total precipitation and rain. The effect of seasonal ice cover was accounted for by assuming that snow accumulated during the period January through March and was released to enter the water budget in April. Thus from January to March precipitation consisted of rain, in April it consisted of total precipitation plus the water equivalent of the snow that fell during the previous three months, and from May to December it consisted of total precipitation.

Evaporation. Evaporation was calculated on a monthly basis using the relationships developed by Meredith (1975). Input to these relationships consisted first of mean air temperatures computed from daily values again obtained from Environment Canada (Environmental Services Branch) for the weather station at Trenton. The second input consisted of monthly mean surface water temperatures by bay section. For the period May to October, these were time-series data from the Project Quinte stations “B”, “HB”, and “C” representing the upper, middle, and lower bays, respectively (Minns et al. 1986a). Surface temperatures during these months were those values measured either at the surface or at the depth nearest the surface. For remaining months of the year, intake temperatures at the Belleville water treatment plant were used. Regressions were developed between the Belleville intake temperature and each of the Project Quinte stations to predict surface water temperatures in November and December. Evaporation was assumed to be nil for the months of January to March when the Bay is covered with ice. Negative evaporation values calculated for the lower bay in July 1977, June 1978 and

June 2001 were set to zero. As was done with precipitation, the resulting evaporation values (having units of distance per month) were multiplied by each bay section's area to obtain the monthly evaporation output for that section.

In-bay storage. The change in bay section volume due to water level fluctuation was calculated on a daily basis using Kingston daily water elevation data (Fisheries and Oceans Canada (DFO), Canadian Hydrographic Service, Tides, Currents and Water Levels Section), taking the product of the daily elevation change (applied to the beginning of a day interval) times the section surface area as volume change. These data were then scaled and summed to provide a monthly change in volume.

Though not strictly required for the water budget, section volumes were required elsewhere (to compute section substance stores). They were developed from the water budget data by applying the delta volume monthly time series (generated as described above) to estimates of initial volumes by bay section. The latter were obtained by varying arbitrary values for December, 1970 and finding those which minimised the differences between the resulting volume time series and the (unpublished) volume time series used by Minns et al. (1986b) for 1971 to 1981. This process resulted in reference values for December of 1971 which were 522.6386818, 271.9802273, and 1780.092386 (millions of m^3) for the upper, middle, and lower bays, respectively. The mean relative difference between the Minns et al. (1986) time series and the new volume time series was less than 0.1 percent, though it could occasionally be as large as 6 percent, especially in the upper and middle bays. Note that these volume estimates again depend on the same fixed estimates of bay section areas used elsewhere, and as such: a) probably represent underestimates and b) certainly do not reflect the fact that section area would in reality vary along with section volume.

RIVER CHEMICAL INPUTS

Monthly river inputs of total phosphorus, total nitrogen, and chloride were estimated using a rating curve technique as done in Minns et al. (1986b), based on the work of Minns and Johnson (1979) and Johnson and Owen (1971). egressions of the form:

$$\log_e(M) = \log_e(a) + b*\log_e(Q)$$

where M was the daily substance export (kg day^{-1}), Q was the daily flow (m^3 day^{-1}), and a and b are regression coefficients. The latter were obtained in a variety of ways, all ultimately based on water quality data for the rivers provided by the Ontario Ministry of the Environment (MOE) for these water quality stations (Table A3) where stations in italics were those also used by Minns and Johnson (1979). The availability of data from these stations varied by station and substance, so a considerable amount of gap-filling was required. The protocol used for developing regressions was as follows:

1. Concentration values in excess of plus or minus two standard deviations from the station mean were rejected as outliers
2. ANCOVAs were performed for each tributary with station as the treatment and year as the covariate, and if the stations were determined not to be statistically different, the data were pooled across stations
3. Substance export by river was computed from the concentrations and Q.
4. Regressions of the form $\log_e(M) = \log_e(a) + b*\log_e(Q)$ were developed for each river-year-substance combination.

5. If a regression was highly significant (P#=0.01), it was not changed and used to estimate substance export.
6. If n<5, the regression result was insignificant (P>0.01), or the regression result poor (r^2 <0.75), a common slope b from all other years was used to estimate the coefficient a.
7. For those years with no data, an overall regression using all the data was used, with (year-1971) included as an additional independent variable in a stepwise regression, varying from linear up to a quadratic term, depending on the river and substance.
8. In some cases, the application of the (year-1971) terms produced negative results for total phosphorus, in which case those regression terms were ignored. This was true for one instance of the Napanee River in September, 1991, and for three instances of Wilton Creek (September, 1983, August, 1985, and August, 1987).

Note that from 1972 to 1980, total nitrogen was taken to be the sum of total Kjeldahl N (TKN), filtered nitrite-N (NO_2), and filtered nitrate-N (NO_3). From 1981 to 1994, the latter two substances were represented by total filtered nitrates. All regression results were corrected for bias as per Sprugel (1983).

Finally, daily substance exports were summed to obtain monthly values, and the contribution of the miscellaneous drainage areas was accounted for by using WCE as described above.

ATMOSPHERIC LOADING

Bulk precipitation chemistry data for total P, chloride, NO_3+NO_2, and TKN was obtained from Environment Canada's Envirodat database. This data consisted of measurements from samples collected with several different types of samplers at Trenton and Kingston during the period 1969 to 1994 (Shiomi and Kuntz, 1973; Kuntz, 1980). Additional data for total P, TKN, and NO3 was obtained from Environment Canada (ECB/EHD, C. Chan and K. Kuntz, pers. comm.) for nearby Point Petrie for the years 1994 to 1999. There was no overlap in time between the two sets of data. All data were combined, zeroes were rejected, and the remaining data subjected to log- transformation. Values outside plus or minus two standard deviations of a parameter's grand geometric mean were rejected as outliers.

Monthly geometric means (where possible) were generated from the remaining data with n=1 to 8, averaged by month strictly according to sample date. Those data was then used to generate regressions of log concentration (mg L^{-1}) on total precipitation (m·month^{-1}) and year (as YYYY):

$\log_e([Cl])=97.8976-10.1043*Precip-0.0491*Year$; n=158, r=0.5125

$\log_e([TotalN])=55.401-4.6829*Precip-0.0275*Year$; n=175, r=0.6295

$\log_e([TotalP])=118.7419-6.6645*Precip-0.0618*Year$; n=301, r=0.5309

These equations were used to estimate precipitation concentrations, and loads were then computed as the product of precipitation and concentration. Entry into the budget of material deposited as snow (January to March) was deferred until April as described above for the water budget.

Note that for Point Petre, NO_3 was treated as though it were NO_3+NO_2. Also, ANOVA showed that within the Trenton-Kingston dataset, sampler types could give significantly different results, but Trenton and Kingston did not differ. A comparison of Trenton-Kingston dataset with the Point Petrie dataset was not possible, because there was no overlap.

A much more elaborate protocol was initially used to generate monthly means, involving much gap-filling and multiple relationships between parameters. The results were only slightly different (higher) than those obtained with the three equations above and variability was much higher.

POINT SOURCE INPUTS

The information required consisted of flows and final effluent concentrations of total P, total N, and chloride from the Belleville, Trenton, CFB Trenton, Deseronto, Napanee, and Picton sewage treatment plants (STPs), along with the same information for various industrial inputs to the Bay of Quinte. In practice, much of this information proved to be very difficult to obtain. The final dataset represented a patchwork of data from different sources, as well as estimates varying in quality from reasonable to subjective estimates.

The STP data were assembled from various sources and given precedence in following order:

1. Data obtained from various sources in MOE. These data included effluent total P and flows, but no useful nitrogen or chloride data. There were also many gaps in these data. This source was the only available STP data that included flows, but many of those were missing. Analysis of the available flow data indicated that there were very strong year and month effects, so gap-filling of flows was limited to: a) mean for a month of adjacent years where the gap was only one year or b) if the gap was two years, estimate the first year as the mean of the previous two plus the year following the gap and estimate the second year as mean of the year just previous to the gap and the two following the gap. Any other missing flows were left as is, meaning any corresponding effluent concentration values could not be used. Thus were eliminated, for example, Napanee (1972 to 1986), Picton (1972 to 1986), CFB Trenton (1972 to 1985 and 1996 to 2001). Where flows and total P concentration were both available, P loading rates were computed as the product of the flows and concentrations.
2. Total P, total N, or chloride loading rate data used by Minns et al. (1986b) for 1972 to 1981.
3. Annual mean P loading rates by STP extracted from Project Quinte annual reports (Project Quinte 2003).
4. Where there were MOE flows, chloride loads were estimated from the flows and estimates of effluent chloride concentration derived from ambient in-bay chloride concentrations by adding 100 mg L^{-1} to ambient values to reflect chemical additions during sewage treatment.
5. Estimates of total N and chloride loading rates were also derived as the average by STP and month of the monthly values used by Minns et al. (1986b) for 1972 to 1981.

The frequency distribution of monthly loadings estimates by data source and STP was (where "source number" corresponds to the items in the list above) is noted in Table A4. Where it was possible to compare the Minns et al. (1986b) total P loading data with data obtained from MOE, there were only minor discrepancies.

As noted above, there was no total nitrogen or chloride data available in the MOE STP data, and no suitable surrogates were found, so all total N and chloride loads either represent the Minns et al. (1986b) data or represent estimates as described above. Chloride loading rates estimated from ambient concentrations may have been too high, exceeding the Minns et al. (1986b) means by an average of 40% for upper bay and 350% in middle bay.

A 10% annual by-pass adjustment was made in all years, done as described in Minns et al. (1986b; 2.5 % in March and April, 1.7% in each of November through January), though in the data assembled for this exercise, there was no direct evidence of by-passes occurring.

Industrial point source data were assembled from two sources, in order of precedence, where the first is by far the most important:

1. Input loading rates of total P and total N used by Minns et al. (1986b) for Domtar Packaging and Metcalfe Foods, 1972 to 1981. Both were assumed to discharge to the upper bay.
2. A sparse dataset consisting of flows plus total P concentration obtained from various MOE sources for Domtar Packaging and Metcalfe Foods, 1972 to 1982. Data for other sources were included, but these were treated as though their effluents were included in one of the river or STP inputs.

No chloride data were available for any of the industrial inputs at any time, so all industrial chloride loading rates were assumed to be zero. After 1982, all significant industries were assumed to have closed or to have their effluents included in either one of the river inputs or one of the STP inputs. The point source load to a section of a substance was then just the sum of the STP loads and industrial loads for that section.

BAY SUBSTANCE CONCENTRATIONS

All water column substance concentrations were generated as time-weighted monthly means of depth-weighted means of Project Quinte cruise data provided by Project Quinte. Samples were collected typically from May through October at stations "B"',"HB", and "C", representing the upper, middle, and lower Bays respectively, with weekly frequency from 1972 to1982, and bi-weekly thereafter through 2001. At all stations, each sampling effort consisted of an integrated sample taken from the surface to twice the Secchi depth, and a bottom sample taken one metre off bottom. At the middle and lower Bay stations an additional mid-depth sample was taken mid-way between the lower extent of the integrated sample and the bottom sample. For the purpose of defining a profile for depth-weighting, the integrated sample was treated as two samples, one at the surface, and the other at twice the Secchi depth. A more detailed description of sampling methods is provided in Project Quinte (1999).

Concentrations were determined for a number of substances, including total P, NO_2 plus NO_3, TKN, sodium (filtered reactive), and chloride. Total N was taken to be the sum of NO_2 plus NO_3 and TKN. Chloride concentrations were largely missing, but could be estimated from sodium concentrations (both concentrations as mg $L^{-1)}$:

$$[Cl]=2.280*[Na] -3.141; n=2137, r=0.981$$

For purposes of doing time-weighted monthly means the whole data series (1972 to 2001) for each station was treated as a time-series, i.e., values for winter months were derived by interpolation between the end of one season and the start of the next. For 1972, winter month values were obtained by interpolation between the start and end of that year's values, i.e. "wrap-around" was used (Minns et al., 1986b). A similar treatment was used for 2001.

To examine the effect of interpolating between the end of one year and the beginning of the next, comparisons were made between the interpolated Project Quinte values for station "B" and values observed at the Belleville water intake, 1985 to 2001 (K.H. Nicholls, Ont. Ministry of the Environment, Toronto, pers. comm.). The intake concentrations of total P (Figure A1) were on average lower in winter than the Project Quinte estimates based on interpolated cruise data , and slightly higher during summer months. Total N and chloride generally were higher during the winter months and the same during summer months. A set of correction factors was developed from these results by setting all ratios for the May to October period to one. Application of these factors to all values in all sections produced what appeared to be distorted corrected flows, so at first they were applied to the upper bay only, and in the end were not employed at all. The discrepancy between interpolated in-Bay concentrations and Belleville intake concentrations remains unexplained though it might be due to the different locations of sampling points in relation to bay water movements and the inflow of the Moira River, or, simply that interpolation between the end of October and early May does not generate a realistic winter value. This should be investigated further if there is a need for more precise chemical budgets year-round.

LAKE ONTARIO SUBSTANCE CONCENTRATIONS

Monthly mean concentrations for total P, total N, and chloride were also required for the Lake Ontario outlet basin. To get these values, a similar approach to calculation of in-bay concentrations was taken, i.e., develop a time-series of depth-integrated values, then generate monthly time-weighted means. The time-series employed was a composite of several datasets:

1. DFO's Long-term Bio-monitoring (Bioindex) Program (Johannsson et al. 1998) provided estimates total P, total N, and chloride for Station 81 in 30 to 35 metres of water near the upper gap, the entrance to the lower bay from Lake Ontario. These data were collected from 1981 to 1995 typically from April through October at weekly intervals. The data employed here were based on integrated epilimnetic samples collected from the surface to one metre above the thermocline, or to 20 metres, when the water column was unstratified.
2. Other data collected at the same location as part of EC's Great Lakes surveillance program and retained at EC's National Water Research Institute in a database known by the acronym STAR. These data represent samples collected at a number of depths at monthly or longer intervals, covering the period 1974 to 2001. Depth-weighted means to the lowest depth (usually near the bottom) were generated from these data for inclusion in the parameter time-series.
3. A weekly January to December time-series of data collected at the Kingston water intake during the period 1976 to 2000 (K.H. Nicholls, Ont. Ministry of the Environment, Toronto, pers. comm.) helped with some of the gap-filling that was necessary. This was employed in some cases as is (source 3a) and in others with the Kingston value decreased by 10 percent (source 3b).
4. Estimates based on data from other years. All values for 2001 were assigned the corresponding values from 2000. Total N values for 1972 to 1977 were assigned the corresponding 1978 values.
5. Estimates done as per Minns et al. (1986b), where total P was estimated as the lower bay concentration ($mg \cdot L^{-1}$) minus 0.003 and chloride ($mg \cdot L^{-1}$) was estimated as:

$$[Cl] = 25.24 + 0.5952*(Year-1964) - 0.03254*(Year-1964)^2$$

Dates with missing chloride values generally also were missing sodium, so chloride for those dates couldn't be estimated. Two relationships were used to estimate total N from NO_3+NO_2 when TKN missing (depending on dataset):

Bioindex: $[Total\ N] = 0.822*[NO_3+NO_2] + 0.269$; n=399, r = 0.728

STAR: $[Total\ N] = 0.747*[NO_3+NO_2] + 0.284$; n=57, r = 0.865

The Bioindex and STAR series were intermingled in 1981-1995 period, averaging 28 instances of concurrent values. The two chloride series were nearly identical, but where the data from the two datasets were concurrent:

- Total N tended to be less for Bioindex than for STAR, especially during the summer months, the ratio varying from 0.6 to1.6 and averaging .98.
- Total P tended to be greater for Bioindex than STAR, again especially during the summer months, the ratio varying from 0.9 to1.3 and averaging 1.05.

The resulting time series was very well represented in the middle years, but weak or missing early and late in the study period. Monthly time-weighted means for the Kingston intake series were computed and compared with the same means from Bioindex-STAR series where overlap occurred, yielding these results:

- Paired t-tests showed that during the core1981 to 1995 period, chloride was not significantly different both annually and in summer, while total P was weakly ($P<0.038$) significantly different annually but not in summer.
- During the same core period, Kingston intake nitrogen was highly significantly different ($P<0.001$) both annually and in summer, being higher by 10 and 16 percent respectively.
- A visual examination of plots of the two series suggested that the intake series departed from the STAR series prior to 1978, the chloride and total P values appearing to be much higher.

The final monthly means set was thus derived in a manner that depended on parameter and year (Table A4).

MASS-BALANCE METHODOLOGY

The methods used to compute mass balances were essentially the same as those used by Minns et al. (1986b), except that water column concentrations consisted of data from only one station in each bay section, whereas the original work employed multiple stations serving different purposes. An initial set of calculations was done assuming no exchange flows from Lake Ontario into the lower and middle bays. Substance budget elements were defined for each bay section (i; i=1 to 3) and month (j; j=1 to 12) as follows:

Given these morphometric and hydrological inputs:

A_i section surface area, (m^2)
V_{ij} mean section volume, (m^3)
$\bar{Z}_{ij}$ section mean depth = V_{ij} / A_i, (m)
Q_{ij} section net outflow, (m^3)

and these substance inputs and concentrations:

L_{ij} external load = river load + atmospheric load + point source load, (kg)
$[C_{ij}]$ mean substance concentration, (mg L^{-1})

These budget quantities related to the water column were computed:

S_{ij} section store = $[C_{ij}] \cdot V_{ij}$, (kg)
ΔS_{ij} delta store = $S_{ij} - S_{ij-1}$, (kg)
E_{ij} section mass output = $[C_{ij}] \cdot Q_{ij}$, (kg)

I_{ij}	section mass input = $L_{ij} + E_{i-1j}$, (kg)
R_{ij}	section mass retention = $I_{ij} - E_{ij} - \Delta S_{ij}$, (kg)

Several quantities related to mass transfer of P and N to and from the sediments were also computed:

v	fixed sinking rate = 0.115, ($m \cdot day^{-1}$)
t_j	month length, (days)
X_{ij}	mass sedimented = $\left(S_{ij} v / \dddot{Z}_{ij}\right) \cdot t_j$, (kg)
F_{ij}	sediment reflux = $X_{ij} - R_{ij}$, (kg)

These quantities and relations defined all budget calculations. The constant quantity v is the same value used by Minns et al. (1986b) for the same purpose and is based on field measurements in in-situ experimental enclosures in the Bay of Quinte (Charlton 1975). It should be noted that, by way of the sediment reflux calculation, the monthly total P and total N budgets for each section were always forced to balance, because sediment reflux was not measured directly, unlike other components of the mass balance.

CHLORIDE-BASED BACKFLOW CALCULATIONS

Exchange of water masses between Lake Ontario and the lowermost two sections of the Bay of Quinte is well documented (Freeman and Prinsenberg (1986). The calculations described above therefore were really only valid for the upper bay. A method was needed to correct the budgets for the middle and lower bays for the displacement of bay water by incursions of Lake Ontario water. This was done using the same technique described by Minns et al. (1986b). It essentially consisted of forcing the chloride budgets of the two bay sections to balance with zero retention and depended on there being substantially higher chloride concentrations in Lake Ontario than in the Bay of Quinte. This difference is illustrated by comparing means ($mg \cdot L^{-1}$) and ranges (n=360) of monthly mean chloride concentrations for the upper bay (mean = 8.8, min. = 2.3, max. = 16.5) and for Lake Ontario (mean = 24.0, min. = 18.4, max. = 30.3).

The calculation of exchange flow corrections started by estimating two quantities for each month (dropping the month subscript for convenience):

$$Q_A = \left(Q_2[Cl]_2 + \Delta S_2 - E_2\right) / \left([Cl]_3 - [Cl]_2\right)$$

$$Q_B = \left(Q_3[Cl]_3 + \Delta S_3 - E_3 + Q_A\left([Cl]_3 - [Cl]_2\right)\right) / \left([Cl]_O - [Cl]_3\right)$$

where the quantities on the right are defined as described above for the mass balance equations (except that concentrations are explicitly defined as chloride concentrations), the subscripts 2 and 3 refer to the middle and lower bays, respectively, and the quantity $[Cl]_O$ is the chloride concentration in the outlet basin of Lake Ontario. Note that the sign of the storage change term is positive here, whereas it was incorrectly given a negative sign in Minns et al. (1986b).

The quantities Q_A and Q_B represent the middle/lower and lower/Lake Ontario exchange backflows, respectively. If the expressions above yielded negative values, they were set to zero. The effects of these estimated flows were applied to the total P and N budgets in a manner which may be pictured as follows:

1. The flow Q_A brings water into the middle bay having the concentration of the substance (total P or N) in the lower bay. An equal volume of water is displaced from the middle bay having the concentration of the substance in that bay section.

2. That in turn displaces an equal volume of material from the lower bay at the lower bay concentration.
3. Finally flow Q_B brings water into the lower bay having the concentration of the substance in Lake Ontario. An equal volume of water is displaced from the lower bay having the concentration of the substance in that bay section.

Note that because only one water quality station per bay section was used, the same station's in-situ chloride concentration was used to estimate all mass components for a section, whereas in Minns et al. (1986b) different stations were used to estimate storage change and section concentrations.

Finally, where whole bay corrected loads are reported, they represent the sum of all external loads from rivers, point sources, and the atmosphere plus a load computed as the product of Q_B and the Lake Ontario concentration of the substance in question.

DOCUMENTATION

All the raw data, analysis procedures and budget calculations assembled for this study have been assembled in a Microsoft ® Access database which can be obtained upon request from:

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RESULTS

WATER BUDGET

The whole bay water budgets were calculated first without correction for exchanges with Lake Ontario (Figure 1). Compared to Minns et al. (1986b)(PQ86 hereafter) there are a few trends worth noting (Table 1). If the time series is divided into two equal periods, 1972 to 1986 (early) versus 1987 to 2001 (late), we can note that peaks in runoff were lower during the late period, outflow was lower and volume was lower. The first two reflect changes in precipitation and discharge while the later reflects the long-term downward trend in the managed level of Lake Ontario. As a consequence, upper bay flushing rates were lower, especially in summer (mean early period = 2.91, versus 2.53 for the late period). Given that the highest value occurred in 2000 at 5.40, the decline was greater than implied by the means. Indeed, in the early period there was only one instance of a summer upper bay flushing rate < 2 while in the late period there were five. Linear regressions of mean annual flow versus year for the five main tributaries all had negative slopes but none was significant (P>0.05).

Compared to PQ86, the corrected flushing rates are lower in the middle bay whilst higher for the lower bay section and the whole bay, in spite of lower flushing in the upper bay. This result occurs because of methodological differences between the two studies. In PQ86, calculations were based on a two layer model with backflows entering the deep layer and exiting with outflow via the surface layer. Decreases in the quantity of data available to define in situ conditions, particularly at the boundaries of the bay sections, made it necessary to simplify the calculations using a single layer. In PQ86, middle bay backflows were much larger than those in the lower bay. In hindsight, this is difficult to rationalize as the water movements to and from Lake Ontario are continuous from the lake through the lower and middle bay sections. In these new calculations, the middle and lower bay backflows are more similar. Without an expensive current meter study similar to that reported by Freeman and Prinsenberg (1986) there is no objective way to estimate the backflows.

RIVER INPUTS

Tributary loadings continued to co-vary with runoff (Figure 2). The general pattern of positive relationships between loadings and flushing rate was maintained for P, N, and Cl compared to PQ86. P loadings tended toward lower levels over the time period while N loadings were relatively level and Cl loadings increased somewhat. Declines in loadings are consistent in part with lower runoff rates. Annual mean runoff concentrations (total load /total flow) show some trends (Figure 3). For P, Wilton Creek showed the biggest downward trend, along with the Moira and Napanee rivers, but only the Wilton Creek concentration decline was significant (Table 2). This suggests that progressive efforts to improve land use practices with respect to P export have made some progress in the smaller sedimentary drainages close to the bay where most of the agricultural activity is concentrated. The lack of any appreciable trend in the Trent River [P] indicates, as it dominates inflows to the bay, that upland water quality improvements, while beneficial locally, cannot be expected to have major impact on in-bay conditions. None of the N trends was significant with three negative and two positive slopes. All the chloride concentrations trended upwards and three of five were significant at P=0.05, while all were significant at P=0.10 (Table 2).

ATMOSPHERIC LOADING

Bulk precipitation loading measurements were available for the entire period of study. Based on the 1972-2001 time series there was little seasonal variation in atmospheric loading although the range of loadings varied considerably (Figure 4). Mean daily loading rates of 426.4, 936.4, and 7.4 kg day^{-1} for Cl, N, and P, respectively, were insignificant compared to inputs from tributaries and point sources. While precipitation rates exhibited no long term trend (Figure 1) the significant decline in concentrations of all three substances meant that atmospheric loadings declined over the 30 year period.

POINT SOURCE INPUTS

The downward trend in point source P loading that was already evident in the early 1980s (PQ86) has continued to the present day (Figure 5). The initial phase of decreases arose mostly from renewal of STP facilities and the implementation of P removal in the sewage treatment process. During the 1980s, the decreases continued as plant performances were enhanced as a result of the program of audits under the Remedial Action Plan for the Bay. The original objectives in the Bay of Quinte STPs were to achieve 1 mg L^{-1} year-round, as set out in the Great Lakes Water Quality Agreement, and 0.5 mg L^{-1}during the summer. In recent years, STP performances have been consistently approaching 0.1 mg L^{-1} year-round.

Estimates of nitrogen loading are approximations from the early 1980s onwards as there were few regular measurements of all the components that make up total N in final effluents. Chloride loadings rose in the mid-1980s but their contribution to total loading continued to be negligible compared to tributary inputs both annually and seasonally.

UNCORRECTED WHOLE-BAY BUDGETS

Uncorrected whole-bay budgets lack any adjustment for exchange flows with Lake Ontario. The results presented here (Table 3) parallel the values obtained earlier for the overlap period 1972-1981 (PQ86). The chloride budgets show negative retention while those for P and N indicate moderate to high retention. Total and summer loadings of P and N have decreased over the 30 year period. Comparing 1972-1986 to 1987-2001, annual loadings have declined from 3.5 to 2.5 kg km^{-2} day^{-1} for P and 67.6 to 59.5 kg km^{-2} day^{-1} for N while summer loadings declined from 2.1 to 1.4 kg km^{-2} day^{-1} for P and from 40.0 to 33.9 kg km^{-2} day^{-1} for N. Most of this decline is attributable to declines in tributary flows. Chloride loadings increased annually from 591.7 to 694.1 kg km^{-2} day^{-1} and from 340.6 to 372.8 kg km^{-2} day^{-1} during summer. Increases in tributary concentrations of chloride have offset decreases in flow.

The negative retention values have moved closer to zero from -143.5 to -86.0 % (annual) and from -349.2 to -185.5 % (summer), consistent with tributary flow and concentration changes. Nitrogen retention values are unchanged. P retention rose on average from 48.1 to 64.2 % for the annual period but declined from 29.6 to 19.0 % during summer. That result is consistent with internal loading (which arose from excess external loading in earlier decades) being dissipated in the recent period of low external loading, especially from point sources in the summer.

In the previous analysis (PQ86) there tended to be an inverse relationship between percentage point-source loading and flushing rate both in the summer and on an annual basis. That relationship has shifted in the post-P control era (Figure 6) as point-source loadings have declined to very low levels and there is a greater frequency of lower flushing rates in recent years. For each time period (72-77, 78-86, and 87-01) there is an inverse relationship with the slope becoming less as the level of point source loading declines across time periods.

CORRECTED BAY BUDGETS

The corrected whole-bay budgets have some significant differences, compared to the earlier work (PQ86). The middle-lower (Q_A) exchange flows are lower and the lower-Lake Ontario (Q_B) exchange flows are much higher (Table 4). The changed back flows coupled with the difficulties encountered with less spatial coverage of in-bay and in-lake nutrient concentrations, leads to a situation mainly in summer whereby percent retention of P and N is often negative. These results highlight the difficulties associated with chemical budgeting in open systems. There is no way to estimate the exchange flows independently of the chloride mass balance method. Further, any concentration differences among middle and lower bay sections and Lake Ontario (generally [middle] > [lower] > [L. Ontario]) will worsen input-output imbalances. Surface to bottom concentration gradients, which are not considered here, will also affect mass balance calculations, especially in the lower bay. These issues are of greater concern in the summer analyses, because, in the winter, when the bulk of the net outflow occurs, the back-flows are lower and less influential.

Some trends in whole-bay budgets can be discerned when comparing the two halves of the time series (Table 4). Both corrected annual and summer P loads have decreased. There has also been a shift to more positive retention of P in line with expectations for reduced loadings (annual, +26.3 vs. +39.6 %; summer, -14.8 vs. +13.2). N loadings have increased slightly with no shift in estimated retention. Individual budget year data can be hard to interpret as longer term changes in sedimentation and reflux may confound computation especially as the bay responds to the large decreases in point-source loadings attained over the 1972-2001 period.

Responses in the middle and lower bay sections are of less concern as the greatest effects of point source P control were expected in the upper bay section which is unaffected by exchange back-flows.

SECTIONAL BUDGETS

The sectional budgets provide a more detailed analysis of the movement of P and N through the bay. The water and material flows are described in Figure 7. The year-by-year analyses show some trends (Figure 8). The bar length variations (positive bars are inputs, negative bars are outputs) in Figure 8 tend to document the temporal variations in river flow and estimated exchange back-flows. The trends in retention values are more revealing. The uncorrected upper bay chloride retention values were generally close to zero, though with an overall trend from more positive to more negative over the 30 year span. As expected, the middle and lower bay retentions were mostly negative and have trended towards zero over the time period.

The corrected P budgets showed mostly negative retention in the upper bay annually, but a trend from negative to positive retention in summer. The middle bay retentions showed little temporal trend with slightly more negative values for annual budgets compared to summer budgets. The lower bay retentions were mostly positive but showed some downward trend over the 30 year period. The shortening of the bar lengths reveal the overall decline in loadings over the time series with the most contrast between the 1972-1986 and 1987-2001 time periods.

The upper bay N budgets generally showed positive retention with some upward trend over the time series. The middle bay budgets have shifted gradually from slightly negative retention to slightly positive over the 30 years. The lower bay budgets tended to be positive in the first few years, but have been consistently negative since.

The computed monthly (May to September) P reflux rates show (Figure 9) both the downward trends in upper and middle bay sections as external loadings declined, and the difficulties in trying to balance nutrient budgets in the lower bay where computed reflux values are just as likely to be negative as positive. The mean summer P reflux rates further show the improving situation in the upper and middle bay sections (Table 5). It is worth noting the later peak in the middle bay values compared to those in the upper bay which were in synchrony with external loadings. This outcome would be expected as the turnover of surface sediments occurs more slowly than water turnover (Minns 1986). Enriched upper bay surface sediments are both gradually buried by cleaner sediment as external loads decrease and moved down through the bay and out into Lake Ontario.

To create a simpler overview of the P and N budgets which fluctuate from year to year, we computed mean annual and summer sectional budgets for four time stanzas (Figure 10). The time stanzas cover 1) pre-P control (1972-1977), 2) the first phase of P control (1978-1988) when point source loads were decreased by implementation of P removal at STPs, 3) the second phase of P control (1989-1994) when loads decreased much further as removal efficiencies were optimized, and 4) post-zebra mussel arrival (1995-2001) to see if their effect could be discerned.

The summer P store declined from the 1972-77 period through to the 1989-1994 period (Figure 10A). The upper bay summer P store did not change appreciably in the 1995-2001 period, though further declines occurred in the middle and lower bay section, due no doubt to the expansion of zebra and quagga mussel populations. In the upper bay mean summer [P] values were higher in the 1995-2001 period compared to 1989-1994, suggesting that the lower water levels may have partially offset increased concentrations. In all four periods, the reflux estimates exceeded those for sedimentation in the upper and middle sections. In the lower section the reflux term fluctuated between negative and positive, no doubt due to errors in the exchange back-flow estimates. The summer point source inputs to the upper bay declined more than 90 percent from 175 kg day^{-1} in 1972-78, to 16 kg day^{-1} in the 1994-2001 time period.

The annual P store changes paralleled those seen in the summer though with some decline in the upper bay between 1989-1994 and 1995-2001 (Figure 10B). In the upper bay, there was a shift from reflux exceeding sedimentation (negative retention) in the first two periods to an excess of sedimentation over reflux (positive retention). In the middle bay, reflux exceeded sedimentation in the middle two time periods. In the lower bay, the annual reflux shifted from negative in the first three time periods to positive in the zebra mussel period. Annual tributary P loads declined across the four periods.

The summer N store decreased over the four periods in the upper and middle bay sections while increasing in the lower bay (Figure 10C). In the upper bay, reflux was always less than sedimentation, indicating positive retention. In the middle bay, reflux exceeded sedimentation in the first three periods. Estimated reflux greatly exceeded estimated sedimentation for N in the latter three periods in the lower bay, N loads were little changed over the whole time span.

The annual N store decreased over the four periods in the upper and middle bay sections while increasing slightly in the lower bay (Figure 10D). The annual N retention patterns were similar to those for the summer period.

DISCUSSION

LIMITATIONS ON BUDGET ANALYSES AND INTERPRETATION

It is important to review the various sources of potential uncertainty associated with these data and analyses before exploring the patterns and implications of these results. There are three main areas: data coverage of the various elements contributing to budget analyses, the approach taken to modelling exchange back-flows from Lake Ontario, and the difficulties in the estimation of reflux rates.

Data Coverage

It is useful to contrast the data available for the previous study (Minns et al 1986b) with this analysis. Monitoring networks have undergone considerable changes over the last 20 years, particularly as government agencies have cut back on stations and sampling frequency. There were some changes in the hydrology monitoring. The reference station lowest on the Trent River was discontinued and a station further upstream had to be substituted. The stream water quality monitoring has become much more patchy in recent years with some station-year combinations missing completely. It used to be a rough guideline that 15-20 samples spread throughout the year would be sufficient to develop a flow-load rating curve for estimating daily, monthly and annual tributary loadings. Those frequencies were rarely achieved in recent years. Point source monitoring went from being good but poorly documented early on through a period when records were very patchy to the recent period when a well established record keeping system has been working.

Unfortunately, total nitrogen and chloride were not adequately monitored. Nitrogen will probably assume a greater importance in the future as concern for ammonia loadings increases and chloride is useful because it can be used as a conservative tracer. Atmospheric inputs are still monitored close by on a bulk monthly basis and this is adequate for budget analyses. In-bay water quality monitoring has been maintained year-round at Belleville and Kingston water intakes and at key bay stations by MOE’s Great Lakes Intake Monitoring Program, and at key bay stations by Project Quinte during May to October. Reduced spatial coverage after the early 1980s meant that concentration gradients through the bay could not be characterized to distinguish between in-section and section-boundary differences, making the budget balancing less precise, especially in the chloride budgets in the middle and lower bay. The lack of direct methods for estimating exchange back-flows sets limits on the budget analyses and means that some uncertainties are transferred into reflux uncertainties when budgets are forced to balance. The upper bay budgets partially offset the problems in the middle and lower bay sections. The lack of seasonal sampling in the outlet basin of Lake Ontario is a deficiency, although substitution using Kingston intake data covers the gaps to some degree. It would be useful on a short study basis to examine the non-summer in-bay concentration patterns in relation to the intake observations given the differences observed.

The core elements in data collections necessary each year to interpret in-bay responses should include:

- Gauging on main tributary flows daily
- Main tributary water quality monitoring close to their outfalls, 15 to 20 times per year.
- Weekly water intake sampling at Belleville and Kingston (P, N, Cl, Temperature). Since the Napanee water supply comes from the lower bay at Lennox G.S., it would be useful if it were also monitored weekly.
- Bi-weekly sampling of primary stations in the Bay of Quinte (B, N, C) May to October with supplementary sampling at old (pre-1983) Project Quinte stations and section boundary sites every 3 to 5 years.
- Monthly report of point source flows and loads based on multiple within-month samplings

These elements would allow the main components of budgets to be monitored on an annual basis.

Exchange back-flows

The reduced spatial coverage of concentration gradients affects the estimation of exchange back-flows. Reducing the analysis to single layers for the middle and lower bay sections probably also had some effect. Estimated flows differ between Minns et al. (1986b) and those reported here for overlap years. However, there is no independent direct method of estimating those flows apart from undertaking extensive current meter measurements (Freeman and Prinsenberg 1986), and it would be hard to justify such studies for nutrient budget purposes alone. The main eutrophication concern is in the upper bay which is unaffected by back-flows and the middle and lower bay water quality is improved by the flows.

Reflux estimation

The reflux estimates are most likely the most accurate in the upper bay and least accurate in the lower bay. Uncertainties in the back-flow calculations contribute to the uncertainty and fluctuations in the middle and lower bay estimates. Nonetheless, since the basis for estimating sedimentation has quite a solid foundation, the reflux estimates should be reasonably accurate. The estimated rates are consistent with reported measured rates (Minns et al 1986b).

TOTAL AND NET PHOSPHORUS LOADING

There is often confusion about how various sources of P loading contribute to eutrophication and about where the most effective investments in P control should be made. Johnson and Owen (1971) recognized that the simple notion of reducing total annual P loading as a means to reduce eutrophication becomes misleading when applied to highly flushed systems like the Bay of Quinte. They introduced the idea of “net loading”. Total loading is the product of two components, flow and concentration. However, when loading enters a water body, the inflow must be approximately matched by outflow, after allowance for evaporation and small changes in water level. That outflow exports phosphorus from the waterbody and that export is a product of flow and the *in situ* concentration. Johnson and Owen proposed a simple calculation to allow for the displacement of phosphorus due to inflows: Net loading = inflow times the difference between the inflow and outflow concentrations (Net = Flow *([Inflow]-[Outflow]). Therefore two equal total loads may consist of opposite pairs, high flow with low concentration (HiFlo*LoConc) and low flow with high concentration (LoFlo*HiConc). However, their net loads will be very different with HiFlo*LoConc being much less than LoFlo*HiConc. It is the net load that causes eutrophication. This opposite pair situation exists in the Bay of Quinte and is most in evidence in the upper bay. The river inputs are HiFlo*LoConc and the point source were mostly LoFlo*HiConc. The computed total summer and annual loads of P to the upper bay (Table 6) would always indicate the river loads were greater, sometimes much more so when river flows are higher. However, when the net loading values are computed, it is clear that the point sources always make a greater positive contribution while the river net loads are often negative (Table 6). Net river loads were negative when point source loads were higher because the point source inputs elevated in-bay concentrations far above the river concentrations. Hence when point source loads were high, river inputs actually helped carry away some of the excess loading. As point source loadings declined, so the in-bay concentrations declined and river net loads became positive. In the post-1994 period (after zebra mussels colonized), the summer net river loads have been comparable to net point source loads. Thus the impact of the point source loads on in-bay conditions has been greatly reduced although concentrations still tend to rise over the summer as river flows decline to their lowest point, typically in August-September. Annual net river loads are higher than net point sources reflecting much higher river flows in the October-April period compared to summer (May-October). It is the summer, not the annual net loads, that determine the trophic state of the upper Bay of Quinte.

PHOSPHORUS RETENTION

There is a more general way of examining the P retention behaviour of the bay related to the net load calculations describe above, especially the upper bay. If the total loads from all sources are summed and divided by the sum of all inflows, a composite input concentration is obtained and can be compared with the output concentration. A plot of summer mean output P concentration versus summer mean input concentration (Figure 11) shows the overall agreement between the two values. Values above the 1:1 line indicate an excess of export over import, negative retention, and vice versa. Most of the negative retention episodes, came from the 1972-1988 period when point source loadings were still high (Figure 12). The values were quite variable in the 1989-1994 period as point source loadings continued to decline and then became stable in the last period after dreissenids arrived. The variability may be due in part to the disequilibrium in the surface sediment layer as its pool of P changed in response to decreased external loading. Variation in summer runoff may also have been a factor.

PHOSPHORUS, ZEBRA MUSSELS AND MACROPHYTES

In the previous analysis of the Bay of Quinte nutrient budgets, Minns et al. (1986b) explored the potential catastrophic link between eutrophication due to excess point source P loading and the macrophyte cover in the upper bay. Prior to severe eutrophication there were dense macrophyte beds throughout the upper bay. As P loading increased through the 1950s and into the 1960s the macrophytes declined dramatically. In the early 1970s, macrophyte cover was very sparse. The catastrophe model proposed that there was a hysteresis effect between nutrient levels and macrophyte success; macrophytes would withstand intermediate eutrophication but succumb to excessive nutrient levels. Restoring macrophytes would require that P levels decline to very low levels so that plant regrowth and colonization could occur.

Seifried (2002) has recently documented and analyzed changes in the Bay of Quinte's macrophytes over the period 1972 to 2000. After 1977 when point source P controls were implemented macrophytes showed limited recovery through to the early 1990s despite substantial declines in P and chlorophyll levels and increases in water clarity. Only after zebra and quagga mussels arrived in 1993-4 and rapidly expanded throughout the bay in 1994-5 did macrophytes increase substantially. The large scale filtering by the mussels of tripton as well as phytoplankton reduced chlorophyll concentrations and greatly increased water clarity. Thus the hysteresis model of macrophytes is partially supported. It is now apparent that the linkage is not directly between nutrients and macrophytes but rather mediated via water clarity which may be controlled by multiple factors and not just [P].

The arrival of dreissenid mussels and the important recovery of macrophytes did not appear to have substantially altered the P budgets in the bay. The colonization of the mussels led to an accumulation of P in their biomass and may have caused a transient dip in the water column P pool but despite their biomass the amount of P stored in mussels is small compared to the water column or surface sediment. The mussels may have effectively increased sedimentation rates but have probably enhanced remobilization of P from detritus via their organic faeces which are released near the sediment-water interface. Certainly dissolved P levels have increased substantially since the mussels arrived (E.S. Millard, GLLFAS, Burlington, pers. comm.).

The macrophyte biomass expands and contracts seasonally. This biomass ties up P like the mussels but probably draws much of its P from sediments via roots. The die-back of macrophytes in the fall produces nutrient-rich detritus, some of which settles to the sediment and decomposes and some of which maybe flushed down through the bay as runoff rates increase in the fall. It is possible that macrophytes can enhance the export of P from the bay. However increased macrophyte cover also reduces wind-driven resuspension of P. Thus the overall impact of macrophytes may be neutral.

THE PHOSPHORUS SUCCESS STORY

The results of the program to control eutrophication in the Bay of Quinte via P control of point sources entering the bay can be readily seen in comparative plots of the mean annual and summer P concentrations in the river input, in the point sources and in the upper bay (Figure 13). These plots show the dramatic decline in point source [P] both after the switch from secondary to tertiary treatment and after progressive improvements in the performance of the STPs. The upper bay [P] values declined into the earlier 1990s, approaching the interim recovery target, 30 Φg L^{-1}, set out in the Bay of Quinte Remedial Action Plan (Stage II Report: "Time To Decide"). Concentrations are now (2001) close to, but generally below, the values in the river runoff. Since the arrival of zebra mussels and the accelerated recovery of macrophyte cover especially in the upper bay, in-bay concentrations have tended to be higher and closer to the river concentrations. Thus, summer in-bay values are now controlled primarily by river inputs.

CONCLUSIONS

- Point source P control in the Bay of Quinte has been highly successful
- A point source P loading limit on the order of 15-20 kg day^{-1} should ensure that the bay does not return to past levels of nutrient enrichment, though a more complete model analysis will allow a better definition of the limit.
- Colonization by dreissenid mussels from 1995 onwards and the associated upsurge in macrophytes have led to increased water [P] values perhaps owing to enhanced recycling.

RECOMMENDATIONS

- The P budget analyses should be used in conjunction with some simple input-output modelling to establish a point source P loading limit. (The results of the modelling work are reported in a companion publication by Minns and Moore (2004)).
- A core monitoring program should be specified and endorsed by the Bay of Quinte Restoration Council to allow cost-effective tracking of both loads and in-bay responses in the future, based on the data needs identified in this report ("Data coverage" section of DISCUSSION).

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Figure 1. Monthly water budget of the Bay of Quinte by component, 1972-2001, uncorrected for Lake Ontario incursions (see also Table 1)..

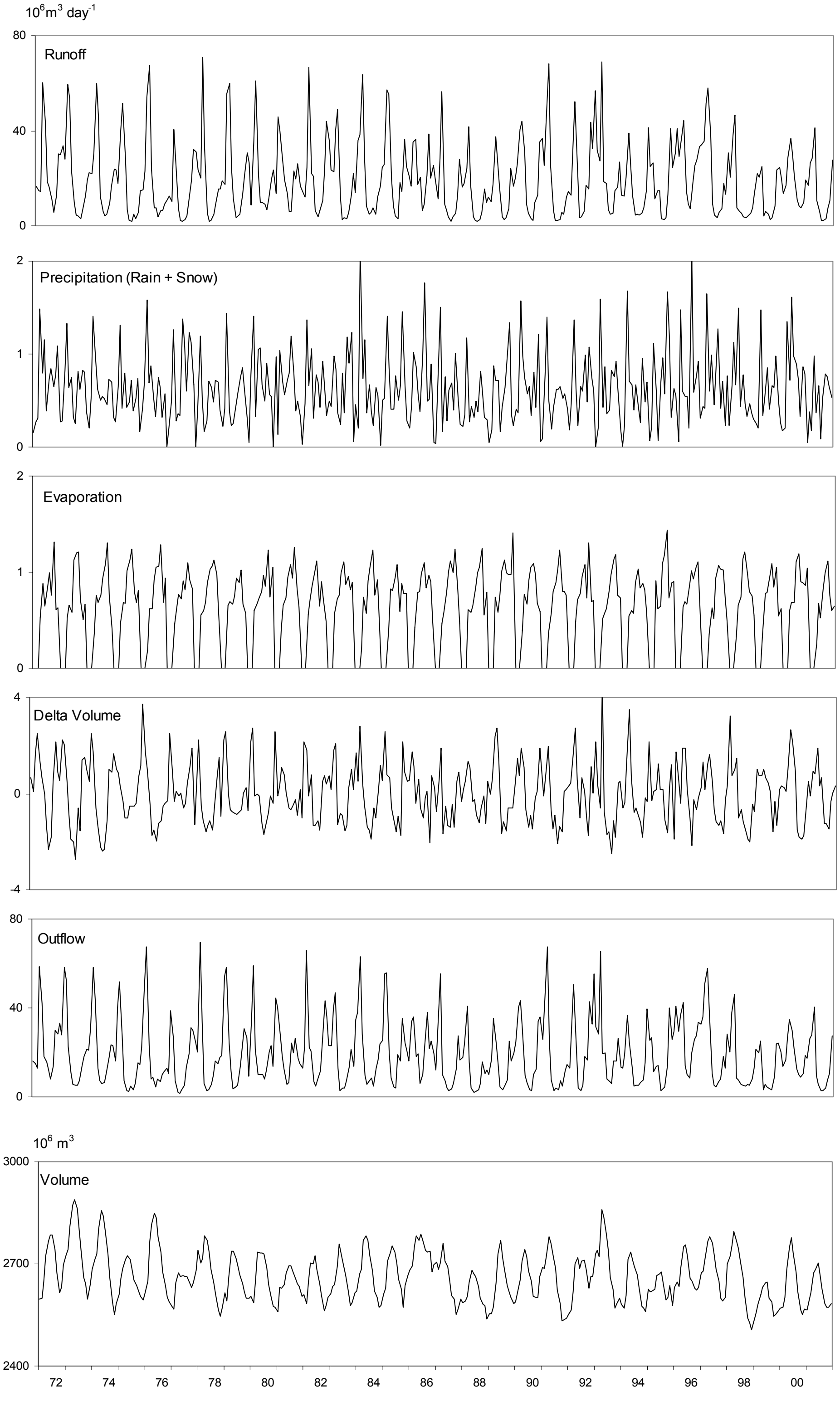


Figure 2. Trends in the annual and summer river loadings (kg day^{-1}) of P, N, and Cl with time (left panels) and uncorrected Bay flushing rates (right panels), 1972-2001.

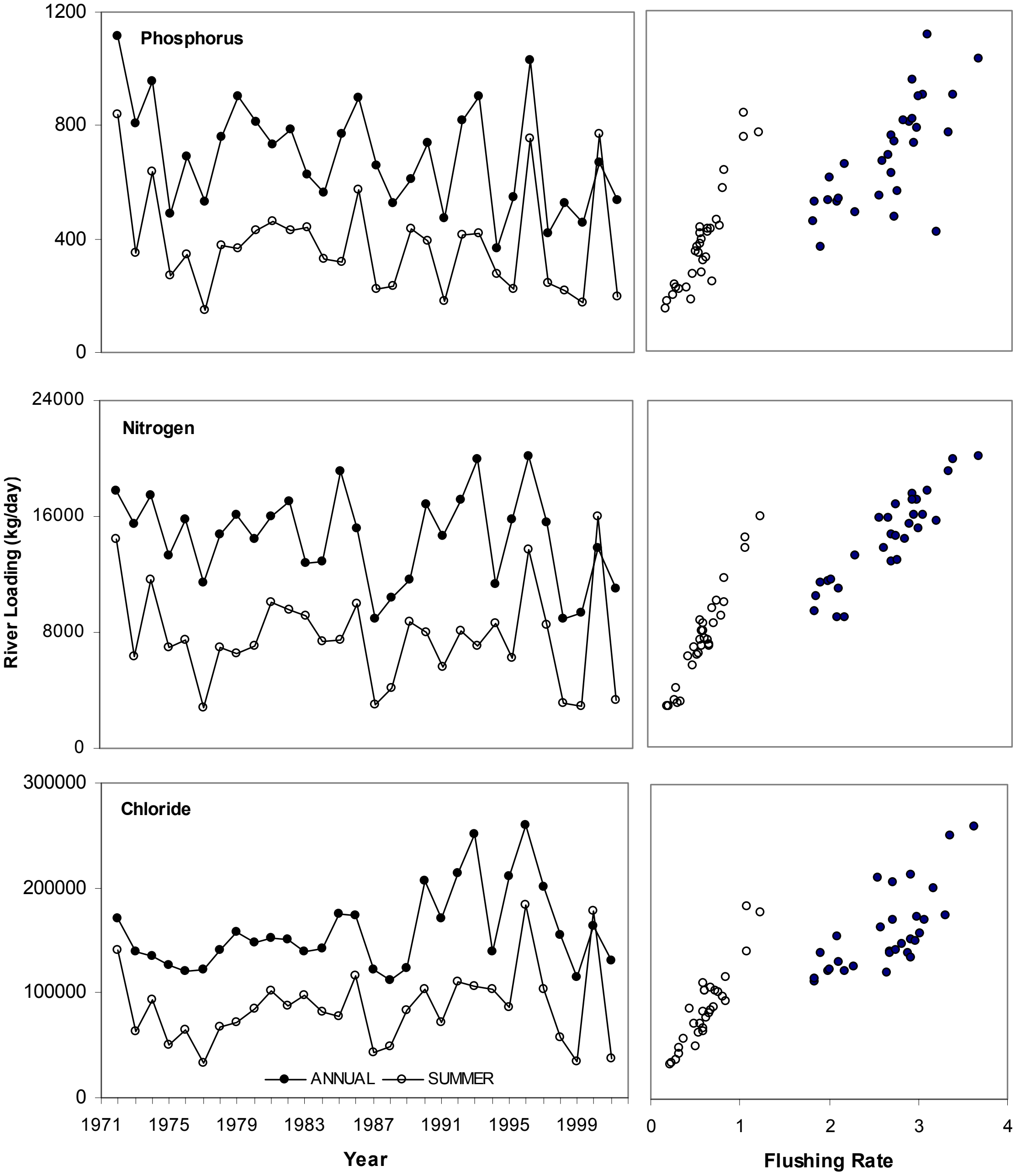


Figure 3 Trends in annual mean runoff concentrations (total load/total flow; mg L^{-1}), 1972 to 2001, in the five main tributaries to the Bay of Quinte: A) phosphorus, B) nitrogen, and C) chloride.

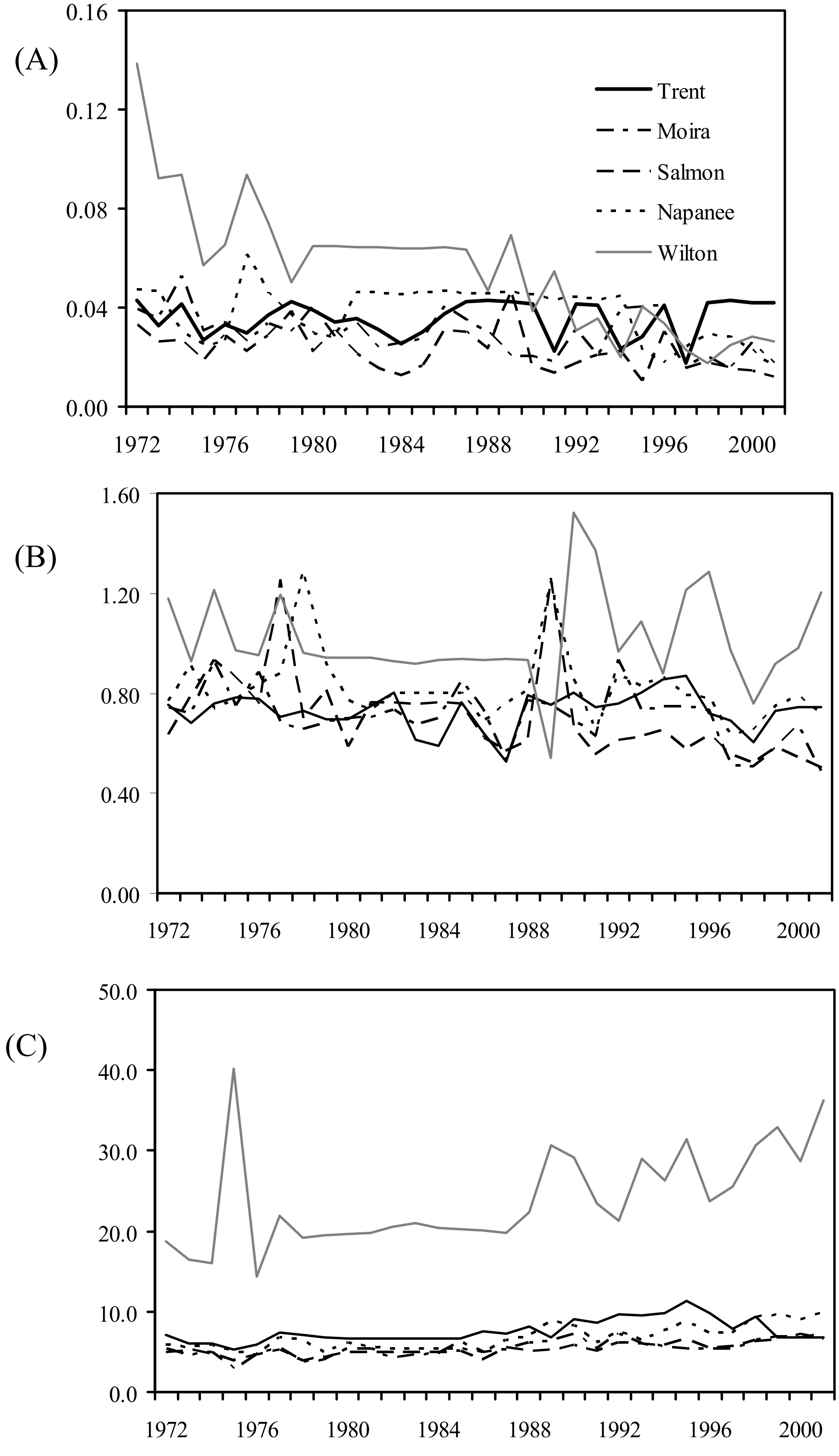


Figure 4. Seasonal trends in the atmospheric loadings (kg day^{-1}) to the Bay of Quinte of chloride, nitrogen, phosphorus, showing means (●), minima (△), and maxima (○) for the period 1972-2001.

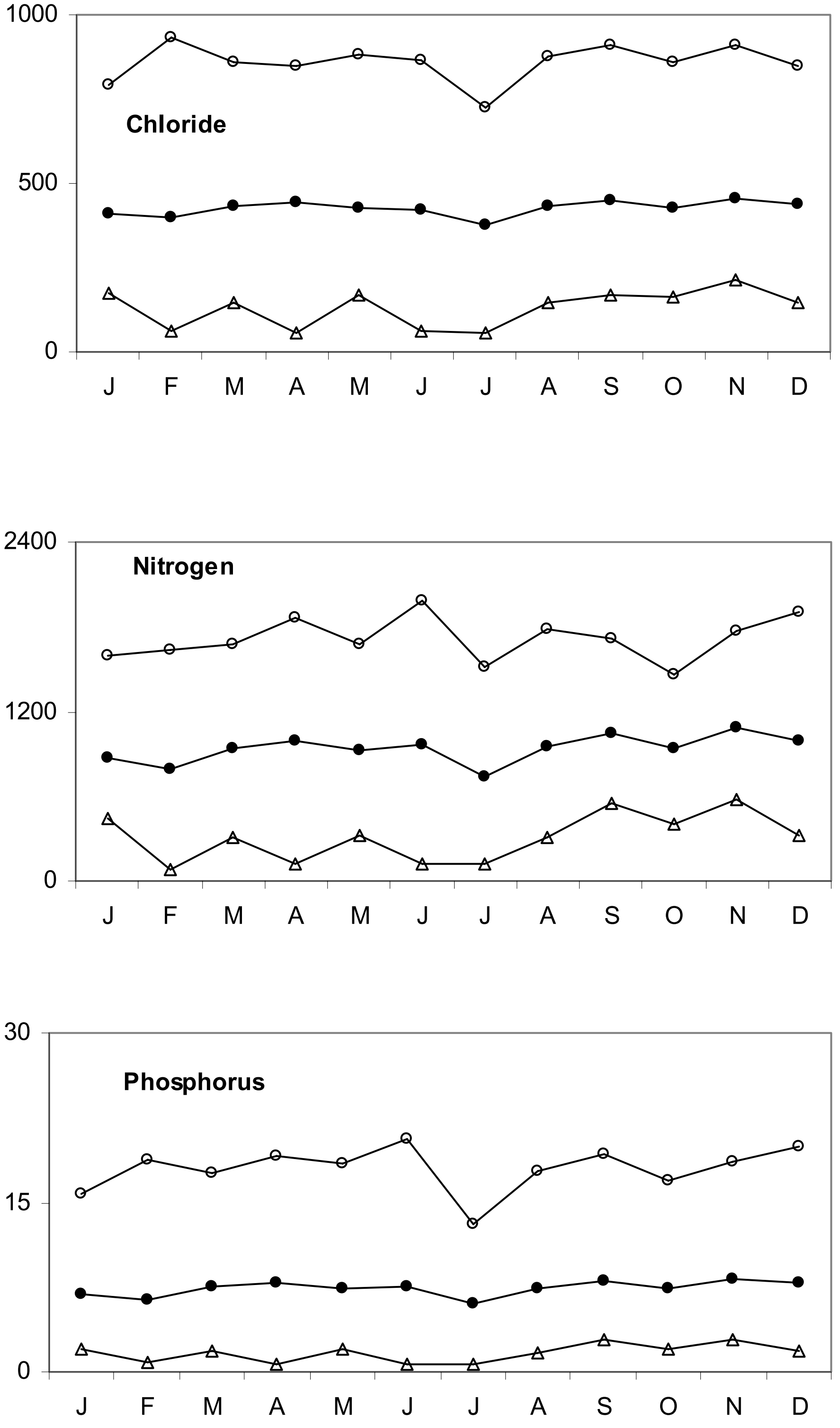


Figure 5. Annual mean point source loadings (kg day^{-1}) of phosphorus, nitrogen and chloride to the Bay of Quinte, 1972-2001.

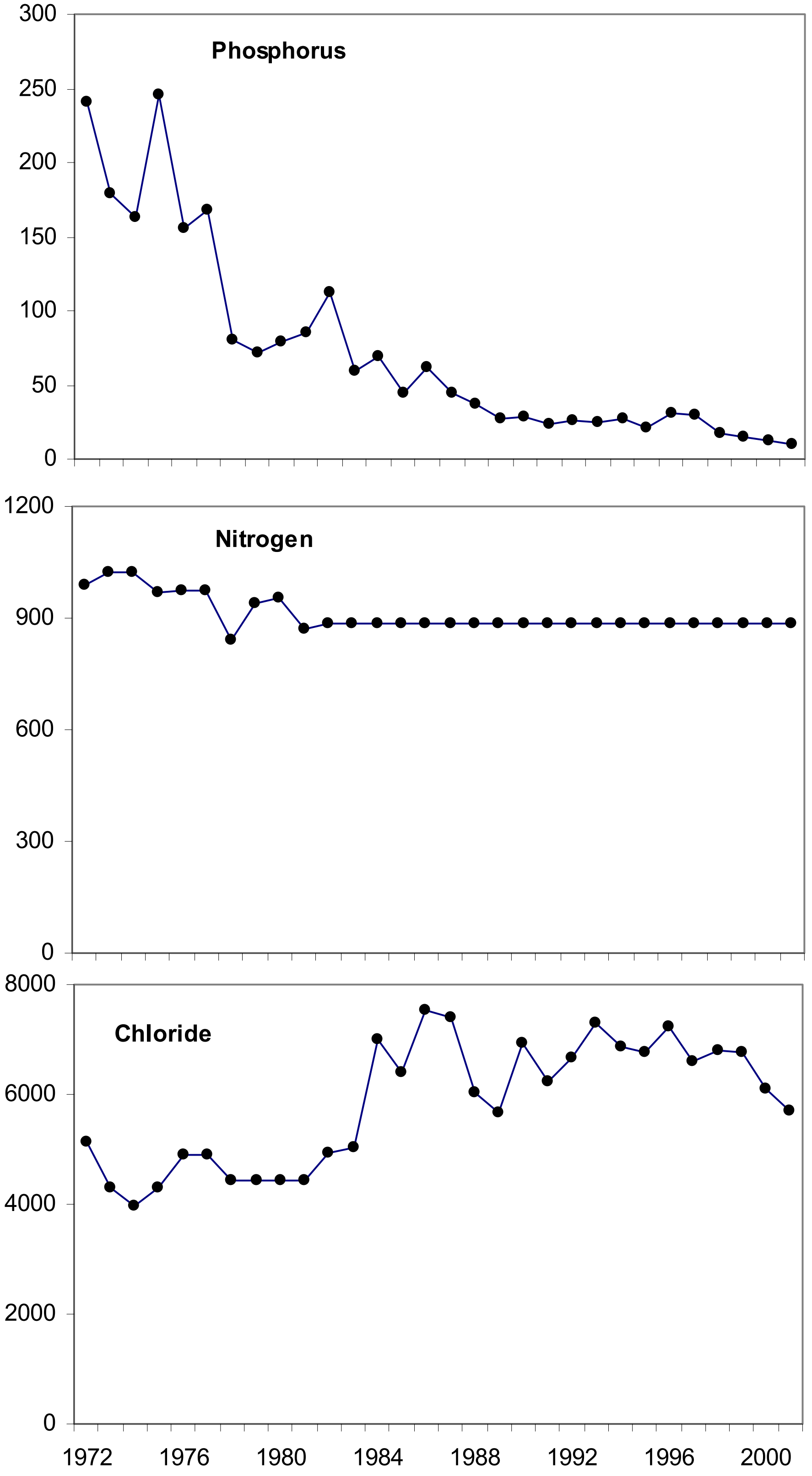


Figure 6. Relationship between point source P loading as a percentage of total external loading and the uncorrected Bay of Quinte flushing rates, annual and total.

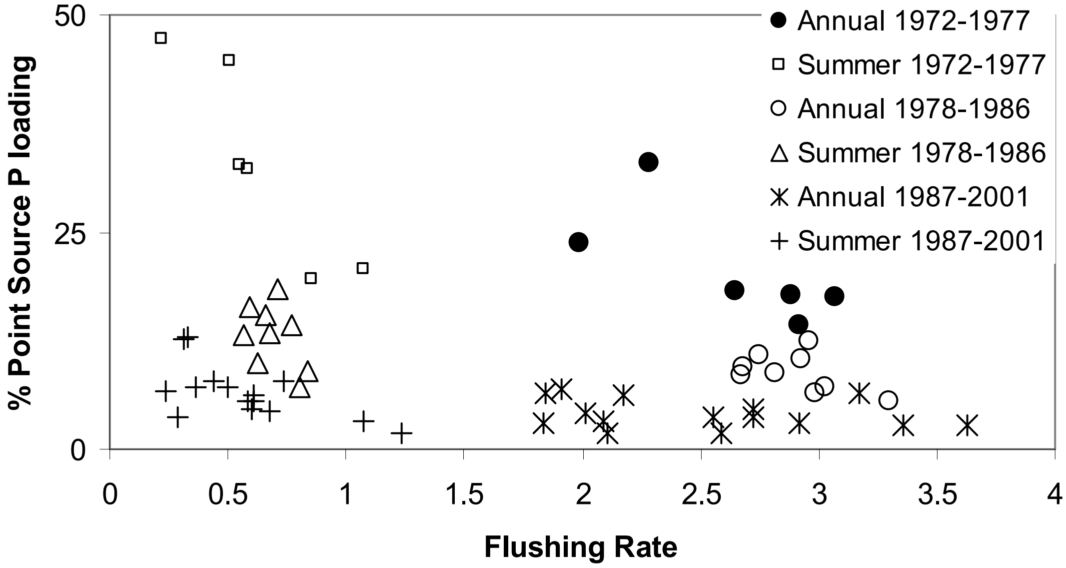


Figure 7 Conceptual model of sectional budgets for the Bay of Quinte.

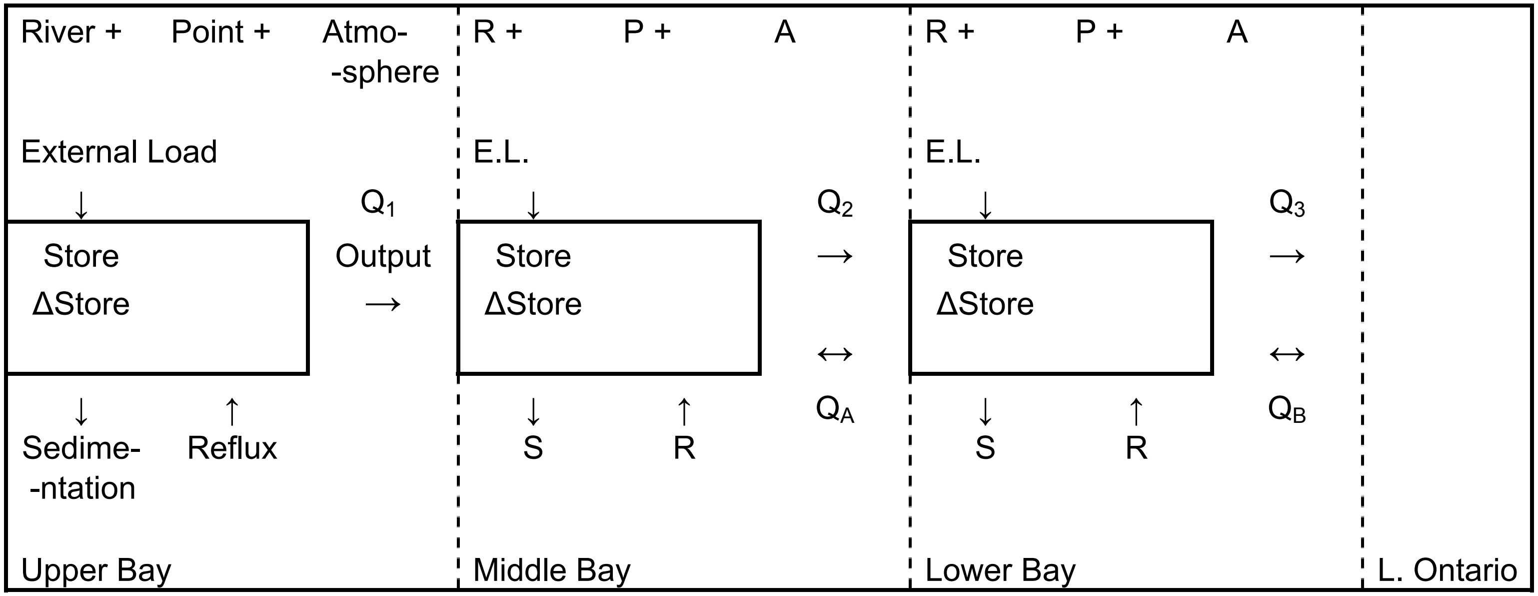


Figure 8. Sectional annual and summer inputs (positive bar), outputs (negative bar), and retention values (line-connected dots) for 1972-2001. The upper panels are annual results and the lower summer.The units are mg m^{-2} day^{-1} on the left Y axes and dimensionless for percent retention on the right Y axes. Each bar and dot represents a year from 1972 to 2001. The scales vary from graph to graph.

A) Uncorrected Chloride

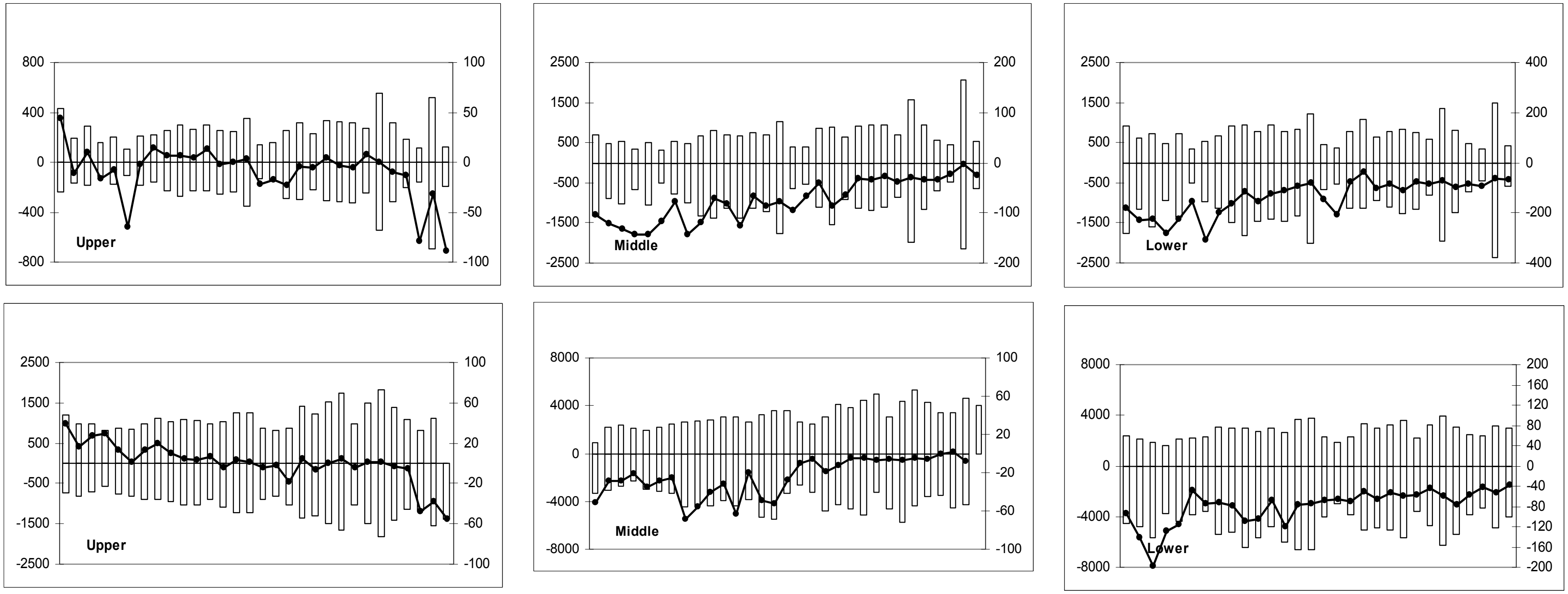


Figure 8 continued.

B) Corrected Phosphorus

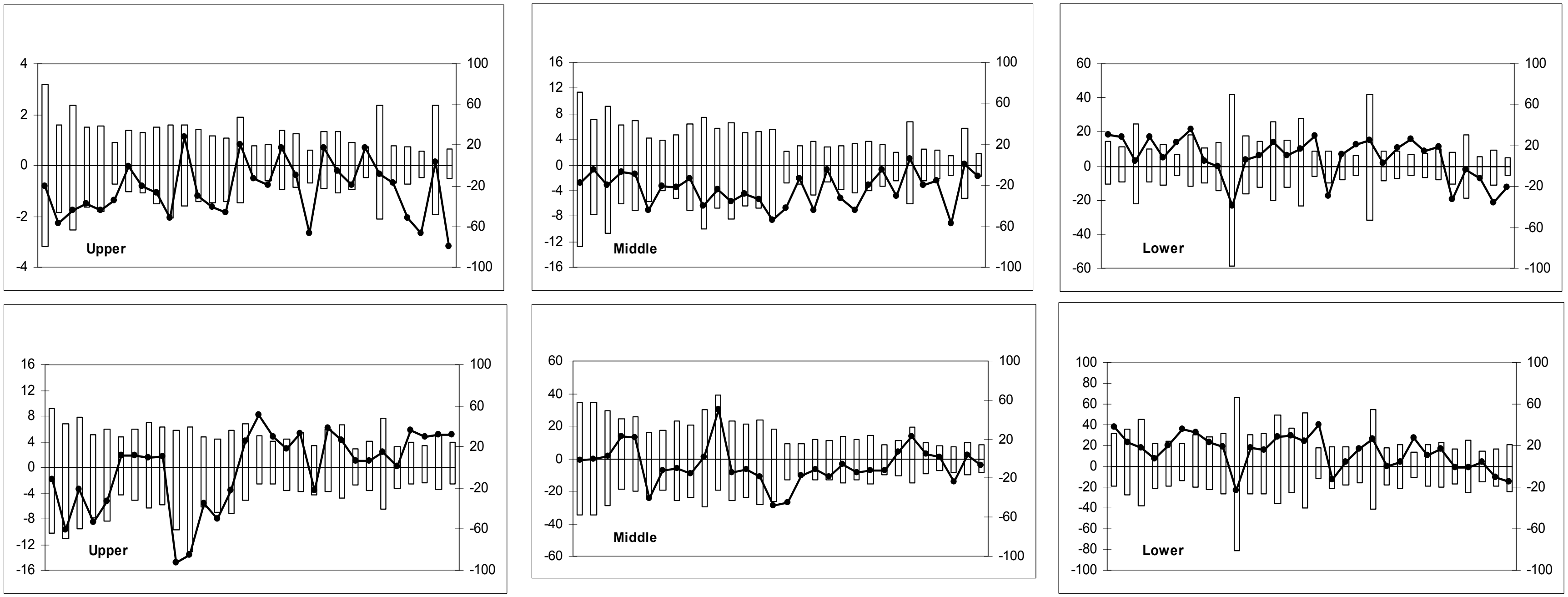


Figure 8 continued.

C) Corrected Nitrogen.

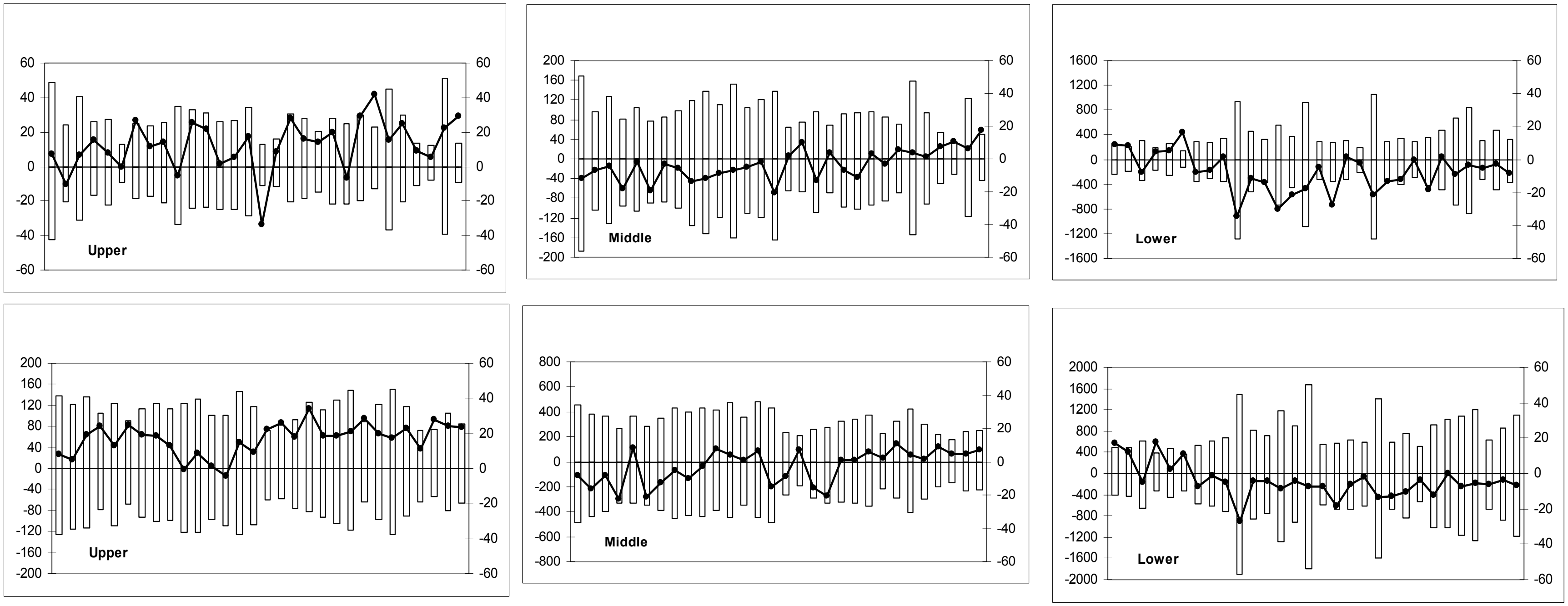


Figure 9. Calculated P release rates (mg m^{-2} day^{-1}), May to September, 1972-2001 by Bay section.

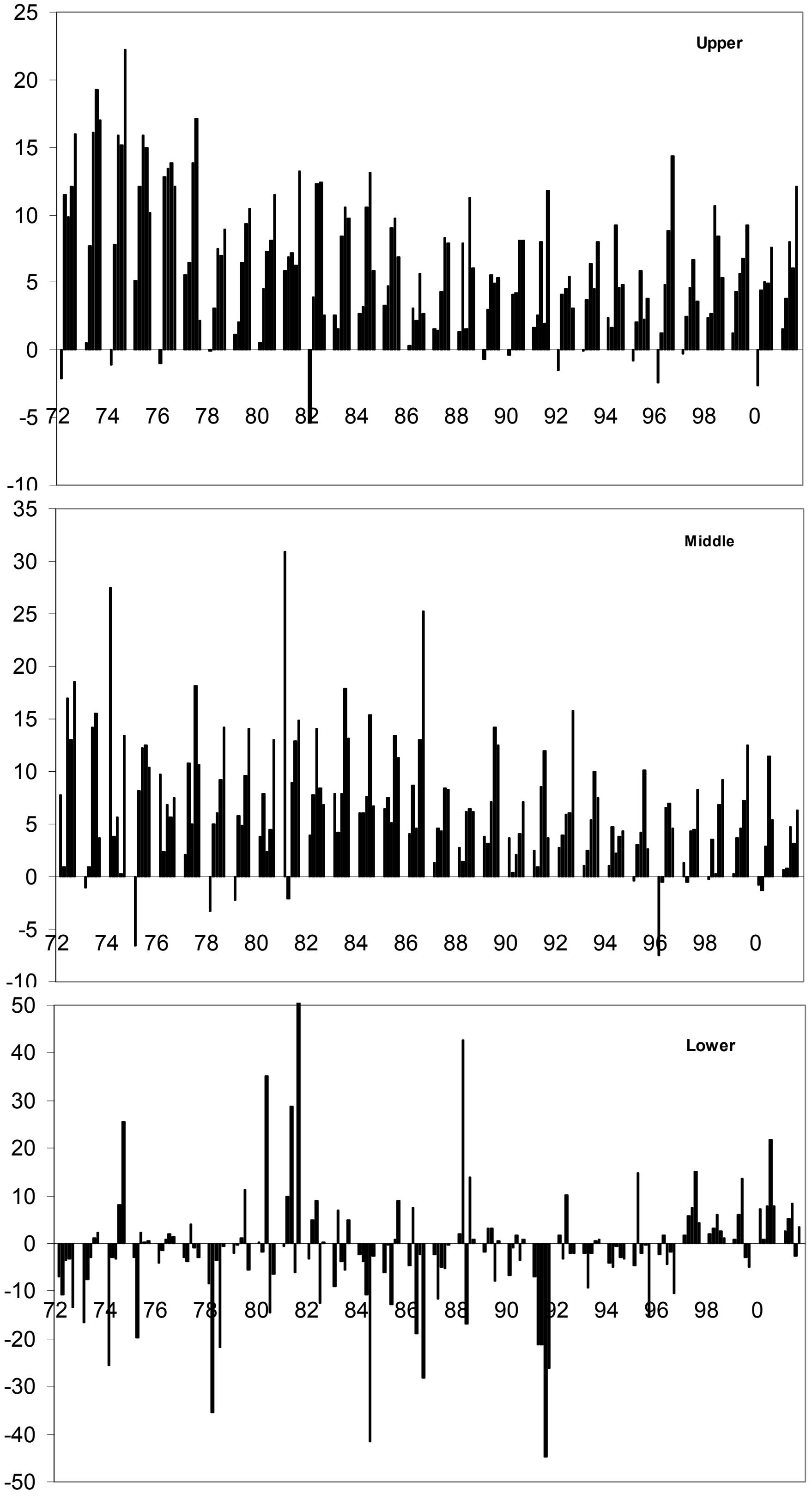


Figure 10. Average sectional summer and annual budgets of phosphorus (A and B) and nitrogen (C and D) (kg day^{-1}) for time periods: pre-control (1972-1977), post-control period 1 (1978-1988), post-control period 2 (1989-1994), and post-zebra mussels (1995-2001). (Layout of numbers corresponds to the conceptual budget diagram in Figure 10.).

A) Summer Phosphorus

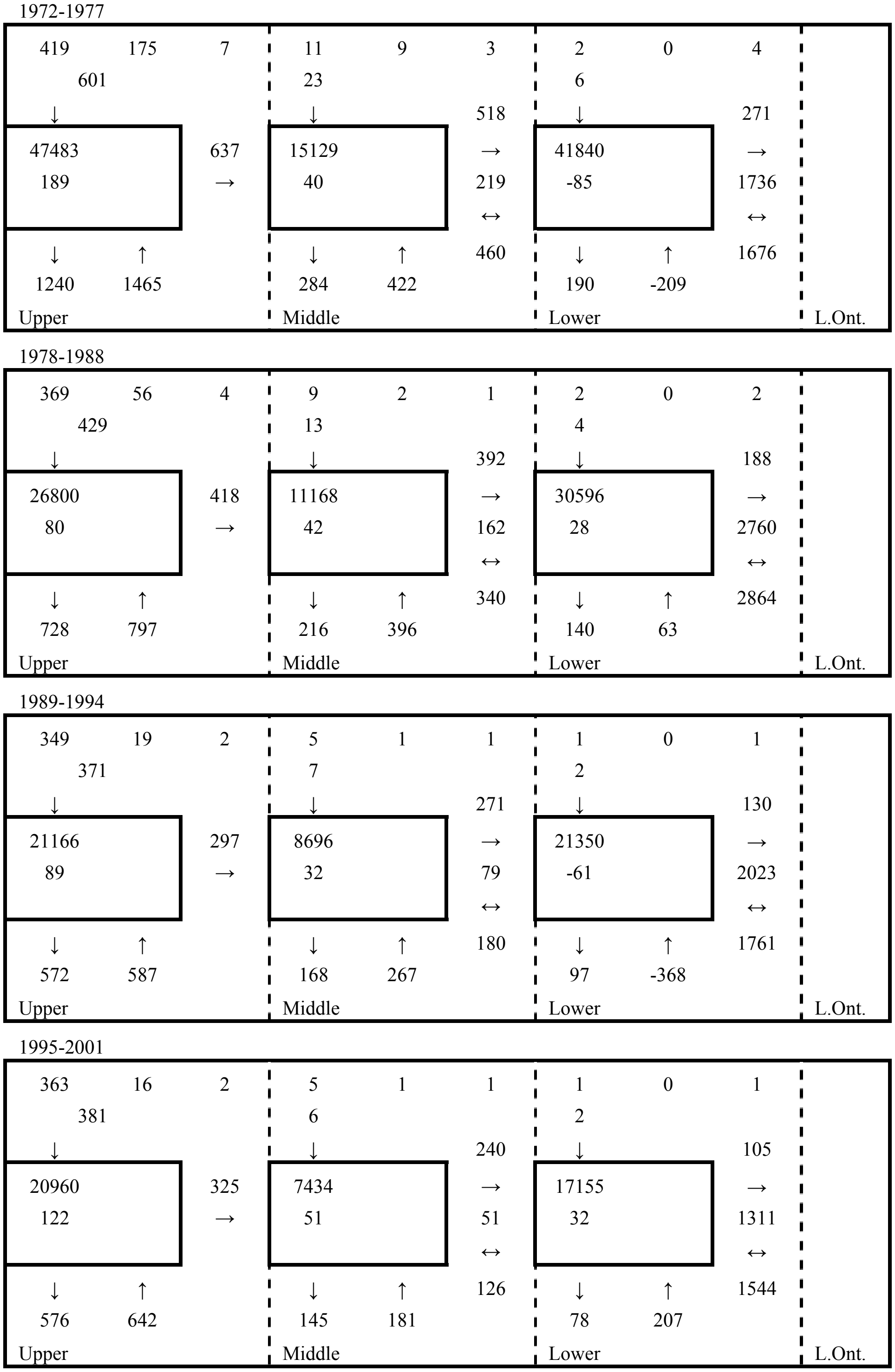


Figure 10 continued.
B) Annual Phosphorus

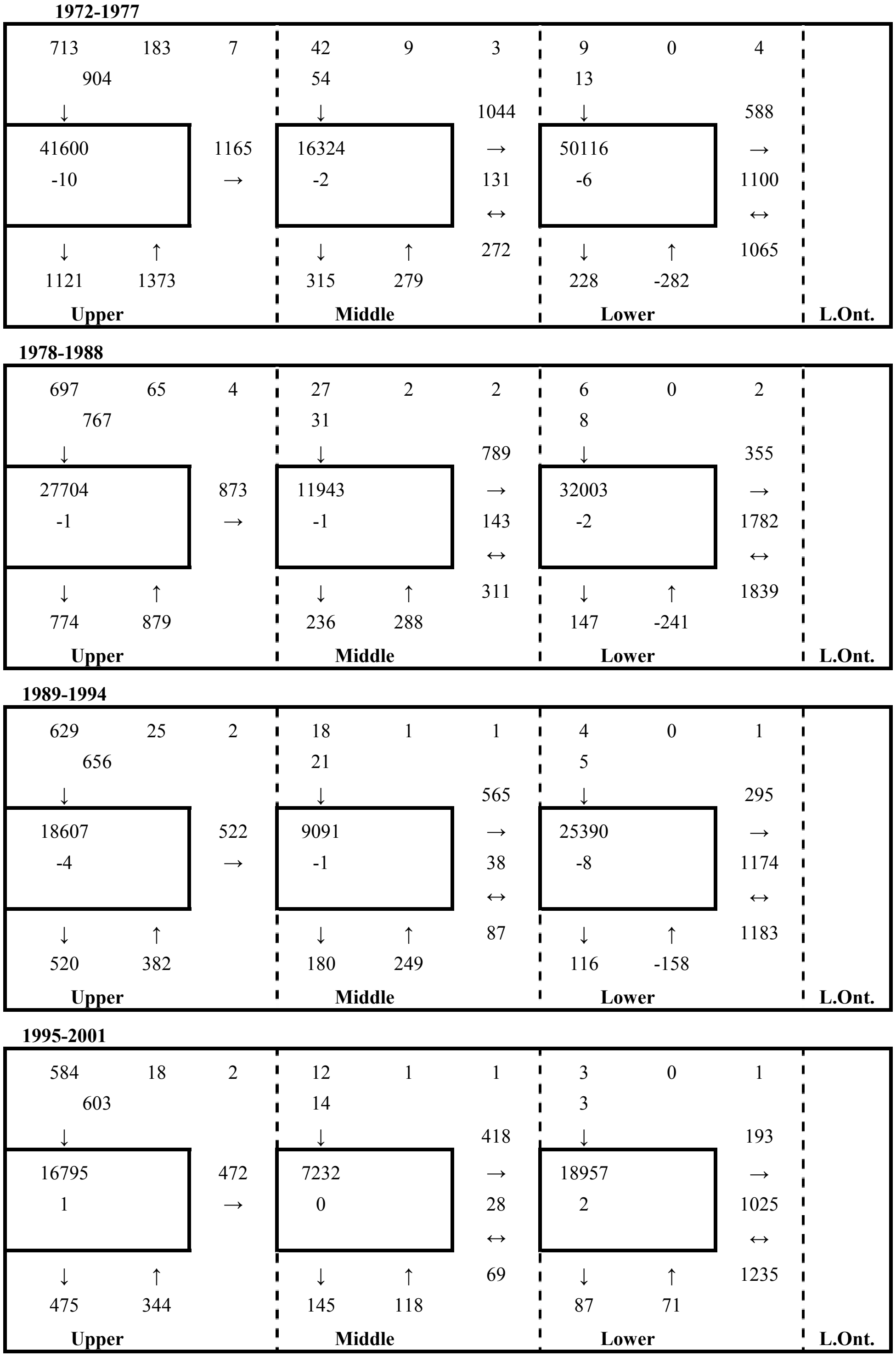
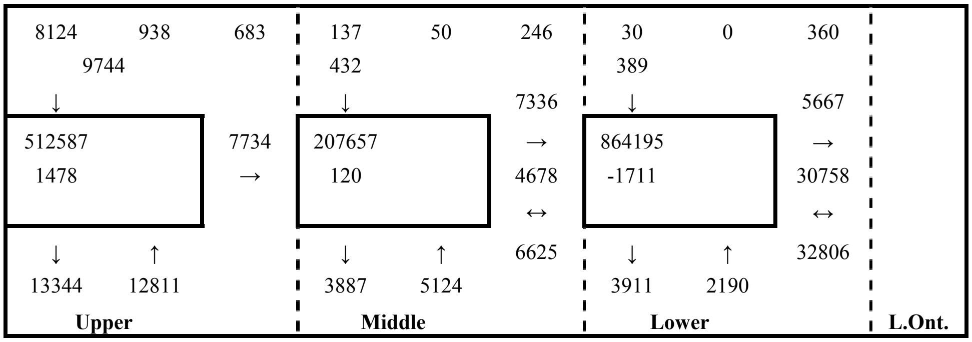
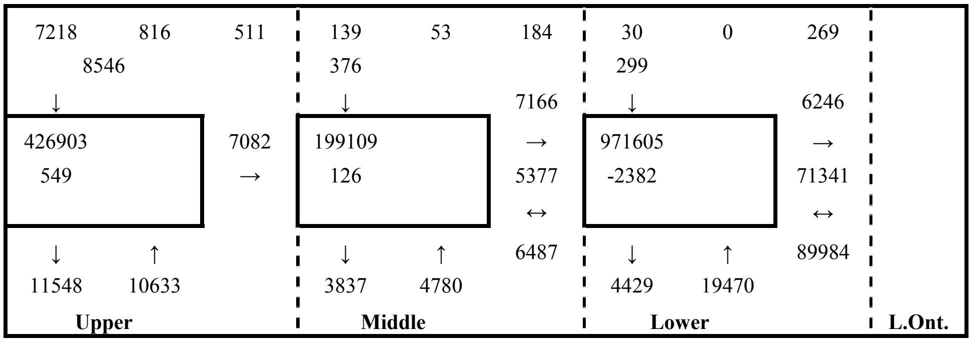


Figure 10 continued.
C) Summer Nitrogen

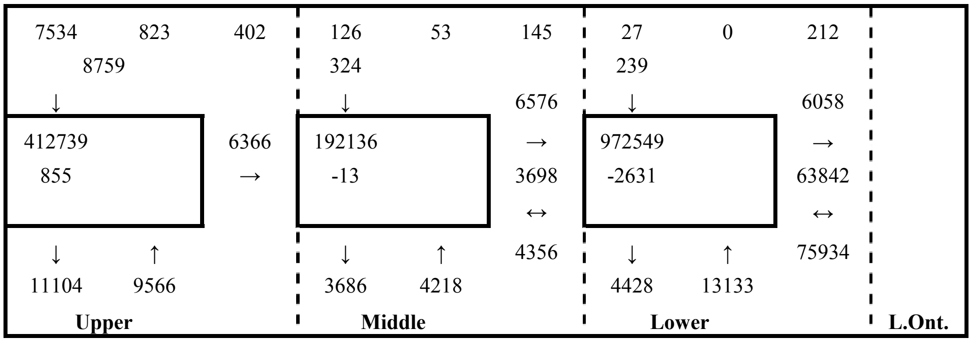
1972-1977



1978-1988



1989-1994



1995-2001

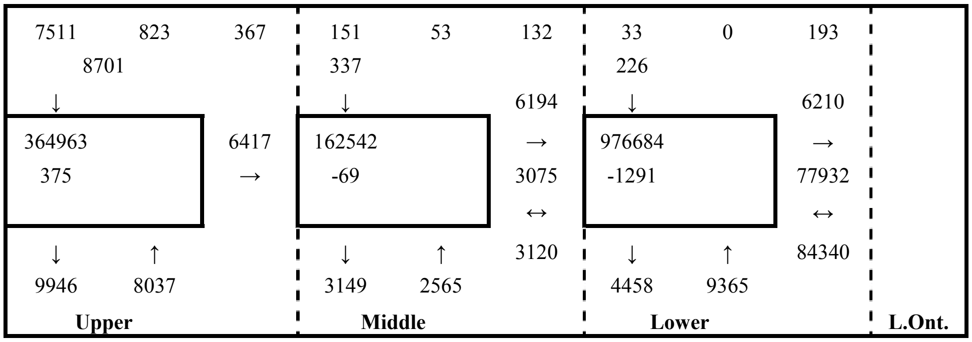


Figure 10 continued.
D) Annual Nitrogen

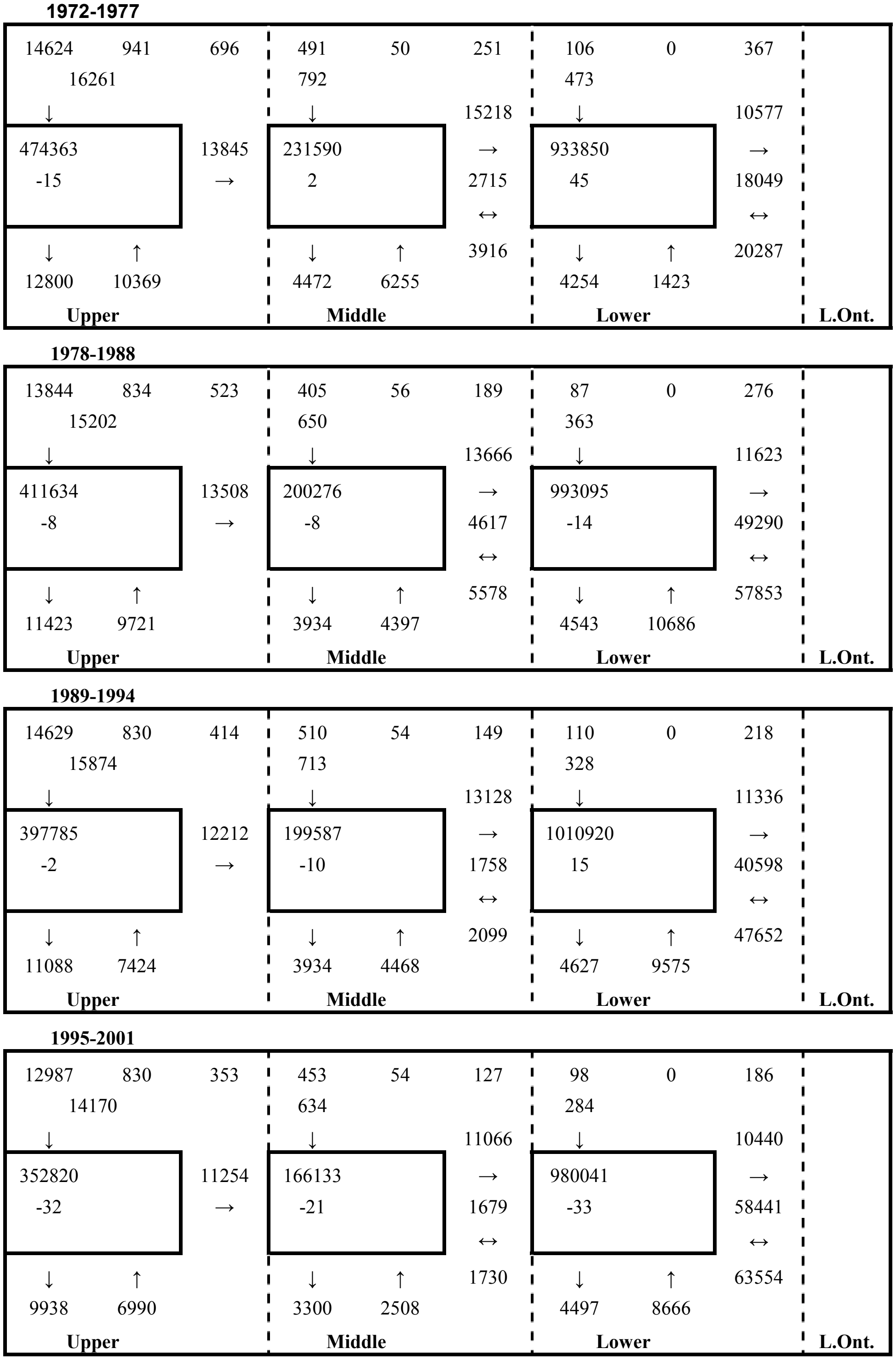


Figure 11. The relationship between estimated summer mean input [P] (µg.L^{-1}) and the measured summer mean output [P], *in situ* value, for the upper Bay of Quinte.

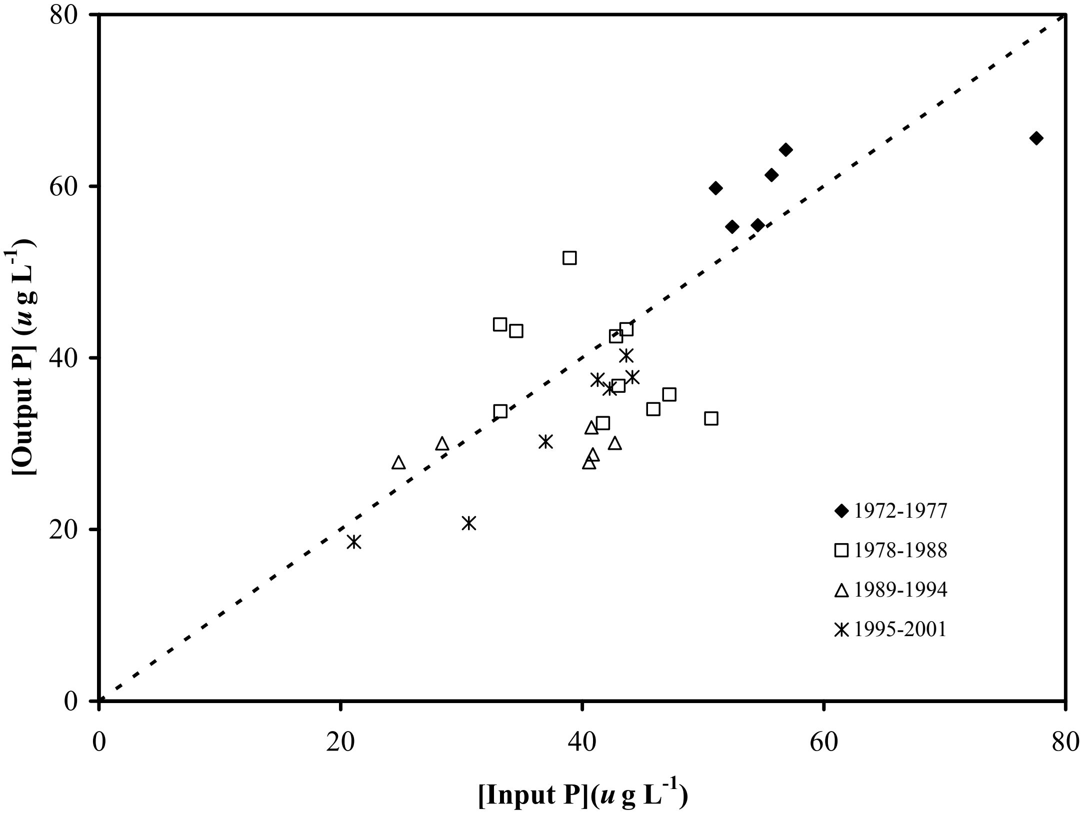


Figure 12. Upper Bay of Quinte output phosphorus concentrations (µg L^{-1},○) and output-input phosphorus concentrations (µg L^{-1} deviations from zero, △), 1972-2001. Values of output minus input >0 indicate negative retention.

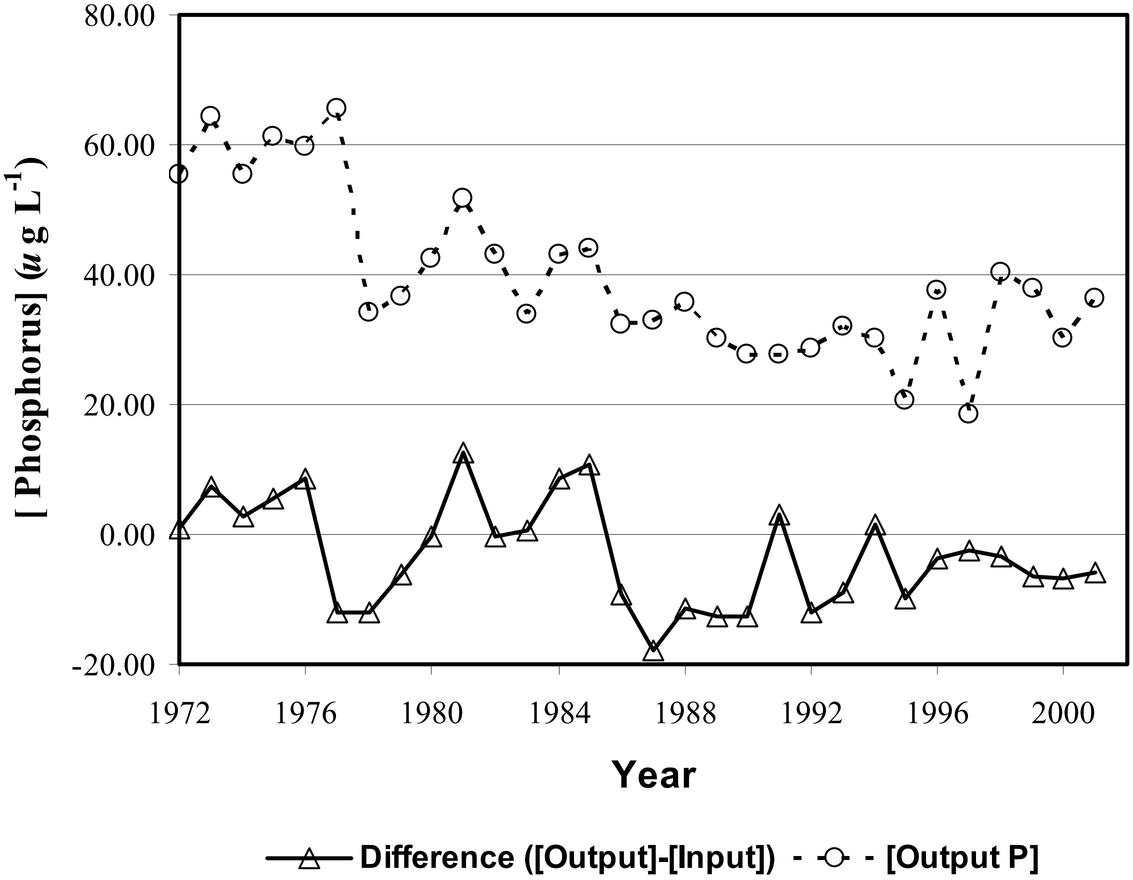


Figure 13. Annual (A) and summer (B) mean P concentrations (μg L^{-1}) in rivers, point sources, and in the upper Bay of Quinte, 1972-2001.

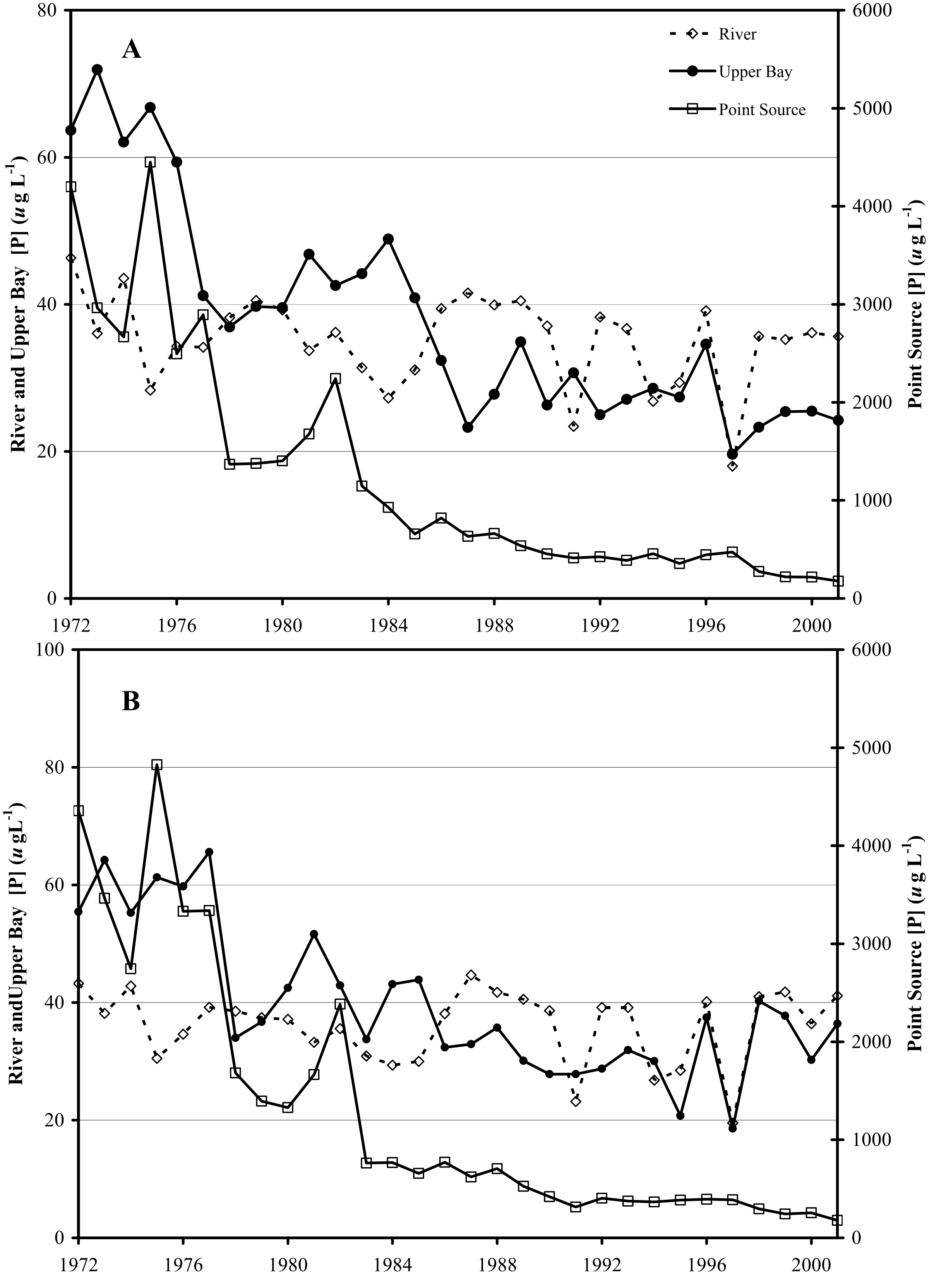


Table 1. Whole-bay and sectional flushing rates, uncorrected and corrected for back-flows from Lake Ontario, 1972-2001.

Year	Annual							Summer						
	Uncorrected				Corrected			Uncorrected				Corrected		
	Upper	Middle	Lower	Whole	Middle	Lower	Whole	Upper	Middle	Lower	Whole	Middle	Lower	Whole
1972	13.80	27.98	4.56	3.07	37.92	9.78	7.67	4.67	9.55	1.62	1.08	14.75	5.78	4.42
1973	12.47	25.73	4.33	2.88	31.29	10.85	7.84	2.24	4.69	0.83	0.55	9.19	5.14	3.89
1974	12.92	26.29	4.35	2.91	31.76	17.38	12.26	3.60	7.43	1.29	0.85	12.59	9.85	7.09
1975	10.38	20.93	3.36	2.28	25.26	8.72	6.38	2.30	4.61	0.76	0.51	8.64	4.83	3.70
1976	11.67	23.87	3.95	2.65	29.51	12.10	8.74	2.43	5.06	0.88	0.58	10.02	7.43	5.47
1977	9.06	18.29	2.92	1.99	28.79	7.52	6.25	0.95	1.93	0.32	0.22	8.22	2.89	2.64
1978	12.06	24.41	3.97	2.68	31.76	13.31	9.80	2.60	5.26	0.88	0.59	8.67	9.33	6.66
1979	13.80	27.81	4.46	3.03	43.26	14.04	11.20	2.50	5.06	0.84	0.56	10.61	7.50	5.66
1980	12.85	25.83	4.15	2.82	37.82	16.46	12.47	2.95	6.03	1.01	0.68	12.36	8.86	6.65
1981	13.45	26.92	4.30	2.92	35.67	49.76	34.80	3.45	6.97	1.14	0.77	11.58	35.84	24.70
1982	13.68	27.32	4.35	2.96	34.52	20.82	14.97	3.16	6.37	1.05	0.71	10.45	13.14	9.33
1983	12.24	24.58	3.94	2.68	45.47	18.40	14.76	3.61	7.28	1.20	0.81	16.76	9.37	7.35
1984	12.40	25.07	4.07	2.75	29.73	35.27	24.36	2.84	5.84	0.99	0.66	9.44	19.54	13.49
1985	15.09	30.27	4.88	3.30	44.45	23.28	17.30	2.77	5.59	0.93	0.63	11.07	11.30	8.20
1986	13.02	26.75	4.47	2.98	39.67	44.32	31.00	3.58	7.42	1.27	0.84	13.30	27.13	18.66
1987	9.79	19.81	3.19	2.17	26.79	15.08	11.00	1.40	2.85	0.48	0.33	6.87	9.09	6.61
1988	8.63	17.11	2.69	1.84	21.82	17.55	12.53	1.46	2.87	0.46	0.31	7.00	7.56	5.59
1989	9.35	18.65	2.96	2.01	22.87	16.42	11.64	2.65	5.31	0.87	0.59	9.31	7.88	5.73
1990	12.38	25.02	4.01	2.72	27.28	15.29	10.63	2.70	5.46	0.90	0.61	6.91	5.55	3.91
1991	12.40	24.90	4.01	2.72	31.60	47.86	33.22	2.15	4.39	0.73	0.50	10.12	38.64	26.75
1992	13.31	26.83	4.30	2.92	30.43	16.77	11.77	2.68	5.42	0.89	0.60	8.92	8.98	6.42
1993	14.82	30.32	5.00	3.36	33.92	21.23	14.65	2.82	5.86	1.01	0.68	9.40	10.51	7.41
1994	8.74	17.55	2.80	1.91	21.90	13.34	9.57	2.72	5.48	0.91	0.61	8.65	7.24	5.22
1995	11.89	23.65	3.74	2.55	28.94	28.00	19.69	2.07	4.06	0.65	0.44	8.11	11.45	8.22
1996	16.44	33.20	5.36	3.63	39.53	26.89	18.89	4.77	9.67	1.60	1.07	15.45	11.92	8.63
1997	14.14	28.77	4.70	3.17	32.41	29.47	20.27	3.17	6.48	1.09	0.73	10.01	18.30	12.64
1998	9.36	18.98	3.09	2.09	22.18	33.34	22.91	1.50	3.12	0.54	0.36	5.49	23.24	15.90
1999	8.74	17.20	2.66	1.83	19.31	19.05	13.36	1.12	2.17	0.34	0.23	3.67	9.33	6.54
2000	11.82	23.82	3.80	2.59	24.84	23.60	16.19	5.40	11.05	1.84	1.23	12.02	12.91	8.76
2001	9.87	19.56	3.08	2.11	25.36	31.12	21.92	1.30	2.60	0.43	0.29	5.27	8.83	6.29

Table 2. Mean runoff concentrations, rate of change per year (slope), percent change per year, and correlations (r) of annual mean concentration and year for tributaries entering the Bay of Quinte.

Source	[Mean]	Slope	%/yr	r	Prob.	Signif.[1]
Phosphorus						
Trent	0.036	0.000	0.0	0.070	1.000	
Moira	0.030	-0.001	-3.3	-0.503	0.558	
Salmon	0.023	0.000	0.0	-0.443	1.000	
Napanee	0.038	-0.001	-2.7	-0.401	1.000	
Wilton	**0.056**	**-0.003**	**-5.4**	**-0.857**	**0.000**	*
Nitrogen						
Trent	0.730	0.001	0.1	0.071	1.000	
Moira	0.706	-0.006	-0.8	-0.446	1.000	
Salmon	0.708	-0.011	-1.6	-0.522	0.368	
Napanee	0.819	-0.004	-0.5	-0.266	1.000	
Wilton	1.015	0.001	0.1	0.038	1.000	
Chloride						
Trent	7.57	0.097	1.3	0.589	0.074	
Moira	**5.49**	**0.080**	**1.5**	**0.682**	**0.004**	*
Salmon	**5.40**	**0.078**	**1.4**	**0.787**	**0.000**	*
Napanee	**6.80**	**0.139**	**2.0**	**0.790**	**0.000**	*
Wilton	23.97	0.424	1.8	0.595	0.062	

[1] Bonferroni-corrected significance at $P > 0.05$

Table 3. Loadings (kg km^{-2} day^{-1}) and percentage retention (%R) for P, N, and Cl in the whole Bay of Quinte, 1972-2001, uncorrected for Lake Ontario backflows. Means for 1972-1986 and 1987-2001 are also shown.

Year	Annual						Summer					
	P		N		Cl		P		N		Cl	
	Load	%R	Load	%R	Load	%R	Load	%R	Load	%R	Load	%R
1972	5.3	55.5	78.7	39.1	687.1	-85.2	4.2	40.1	66.3	40.2	572.0	-212.2
1973	3.9	11.5	69.3	28.7	563.0	-157.2	2.1	69.8	33.5	36.2	264.5	-467.2
1974	4.4	51.3	77.1	43.3	544.3	-186.7	3.1	-8.2	54.5	39.8	379.4	-361.4
1975	2.9	13.7	60.3	46.5	511.8	-104.3	2.0	75.5	35.3	42.1	214.3	-531.7
1976	3.3	54.3	70.1	40.5	492.1	-155.9	2.1	23.0	37.6	68.0	273.8	-525.5
1977	2.8	53.0	53.0	39.3	498.1	-85.5	1.2	11.1	19.1	83.2	151.6	-413.9
1978	3.3	43.1	64.5	18.4	564.3	-96.0	1.8	24.6	33.8	97.2	282.5	-460.2
1979	3.8	55.2	70.2	29.0	634.8	-136.7	1.7	0.6	31.9	39.1	297.3	-392.6
1980	3.5	54.2	64.1	22.0	594.2	-153.6	2.0	31.6	35.2	63.2	350.2	-380.7
1981	3.2	7.9	69.9	26.8	612.9	-183.0	2.2	6.1	47.6	47.9	414.9	-233.0
1982	3.5	87.1	73.9	35.5	609.0	-159.0	2.1	81.1	44.9	60.3	357.8	-292.1
1983	2.7	37.0	57.3	26.9	564.4	-152.1	1.9	9.0	42.3	40.0	396.8	-280.0
1984	2.5	69.2	57.3	32.2	581.9	-180.0	1.5	39.2	36.0	41.2	350.0	-236.3
1985	3.2	53.8	81.5	39.1	709.6	-155.2	1.4	-23.3	36.0	27.3	323.1	-241.1
1986	3.7	75.4	66.1	25.1	708.0	-162.2	2.5	63.4	46.5	39.3	481.1	-209.5
1987	2.7	83.1	41.4	25.6	502.0	-121.1	1.0	26.6	18.0	67.7	190.0	-337.5
1988	2.2	51.9	46.7	28.3	461.6	-85.6	1.1	-52.0	21.8	48.7	214.1	-307.8
1989	2.5	61.0	51.5	27.5	502.9	-111.5	1.8	64.6	40.3	70.5	346.9	-180.3
1990	3.0	61.6	72.2	36.3	830.9	-70.8	1.6	35.9	37.9	53.8	427.7	-144.3
1991	1.9	49.9	63.1	39.4	686.3	-98.0	0.8	25.0	27.8	43.7	297.6	-214.2
1992	3.3	57.0	73.2	28.8	858.7	-59.7	1.7	39.1	37.8	63.9	453.8	-124.3
1993	3.6	54.4	83.8	28.8	1006.8	-60.2	1.7	59.9	33.9	39.4	437.5	-178.6
1994	1.5	73.3	50.3	38.6	569.8	-74.0	1.2	65.9	39.7	48.8	422.6	-120.8
1995	2.2	60.8	67.7	41.6	849.6	-52.0	1.0	80.3	30.4	67.0	354.8	-124.7
1996	4.1	74.0	84.6	31.4	1037.7	-68.0	3.0	51.1	59.6	38.7	737.9	-119.6
1997	1.8	57.4	67.0	22.8	808.8	-87.7	1.0	8.8	39.9	25.6	427.1	-167.0
1998	2.1	67.2	40.8	19.2	630.4	-72.6	0.9	-33.7	18.4	43.3	246.1	-158.6
1999	1.8	69.9	42.3	37.5	473.7	-103.5	0.7	-63.2	16.9	48.1	154.7	-241.8
2000	2.7	73.1	59.8	31.5	661.1	-104.0	3.1	30.7	68.7	34.6	719.6	-121.4
2001	2.1	68.7	48.1	33.8	530.4	-120.8	0.8	-53.8	18.1	90.3	162.4	-241.1
72-86	3.5	48.1	67.6	32.8	591.7	-143.5	2.1	29.6	40.0	51.0	340.6	-349.2
87-01	2.5	64.2	59.5	31.4	694.1	-86.0	1.4	19.0	33.9	52.3	372.8	-185.5

Table 4. Calculated mean annual and summer net bay outflows (106 m3 day^{-1}), exchange flows from Lake Ontario (Q1 and Q2), and corrected whole Bay nutrient loads (mg m^{-2}.day^{-1}) and percent retention (%R), 1972-2001.

Year	Annual							Summer						
	Net Bay	Exchange flows		P		N		Net Bay	Exchange flows		P		N	
	Outflow	Q1	Q2	Load	%R	Load	%R	Outflow	Q1	Q2	Load	%R	Load	%R
1972	22.6	8.0	25.8	7.3	49.9	119.6	27.6	19.3	10.4	49.8	7.8	26.3	146.8	16.2
1973	21.7	4.7	32.7	7.2	1.7	121.7	12.4	10.0	9.2	51.8	6.0	41.2	119.4	14.2
1974	21.6	4.5	64.9	11.5	34.1	170.0	0.4	15.4	10.5	102.8	14.7	-46.3	198.5	-27.8
1975	16.6	3.4	26.4	5.4	3.1	102.3	34.7	8.9	7.7	48.2	5.7	47.3	112.3	10.8
1976	19.6	4.6	40.5	6.1	40.1	134.4	25.7	10.6	10.1	78.5	7.1	-21.5	162.9	30.1
1977	14.4	8.2	22.7	4.4	43.4	89.9	21.8	3.8	11.9	30.2	3.0	-18.6	68.9	42.9
1978	19.6	5.9	46.3	8.0	83.1	134.7	-11.8	10.4	6.5	100.1	12.2	227.4	187.2	-24.3
1979	22.0	12.2	47.3	6.9	45.8	152.4	7.6	9.9	10.7	78.9	6.3	-28.5	167.3	-34.2
1980	20.4	9.4	60.6	7.8	40.7	167.1	-13.6	12.0	12.3	93.2	8.1	-48.9	199.4	1.1
1981	21.2	6.8	224.2	16.1	-221.1	400.4	-162.7	13.4	8.8	410.4	25.7	-622.0	605.0	-477.7
1982	21.4	5.6	81.1	8.3	68.5	225.0	3.7	12.4	7.7	142.8	10.5	27.6	293.1	-65.1
1983	19.4	16.4	71.4	6.5	-6.4	171.4	-7.1	14.2	18.2	96.9	7.4	-37.5	181.1	-62.0
1984	20.1	3.7	154.1	11.6	89.5	318.4	-51.4	11.8	7.0	220.6	15.9	173.4	357.6	-320.0
1985	24.1	11.3	91.1	8.1	46.7	242.9	9.1	11.0	10.6	122.9	8.2	-29.4	233.6	-148.3
1986	22.3	10.7	199.3	13.2	75.5	437.8	-60.9	15.2	11.8	309.7	17.3	86.8	583.4	-245.6
1987	15.8	5.5	58.7	5.3	94.4	143.1	-16.7	5.6	7.5	101.4	5.5	112.2	184.7	-78.5
1988	13.2	3.6	72.7	5.6	-15.7	167.9	-30.5	5.4	7.7	83.6	5.4	-196.5	173.3	-207.7
1989	14.6	3.3	66.3	5.2	15.7	171.2	-18.0	10.4	7.8	83.3	5.1	9.8	194.1	20.2
1990	19.8	1.8	55.7	5.8	49.4	174.7	12.4	10.7	2.8	55.0	4.5	38.9	133.3	10.0
1991	19.8	5.3	216.6	14.4	176.4	391.8	-64.8	8.7	10.9	447.9	27.0	781.9	680.5	-529.4
1992	21.2	2.8	61.5	5.8	27.0	175.0	-11.5	10.6	6.8	96.0	5.5	-13.7	186.6	-64.7
1993	24.9	2.9	80.7	6.5	23.9	226.7	-1.9	12.1	7.0	113.2	5.5	33.2	221.8	-83.6
1994	13.8	3.4	51.9	3.5	60.9	152.4	17.5	10.7	6.1	75.0	4.2	75.5	187.6	22.1
1995	18.4	4.1	119.3	6.1	39.6	264.7	-16.9	7.6	7.6	127.1	4.9	60.3	234.5	-95.2
1996	26.5	5.0	106.2	7.8	61.8	290.8	19.4	19.0	11.2	122.5	7.1	38.0	307.9	28.0
1997	23.3	2.9	122.9	4.8	4.4	309.5	-10.9	13.0	6.9	204.7	5.1	-202.4	443.0	-73.4
1998	15.3	2.5	149.7	7.9	34.1	336.3	-28.0	6.4	4.6	269.2	12.3	-124.7	547.3	-84.7
1999	13.0	1.6	80.1	4.4	22.2	185.7	4.7	4.0	2.8	105.4	3.6	-177.2	206.1	-50.9
2000	18.7	0.8	97.2	5.6	14.7	253.0	11.6	21.8	1.9	131.5	6.7	-66.2	333.4	13.3
2001	15.1	4.5	137.7	6.3	-14.3	312.7	-14.1	5.1	5.0	99.0	3.1	-171.4	214.3	-50.0

Table 5. Calculated summer mean sediment P and N reflux rates (mg m^{-2}.day^{-1}) in the three sections of the Bay.

Year	P			N		
	Upper	Middle	Lower	Upper	Middle	Lower
1972	9.4	11.5	-7.5	83.7	136.5	5.5
1973	12.1	6.8	-4.8	108.9	95.2	15.2
1974	12.0	10.2	0.3	87.8	85.2	108.3
1975	11.7	7.3	-3.9	87.5	117.2	34.1
1976	10.2	6.5	-0.2	92.1	78.6	17.5
1977	9.1	9.3	-1.2	103.4	112.5	2.2
1978	5.3	6.2	-13.9	58.6	78.8	116.0
1979	5.9	6.4	1.0	70.4	83.6	102.4
1980	6.4	6.3	2.6	63.6	115.9	48.7
1981	7.9	13.2	41.8	107.4	131.7	842.5
1982	5.2	8.2	-0.3	62.6	105.2	192.5
1983	6.6	10.3	-1.4	57.1	98.7	164.1
1984	7.1	8.4	-12.4	93.3	97.5	466.9
1985	6.8	8.7	-1.9	91.3	84.7	256.1
1986	2.8	11.1	-9.4	58.3	150.2	453.3
1987	4.7	5.4	-4.8	104.9	68.2	89.3
1988	5.6	4.6	8.4	90.2	54.6	249.7
1989	3.6	8.2	-0.6	62.8	115.5	52.6
1990	4.8	3.5	-1.7	71.2	63.8	72.5
1991	5.2	5.6	-24.1	71.7	85.9	587.5
1992	3.1	6.9	1.0	68.5	104.0	156.8
1993	4.5	5.3	-2.3	86.9	64.3	161.0
1994	4.6	3.2	-3.1	59.8	81.2	66.5
1995	2.7	3.9	-1.6	49.9	53.9	212.6
1996	5.3	2.0	-3.4	59.5	55.7	43.8
1997	3.4	3.6	7.0	50.6	61.3	205.6
1998	5.9	3.9	3.0	72.2	53.8	131.2
1999	5.4	5.6	2.6	74.0	53.1	98.3
2000	3.9	3.5	9.1	43.6	48.9	95.1
2001	6.3	3.1	3.4	62.8	38.5	126.2

Table 6. Comparison of total and net loadings (kg day^{-1}) of phosphorus from rivers and point sources for summer and annual periods, 1972-2001.

Year	Summer				Annual			
	Total		Net		Total		Net	
	River	Point	River	Point	River	Point	River	Point
1972	810.9	214.3	-228.9	211.6	1024.6	230.6	-383.8	227.1
1973	337.8	168.4	-231.1	165.3	753.8	169.3	-750.6	165.2
1974	621.6	142.3	-181.0	139.4	914.0	146.5	-388.5	143.1
1975	266.1	222.2	-268.8	219.4	458.0	237.9	-622.1	234.4
1976	336.0	162.2	-244.2	159.3	651.9	146.9	-476.2	143.4
1977	140.7	141.1	-94.7	138.3	477.6	165.1	-98.3	162.7
1978	370.8	72.8	43.6	71.3	721.1	77.4	23.7	75.3
1979	356.3	54.7	6.7	53.3	870.0	69.1	17.7	67.1
1980	417.3	65.6	-60.0	63.5	776.4	76.1	-6.0	73.9
1981	440.6	77.6	-243.9	75.2	697.6	82.1	-271.7	79.8
1982	415.2	96.4	-90.6	94.7	752.7	109.6	-132.9	107.5
1983	427.4	33.3	-39.5	31.9	593.5	57.6	-241.9	55.3
1984	316.6	58.7	-148.7	55.4	529.1	67.0	-419.5	63.5
1985	313.8	35.4	-145.3	33.0	739.5	43.2	-232.9	40.5
1986	551.3	55.4	82.8	53.1	855.8	59.5	153.3	57.1
1987	219.6	32.1	57.8	30.4	624.8	37.9	275.0	36.5
1988	230.3	32.3	33.2	30.7	511.8	34.3	155.6	32.8
1989	426.6	24.8	109.7	23.4	584.8	25.8	80.7	24.1
1990	387.4	21.5	108.3	20.1	712.2	26.6	207.0	25.1
1991	178.8	13.7	-36.1	12.5	446.2	21.7	-139.0	20.1
1992	409.8	19.9	109.0	18.5	795.1	23.9	276.0	22.5
1993	414.9	18.9	76.9	17.3	878.0	24.2	230.7	22.5
1994	275.4	18.0	-33.4	16.5	355.4	26.3	-23.4	24.6
1995	220.4	18.1	59.8	17.2	528.6	20.2	35.7	18.6
1996	741.5	23.3	49.7	21.0	1007.2	28.7	117.1	26.5
1997	235.6	20.2	11.6	19.2	402.7	27.9	-36.1	26.7
1998	216.0	16.4	3.9	14.1	518.1	16.6	179.9	15.2
1999	174.5	11.9	16.9	10.0	449.7	12.8	125.4	11.3
2000	757.5	14.0	128.1	12.3	649.5	11.2	191.9	9.9
2001	196.7	6.9	22.7	5.5	529.2	8.3	169.4	7.1

Appendix A. Sources of information for computing water and nutrient budgets

Table A1. List of river flow stations used and operating dates.

Station ID	Location	First Start Date	First End Date	Second Start Date	Second End Date
02HK002	Trent River at Healey Falls	1-Oct-49	31-Dec-02		
02HK004	Trent River at Glen Ross	1-Oct-63	30-Jun-91	01-Jan-92	06-Dec-95
02HL001	Moira River near Foxboro	1-Oct-15	26-Mar-02		
02HM003	Salmon River near Shannonville	17-Jul-58	26-Mar-02		
02HM001	Napanee River at Napanee	1-Nov-15	1-Nov-26	01-Mar-48	11-Jun-74
02HM007	Napanee River at Camden East	1-Jan-74	31-Dec-02		
02HM004	Wilton Creek near Napanee	1-Oct-65	31-Dec-02		

Table A2. Total and gauged drainage areas for five main tributaries to the Bay of Quinte

Drainage	Drainage Area (km2)	Gauging Station	Gauged Drainage Area (km2)
Trent River	12548.7	02HK004	12038.3
Moira River	2727.2	02HL001	2614.8
Salmon River	897.5	02HM003	890.6
Napanee River	787.0	02HM007	694.1
Wilton Creek	127.4	02HM004	112.4

Table A3 Tributary water quality stations used for estimating river chemical loads. Stations in italics were those used also by Minns and Johnson (1979).

Station Code	Description of Sampling Location
17002100102	*Trent River, at bridge on Highway 2*
17002104502	*Trent River, Hwy 401 bridge, near Trenton*
17002106883	Trent River, new Highway 2 bridge Trenton
17002600102	Moira River, Footbridge, north of Hwy 2, Belleville
17002600202	*Moira River, at bridge in Cannifton*
17002601402	Moira River, at Victoria Street, Belleville
17003100102	*Salmon River, at old Hwy 2, Shannonville*
17003100202	Salmon River at bridge in Milltown
17003500102	Napanee River dnstream from Napanee, River Road
17003500202	*Napanee River, Mink bridge, upstream at 401*
17003500402	Napanee River at bridge in town of Newburg
17003700102	*Wilton Creek, County Road 8, M.E. Chambers*
17003700602	Wilton Creek, Con 4-5 about 3 miles SW of Morven WC-3

Table A4 Frequency in months of point-source loading estimates by method and STP. The five data sources are described in the Methods section under “point sources”.

Measure		STP					
	Source Number	Belleville	Trenton	CFB Trenton	Deseronto	Napanee	Picton
Total P	1	263	328	110	269	179	167
	2	46	10	120	38	120	120
	3	51	22	130	53	61	73
Total N	2	120	120	120	120	120	120
	5	240	240	240	240	240	240
Chloride	2	120	120	120	120	120	120
	4	240	240	120	240	180	180
	5			120		60	60

Figure A1. Mean monthly relative deviation: (Cruise-Intake)/Cruise, Belleville 1985-2001, where the winter cruise data were based on interpolated estimates.

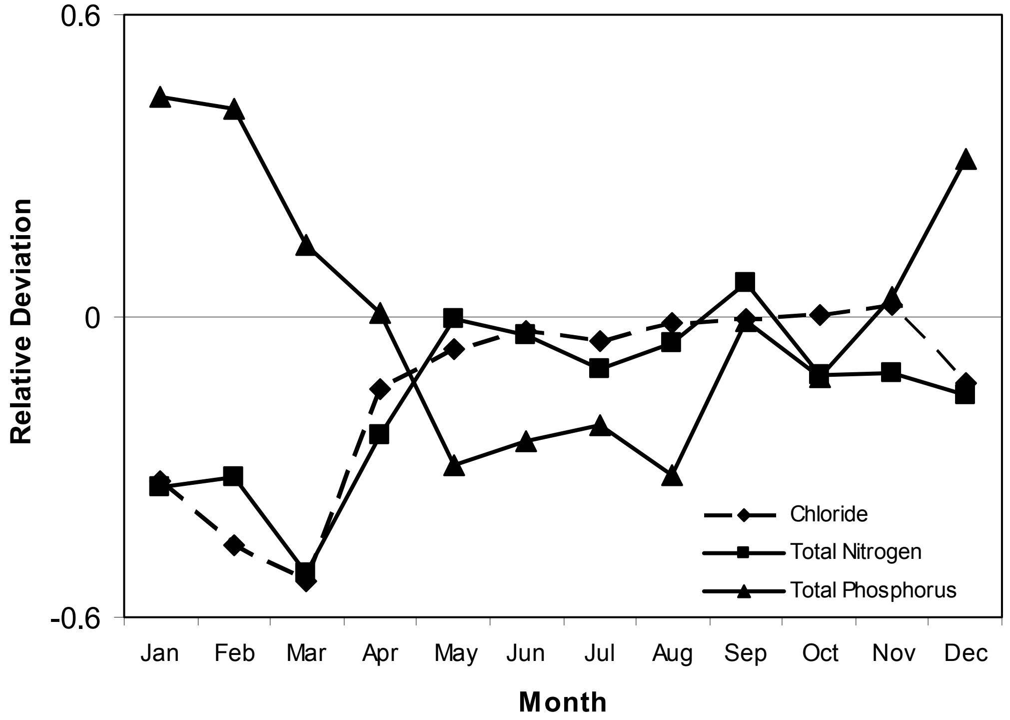


Table A5. Methods used to estimate Lake Ontario concentration data by time period. The six methods (1, 2, 3a, 3b, 4 and 5) are described in the Methods section under "Lake Ontario substance concentrations".

Measure	1972-1977	1978-1980	1981-1995	1996-2000	2001
Chloride	5	3a	1,2	3a	4
Total Nitrogen	4	3b	1,2	3b	4
Total Phosphorus	5	3a	1,2	3a	4

Table A6. Contact information for various data assembled for this report (Fall 2003).

Information	Name	Address	Phone/Email
Flow data:	Susan Saunders	Water Survey Division Environment Canada	(905) 319-6939 Susan.Saunders@ec.gc.ca
Trenton Weather Station Precipitation Data:	Ms. Sandy Radecki	Environmental Services Branch, Atmospheric Issues Division, Ontario Climate Centre, 4905 Dufferin Street, Downsview, Ontario M3H 5T4	(P)1-900-565-1111 (F) (416) 739-4521
	Aaron Thompson, P.Eng	Boundary Water Issues Division, MSC-Ontario, Environment Canada, 867 Lakeshore Road, Burlington, Ontario, L7R4A6	(P) 905-336-4959 (F) 905-336-8901 Aaron.Thompson@ec.gc.ca
Precip chemistry:	Trenton-Kingston:Ken Kuntz,Jo-Ann Hodson Point Petrie:		C.H.Chan@ec.gc.ca
Trib chemistry:	Shenaz Sunderani	Data Management Technician Water Monitoring Ontario Ministry of Environment and Energy Etobicoke	(P) 416-235-6255 shenaz.sunderani@ene.gov.on.ca
STPs (Data for Belleville, Trenton, Deseronto, Napanee, Picton and CFB Trenton)	Lucy Stojko (for data between 1972 and 1986, for Belleville, Trenton and Deseronto plants)	Municipal Data Officer, Data Management Unit Environmental Monitoring & Reporting Branch Ministry of Environment and Energy 40 St. Clair Avenue West, 12th Floor Toronto, Ontario M4V 1P5	(P) (416) 314-7934 (F) (416) 314-7880
	Koshy Mathew (for data between 1987 and 1996, for all plants except CFB Trenton); Obtained additional data from Koshy Mathew (KM set) covering period 1991-2001	Environmental Monitoring & Reporting Branch Ministry of Environment and Energy 40 St. Clair Avenue West, 12th Floor Toronto, Ontario M4V 1P5	(P) (416) 314-7900 or 3540 mathewko@ene.gov.on.ca

	James D. Mahoney	Regional Programs Coordinator Ministry of Environment and Energy, Eastern Region 133 Dalton Avenue, P. O. Box 820, Kingston, Ontario K7L 4X6	(P) 613) 549-4000 ext. 2717 or 1-800-267-0974 (F) (613) 548-6908
	Garnet MacFarlane (for CFB Trenton, no data available for years before 1986)		(P) (613) 392-2811 ext. 7498 (F) (613) 965-7578
	Bob Helliar; Obtained additional data from from Bob Helliar (BH set) covering 1999-2001	Assistant Director's Office, Eastern Region Ministry of Environment and Energy 133 Dalton Avenue, P. O. Box 820 Kingston, Ontario K7L 4X6	(P) (613) 549-4000 ext. 2651 or 1-800-267-0974 (F) (613) 548-6908
Industry sources:	Andreas Radman	Environmental Monitoring & Reporting Branch Ministry of Environment and Energy 135 St. Clair Avenue West, Suite 100 Toronto, Ontario M4V 1P5	(P) (416) 314-7907 (F) (416) 314-7880
	* Footnote		
Belleville intake temperatures:	Ken Nicholls	Contact via E. S. Millard	
Project Quinte data:	E.S. Millard	GLLFAS	
Lake Ontario:	Bioindex: Dr. Ora Johannsson	GLLFAS	
	STAR: Violeta Richardson	EHD-OR Environment Canada 867 Lakeshore Road Burlington, Ontario L7R 4A6	(P) (905) 336-4964 (F) (905) 336-4609 Violeta.Richardson@ec.gc.ca

*General Industry Sources Information:

- Most industries discharge to tributaries, not directly to the Bay. Furthermore, industries that discharge to tributaries have effluent points in the tributaries that are above the MOE monitoring stations for water quality. Therefore, flows and concentrations for industrial inputs were included in the data for the relevant tributaries (F. Stride, pers. comm.). Many industries do not discharge to tributaries or to the Bay. Such industries (i.e. food industries) discharge to the municipal sewer system and effluent is treated with municipal waste.
- Fred Stride identified Domtar plants, ESROC and BTL Resins as industries of concern. He also mentioned that Domtar Wood and BTL Resins have closed. Also, Domtar Packaging discharges to the Trent River. Therefore, it could be assumed that BTL (prior to closure) and ESROC would be the only industries that would need to be considered in the water and phosphorus budgets for the Bay of Quinte.