Changes in Total Waste Water Ammonia Loading during the Last Two Decades in the Hudson Estuary

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Introduction

The lower Hudson estuary receives approximately 5 billion liters of waste water per day that are flushed through the Verrazano Narrows towards the Atlantic Ocean. Another 5 billion liters/day of waste water are discharged into adjacent waterways such as Jamaica Bay, the upper East River and Raritan Bay. Patterns of concentrations of most nutrients versus salinity along the axis of the Hudson estuary are dominated by these external loads, rather than biological processes within the waters of the estuary. During summer months, concentrations of soluble reactive phosphate (SRP) and ammonia (NH_4) are generally between 4-7 µmole/l and 20-50 µmole/l in the region of New York Harbor receiving the highest loading rate.

One of the distinguishing features of the Hudson is that most waste water loading occurs near the estuary mouth in water which has relatively high salinities (15-25 ppt). Estuarine currents which disperse salt and other dissolved species along the axis of an estuary by density-driven circulation are stronger here than at lower salinities (Ketchum, 1969; Hunkins, 1981). The greater axial dispersion, combined with the proximity of waste loading to seaward exits, leads to relatively short residence times of a number of soluble pollutants in the Hudson estuary. Thus, most of the dissolved nutrients are advected rapidly out of the estuary without being incorporated into biomass (Simpson *et al*, 1975; Garside *et al* 1976; Clark *et al*, 1992).

A significant portion of the waste water nutrients is mixed upstream by estuarine circulation to lower salinities. Net phytoplankton uptake of nutrients is usually not very apparent in axial transect data because phytoplankton growth is limited by the high turbidity of the water (Malone, 1977). Only during extreme bloom events when chlorophyll *a* concentrations are an order of magnitude greater than for mean low flow conditions is net uptake of nutrients apparent in the immediate vicinity of the bloom. Relatively weak phytoplankton activity compared to the large external input leads to approximately conservative behavior of SRP in the Hudson estuary (Hammond, 1975; Simpson *et al*, 1975; Deck, 1981; Clark *et al*, 1992). However the effects of microbial processes which mediate transformation of inorganic nitrogen species can sometimes be clearly observed in nutrient vs salinity transects (Deck, 1981; Deck, 1986). Oxidation of NH_4 (nitrification), leading to elevated concentrations of nitrite (NO_2) and nitrous oxide (N_2O) are the most striking features of these transformations.

Nitrification is not unique to the Hudson; it has also been observed in other polluted estuaries such as the Potomac and Scheldt estuaries (McElroy *et al*, 1978; Deck, 1981; Wofsey *et al*, 1981). Nitrification is a multi-step process during which several communities of nitrifying bacteria utilize reduced nitrogen as an energy source (Kaplan, 1983). During the first step one community of bacteria oxidizes NH_4 to NO_2, while during the second a different bacterial population oxidizes NO_2 to NO_3. A by product of the first step, N_2O, is generated in trace amounts. Equations representative of these processes can be written as:

$$NH_4^+ + \frac{3}{2}O_2 \rightarrow \overset{\overset{N_2O}{\uparrow}}{NO_2^-} + 2\,H^+ + H_2O$$

$$NO_2^- + \frac{1}{2}O_2 \rightarrow NO_3^-$$

Intermediate species not included in these equations are formed but are unstable in most natural waters (Kaplan, 1983).

The Hudson estuary

The Hudson estuary (Figure 1), as defined here, extends from the Narrows (mp -8)[1] north to the upstream limit of tidal influence at the Federal Dam at Green Island (mp +154). Less than half of this total reach experiences intrusion of saline

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[1] Axial distance along the Hudson River has traditionally been recorded in mile points, mp, which designate the number of statute miles upstream (+) or downstream (-) from the Battery at the southern tip of Manhattan.

water, even during periods of low fresh water discharge. The general circulation dynamics of the salt intruded reach of the Hudson and other partially-mixed estuaries have been understood for some time (Pritchard, 1969; Abood, 1974; Bowden, 1980; Hunkins, 1981). The Hudson estuary usually has surface and bottom salinities which differ by about five parts per thousand at intermediate salinities during low freshwater discharge. Freshwater discharge usually reaches a maximum during spring months and a minimum during late summer to early autumn. Seasonal extreme values of freshwater discharge at the Battery (mp 0) averaged over periods of a few weeks to a few months are 2000 m^3/s and 150 m^3/s, respectively. During late summer, saline water can extend as far north as Newburgh (mp +60) while during spring months saline water at the surface can extend to just upstream of Manhattan (mp +15). During higher discharge ($Q > 600\ m^3/s$), fresh water replacement times for the salt-intruded reach are less than fifteen days while during low flow conditions ($Q = 150$ to $250\ m^3/s$) replacement times are typically between forty-five and sixty days although they can be greater than seventy-five days during extreme dry periods (Figure 2).

Since the early 1970s improved treatment systems have been constructed at a number of waste water treatment facilities (WWTF) serving the New York City metropolitan area. Total discharge volumes to the Hudson of untreated (raw) waste water during dry weather conditions decreased from 25% in the early 1970s to less than 5% in the late 1980s, while the fraction of secondary-treated waste water increased from 50% to 85% over the same period (Mueller *et al*, 1976; Brosnan *et al*, 1987; Interstate Sanitation Commission, 1989; Dujardin *et al*, 1991). These changes, as well as removal of phosphate-based detergents in New York State, resulted in large changes over the past two decades in the total loading rate of SRP from WWTF to the Hudson estuary (Clark *et al* 1992).

Methods

Axial transect data of nitrogen species have been collected at Lamont Doherty Earth Observatory since 1977 (Deck, 1981; Deck, 1986). Generally, samples of Hudson estuary water were collected 1 meter below the surface and 1 meter above the sediments with a Niskin bottle from a small boat. They were immediately filtered (Whatman GF/F or equivalent) and stored in the dark on board the boat. Subsamples (50 ml) were collected in glass bottles with teflon-lined caps for NH_4 analyses. Two ml of phenol-ethanol solution were added as a preservative to these subsamples in the field (Deck, 1981). Upon returning to the lab (within 6 hours of collection), all samples were transferred to a refrigerator. Analysis of nutrients were completed within 72 hours of collection following procedures outlined by Strickland & Parsons (1972).

Transects discussed here are generally a combination of two or more sample collections which were carried out within a period of two weeks or less. Individual stations were collected in sequence along the axis of the estuary and thus are neither synoptic nor tidal cycle averages. Fifty kilometers of the estuary could usually be sampled in about four hours.

Freshwater discharge rates in the estuary have been estimated from United State Geological Survey gauge station data (USGS WSP 1977-91) and drainage basin areas following procedures outlined by Clark *et al.* (1992).

Results

Plots of NH_4 concentration versus salinity show some variation with season (Figure 3). Maximum NH_4 concentration (20-50 µmole/l) usually occur at salinities between 15 and 25 ppt and vary systematically with freshwater discharge (Figure 4). Plots of NO_2 concentrations versus salinity differ somewhat in general trends from those for NH_4. Maximum concentrations of NO_2 are typically an order of magnitude less than that of NH_4 and mid-salinity maxima occur at slightly lower salinities. In contrast to other nitrogen species, NO_3 appears to mix conservatively between the freshwater and seaward end members, showing no significant mid-salinity maxima (Figure 5).

Rates of waste water flux, NH_4, organic nitrogen (Org-N), total N, and SRP discharged from WWTF which serve the NYC metropolitan area are listed in Table 1. NH_4 and Org-N together comprise more than 75% of total N discharge at most WWTF. Total reported loads of SRP declined substantially (about 50%) between the early 1970s and the late 1980s (Table 1).

Discussion

Qualitative changes in the concentrations of NH_4 and the NH_4/SRP ratio in the Hudson estuary can be discerned directly from the transect data. NH_4 and SRP concentrations found at the Battery, which is located near the two largest waste water influxes to NY Harbor (the East River and Passaic Valley Sewerage

Commission facility) were within 5% of the maximum observed during each transect (Table 2A, Table 2B). Thus, characteristics observed at this location should be generally representative of the integrated WWTF load.

Upstream from the Battery, the NH_4/SRP ratio decreases appreciably. On average, this ratio about 30 kilometers upstream of the Battery (Alpine, NJ) was lower by approximately 60%. The decrease in this ratio could be generated by at least three processes. Conservative mixing of SRP and NH_4 within the estuary would generate systematic ratio changes if the end member ratios at the freshwater and seaward extremes differed substantially from that of the WWTF effluents. Typically the freshwater end member entering the upstream end of the estuary has little or no NH_4 but does have measurable SRP. Secondly, other sources of SRP within the estuary may exist. However addition of SRP from either regeneration of organic material or desorption from suspended material (Fox, 1991) have been estimated to be relatively small (Ammerman, 1988; Clark et al., 1992) and thus probably do not contribute significantly to decreasing this ratio at low salinities. Thirdly, a sink for dissolved NH_4 may exist in the estuary. Profiles of N_2O commonly have concentrations that are supersaturated with respect to atmospheric equilibrium at low freshwater discharge; thus NH_4 appears to be lost from solution due to nitrification (Deck, 1981). The decrease in the NH_4/SRP ratio at low salinities appears to primarily result from the combination of two distinct processes: (1) fresh water with a very low mean NH_4/SRP ratio compared to that for waste water loading is transported downstream, and (2) NH_4 is lost due to nitrification at low to intermediate salinities in the water column of the estuary.

In addition to trends of nutrient ratios observed as a function of salinity at a given period of time, the observed NH_4/SRP ratio at the Battery during summer months has decreased from approximately 10 in the late 1970s to 6 by the late 1980s (Figure 6). Over the same period of time, the ratio of NH_4/SRP reported for WWTF effluents has remained nearly constant (11 to 12, Table 3).

The mid-salinity maximum observed in an individual NO_2 profile reflects the location of most intense nitrification. Generally, it occurs upstream of the NH_4 maximum. The intensity of nitrification is not strongly dependent on NH_4 loading rates and appears to be inversely related to freshwater discharge (Figure 7).

The concentration of NH_4 at a particular location in the estuary is affected by the nitrification rate, the flushing rate out of the downstream exits, and WWTF loading rate. NH_4 concentrations of samples collected at the Battery should be one of the most representative sites of any location in the lower Hudson for integrated

WWTF effluent loading rates. The relative loading rates of NH_4 as a function of time during the last two decades can be evaluated from concentrations measured at the Battery versus freshwater discharge rate. Transects collected during 1977, 1978, 1981 and 1984 follow a similar discharge-NH_4 concentration relationship suggesting that total WWTF NH_4 discharge rates were similar during these years (Figure 4). A different discharge vs maximum NH_4 concentration relationship is apparent for transects collected during 1982, 1988, and 1989. During these years lower concentrations are observed during periods of similar discharge suggesting that the total WWTF NH_4 discharge rates were lower. During 1985 and 1991, maximum concentrations typical of both periods were observed. These relationships suggest that the total load of NH_4 was high during the late 1970s and mid 1980s and low during the early and late 1980s.

Clark *et al.* (1992) observed a similar time trend of loading for SRP. They found the higher loading observed during the mid-1980s coincided with construction at the Passaic Valley Sewerage Commission facility, the largest point source. However, the decline in NH_4 concentations from the late 1970s to the early 1980s was not apparent in the SRP data. The lowering of NH_4 concentrations in the late 1980s is approximately coincident with completion of a secondary treatment system at the Passiac Valley Sewerage Commission facility and thus may reflect this change.

The decline of NH_4/SRP ratios in the water adjacent to the Battery since the late 1970s suggests that the N-dynamics in the Hudson estuary have evolved appreciably during the past two decades. However, at this time we cannot offer conclusive explanations as to why they may be happening.

Conclusions

Profiles of NH_4 as a function of salinity along the axis of the Hudson estuary primarily reflect external WWTF loading rates and freshwater discharge rates, with appreciable conversion of NH_4 to more oxidized species of N at lower salinities during low flow conditions. Although a large fraction of the WWTF NH_4 is advected from the estuary, a significant portion is mixed upstream with the salt. There some of the NH_4 is oxidized, creating a mid-salinity source of NO_2 and N_2O. During the last two decades, changes in the total NH_4 loading rate appear to correlate with reported changes in treatment practices at the Passiac Valley Sewerage Commission, but not to published estimates of total nutrient loading rates from the waste water treatment facilities. The NH_4/SRP ratio in the zone of maximum dissolved nutrient concentrations has decreased by 40% over the same period. One of our most important observations is that the temporal decrease in NH_4 concentrations and NH_4/SRP ratio measured in the lower Hudson estuary would not have been predicted from the reported trends in WWTF loading rates. The cause of the substantial decrease in concentrations in the lower Hudson estuary during low flow summer conditions by the late 1980s, compared to the 1970s remains to be established.

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Table 1: Waste water treatment facilities discharge rates into the Hudson estuary[1]. (Data from Hammond, 1975; Mueller *et al*, 1976; Mueller *et al*, 1982, Dujardin *et al*, 1991; Clark *et al*, 1992)

WWFT	Treatment Level[2]	Discharge (m^3/s)		NH_4 (mole/s)		Org-N (mole/s)		Total-N (mole/s)		SPR (mole/s)		
		1979	1989	1979	1989	1979	1989	1979	1989	1970	1979	1989
Box 1 (2 WWTF)	sec	0.3	0.3	*0.17*	0.14	*0.17*	0.16	*0.43*	0.15	0.09	(0.02)[6]	0.102
Box 3 (3 WWTF)	sec,pri	0.2	0.3	*0.17*	0.16	*0.17*	0.18	*0.43*	0.18	0.04	(0.02)	0.006
Box 4 (3 WWTF)	sec	0.3	0.5	*0.18*	0.26	*0.18*	0.28	*0.45*	0.31	0.09	(0.02)	0.030
Box 6 (2 WWTF)	sec	1.0	1.1	*0.56*	0.56	*0.56*	0.64	*1.40*	0.68	0.09	(0.06)	0.190
Yonkers	sec	3.4	4.9	2.67	2.47	1.99	2.84	5.36	3.01	0.24	0.237	0.280
Edgewater	sec	0.1	0.1	*0.12*	0.08	*0.12*	0.07	*0.30*	0.07	0.02	(0.01)	0.006
North River	pri[4]	7.7	7.8	*5.85*	3.55	*5.69*	5.56	*12.0*	5.08	0.35	0.308	0.409
N. Bergen	pri	0.1	0.1	*0.10*	0.17	*0.10*	0.09	*0.25*	0.12	0.01	(0.01)	0.024
West New York	pri	0.4	0.2	*0.35*	0.36	*0.35*	0.19	*0.88*	0.29	0.05	(0.04)	0.054
Hoboken	pri	0.7	0.6	*0.61*	0.89	*0.61*	0.48	*1.53*	0.71	0.02	(0.06)	0.137
East River	sec	21.9	21.9	11.1	9.00	12.3	14.5	24.9	14.0	1.20	0.701	0.655
Red Hook	sec	2.0	2.0	*1.52*	1.02	*1.48*	1.18	*3.10*	1.26	0.12	0.080	0.069
Jersey City East[3]		1.5		0.57		0.57		1.15		0.06	0.044	
Passaic Valley	sec[5]	11.0	11.8	12.4	13.9	*12.4*	4.66	*31.0*	9.97	3.0	1.249	1.108
Kill Van Kull	sec,pri	3.7	6.3	*2.22*	5.3	*2.22*	3.76	*5.55*	5.87	0.37	(0.22)	0.383
Owl's Head	sec	4.3	5.2	3.56	2.93	2.92	3.50	6.49	2.90	0.35	0.347	0.254
Total		58.6	63.1	42.2	40.8	41.8	38.1	95.3	44.6	6.1	3.43	3.62

[1] Entries in italics estimated from waste water discharge rates: NH_4 concentrations assumed to be 0.75 mmole/l, 0.90 mmole/l, and 0.55 mmole/l for raw, primary, and secondary treated effluent; Org-N and TDN concentrations assumed to equal NH_4 and $NH_4/0.4$ concentrations, respectively.

[2] Treatment level in 1989.

[3] Waste water diverted to the Passaic Valley Sewerage Commission in 1988.

[4] Treatment level was raw in 1979.

[5] Treatment level was primary in 1979.

[6] Parentheses indicate that flux of SRP estimated from flux of NH_4, assuming a ratio of 1:10 (moles/s)

Table 2A Freshwater discharge rate and nutrient data for zone of maximum nutrient concentrations in New York Harbor (mile points 0 to 8)

	Battery Discharge	Salinity		PO4		NH4		NO3		NO2		NH4/PO4		mean (N:P)	Max NO2
		Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot		
18-Mar-77	2553	4.4	16.6	1.54	1.28	25.1	24.6	82.0	98.0	0.58	0.97	16.3	19.2	17.6	
26-Apr-77	1343	3.4	25.2	1.18	1.41	9.3	9.7	44.9	12.0	1.00	0.80	7.9	6.9	7.3	
11-Jun-77	375	10.8	23.3	2.59	2.59	26.7	34.0	24.2	10.4	2.00	2.30	10.3	12.2	11.3	2.50
21-Jul-77	225	23.9	26.4	4.78	4.78	36.8	20.0	8.3	8.0	0.94	1.83	7.7	5.6	6.8	4.20
10-Aug-77	193	15.7	26.6	3.71	4.71	27.4	44.8	13.7	14.5	1.77	3.01	7.4	9.5	8.6	3.80
25-Aug-77	183	18.2	23.9	5.28	5.00	48.0	42.1	23.0	12.8	4.43	1.03	9.1	8.4	8.8	4.45
23-Mar-78	968	12.3	21.8	0.86	1.34	22.6	17.4	45.9	24.2	0.86	0.75	26.3	13.0	18.2	0.90
21-Apr-78	1312	11.6	19.7	1.24	1.24	15.7	15.1	32.5	23.4	0.79	0.90	12.7	12.7	13.4	0.90
12-May-78	781	9.9	23.3	1.56	1.00	18.3	18.6	35.3	17.9	2.14	1.50	11.7	18.6	14.4	2.38
8-Jun-78	643	16.0	24.4	1.82	1.62	19.7	18.5	19.4	19.4	1.77	1.47	10.8	11.4	11.1	2.04
4-Aug-78	185	19.3	25.6	3.30	3.31	38.5	35.1	18.9	10.3	2.79	2.35	11.7	10.6	11.1	2.81
8-Sep-78	162	22.8	26.3	3.73	3.44	35.4	18.1	16.9	8.0	4.34	2.70	9.5	5.3	7.5	4.71
1-Sep-81	160	21.9	21.9	4.84	4.73	33.9	33.9			5.97	5.51	7.0	7.7	7.4	13.30
14-Sep-82	156	20.5	24.9	2.60	3.10	21.5	21.5			3.52	3.22	8.3	7.3	7.8	3.74
22-Jun-84	466	7.2	21.0	1.83	2.28	9.3	24.4	27.4	13.4	1.22	2.21	5.1	10.7	8.2	2.21
13-Jul-84	702	12.1	24.3	2.68	1.89	20.1	12.5	24.1	7.5	1.99	1.23	7.5	6.6	7.1	2.41
15-Aug-84	279	20.5	24.0	3.75	3.36	30.1	30.1	20.2	11.4	4.04	2.62	8.0	7.3	7.7	4.04
23-Aug-88	176	14.7	24.3	3.28	3.62	9.1	18.5	15.1	13.0	2.62	2.50	2.8	5.1	4.0	8.20
7-Oct-88	196	17.2	25.4	3.75	3.80	21.5	19.1	25.5	17.8	4.15	3.45	5.7	5.7	5.4	4.47
1-Sep-89	76	16.9	25.1	3.62	3.26	19.1	19.8			2.81	2.27	5.3	6.1	5.7	3.91
21-Jun-91	224	15.9	24.4	3.09	3.55	17.8	17.8			2.36	2.81	5.8	6.6	6.2	3.02
31-Jul-91	132	25.5	27.3	4.09	3.51	29.2	25.2	14.0	10.0	3.29	2.59	7.1	7.2	7.2	7.41
14-Sep-91	156	21.2	26.4	4.23	3.93	23.5	26.6	19.7	16.1	5.52	3.74	5.6	6.8	6.1	6.06
2-Oct-91	141	20.7	25.1	4.80	4.53	39.2	34.0			6.24	4.57	8.2	7.5	7.8	9.01

Table 2B: Freshwater discharge rate and highest individual sample nutrient concentration observed during each transect.

	Discharge[1] (m^3/s)	SRP[2] (μmole/l)	NH_4[2] (μmole/l)	NH_4/SRP[2]	NO_2[3] (μmole/l)
Mar. 17-18, 1977	2553	1.5	25.1	16.3	1.0
April 6-8, 1977	1343	1.4	9.7	6.9	1.0
June 11-12, 1977	375	2.8	34.0	12.2	2.5
July 14-21, 1977	225	4.8	36.8	7.7	4.2
Aug. 10, 1977	193	4.7	44.8	9.5	3.8
Aug. 25, 1977	183	5.3	48.0	9.1	4.5
Mar. 23, 1978	968	1.3	22.6	16.9	0.9
April 21, 1978	1312	1.2	15.7	12.7	0.9
May 9-12, 1978	781	1.6	18.6	11.9	2.4
June 7-8, 1978	643	1.8	19.7	10.8	2.0
Aug. 2-4, 1978	185	3.3	38.5	11.6	2.8
Sept. 8, 1978	162	3.7	35.4	9.5	4.7
Aug. 26-Sept. 13, 1981	160	4.8	36.5	7.5	13.3
Sept. 13-15, 1982	156	3.1	22.7	7.3	3.7
June 21-22, 1984	466	2.3	24.4	10.7	2.2
July 10-13, 1984	702	2.7	20.1	7.5	2.4
Aug. 14-15, 1984	279	3.8	30.1	8.0	4.0
July 2-31, 1985[4]	223	3.9	21.1	5.4	8.2
Aug. 8-30, 1985[4]	184	5.0	32.5	6.5	4.5
Aug. 23-26, 1988	176	3.6	18.5	5.1	2.2
Oct. 7, 1988	196	3.8	21.5	5.7	3.0
Aug. 29-Sept. 8, 1989	76	3.6	19.8	5.5	7.4
June 21-23, 1991	224	3.6	23.3	6.6	6.1
July 31-Aug. 2, 1991	132	4.1	29.2	7.1	9.0
Sept. 14, 1991	156	3.9	26.6	6.8	6.1
Oct. 2-4, 1991	141	4.5	34.0	7.6	9.0

[1] Calculated flow at the Battery.

[2] Maximum concentration and ratio observed at the Battery (mp 0).

[3] Maximum concentration observed in the saline estuary.

[4] Maximum concentration and ratio observed at mp -3.

Table 3 Summary of nutrient loading rates to Hudson estuary (mp 64 to -8): moles per second

Time period	Discharge (m^3/s)	SPR (m/s)	NH4 (m/s)	Org-N (m/s)	NH4/SRP
Early 70's[1]	64	6.1	41		6.7
Late 70's[2]	58.6	3.43	42.2		12.3
Late 80's[3]	63.1	3.62	40.8	38.1	11.3

[1] Hammond, 1975; Mueller *et al.*, 1976; Clark *et al.*, 1992
[2] Mueller *et al.,* 1982
[3] Dujardin *et al.*, 1991

Figure Captions

1 Hudson estuary location map

2 Replacement times for fresh water in the Hudson estuary as a function of discharge of fresh water (excluding waste waters) into the system; the y-axis of the upper figure is linear in time, while in the lower figure the y-axis is given in units of reciprocal time.

3 Dissolved ammonia vs salinity in the Hudson estuary during high fresh water discharge (March 1977) and low riverine discharge (August 1977)

4 Maximum dissolved ammonia in the Hudson at the Battery as a function of fresh water discharge rate: see text for detailed explantion of symbols, filled circles are generally from after the mid 1980s and open circles from prior to 1985.

5 Dissolved nitrate vs salinity in the Hudson estuary (August 1977): open circles were surface samples and filled circles were deep samples.

6 Ammonia to soluble reactive phosphate ratios at the Battery as a function of year of collection

7 Maximum nitrous oxide concentrations in the Hudson estuary as a function of freshwater discharge rate: open and filled circle conventions were the same as in figure 4

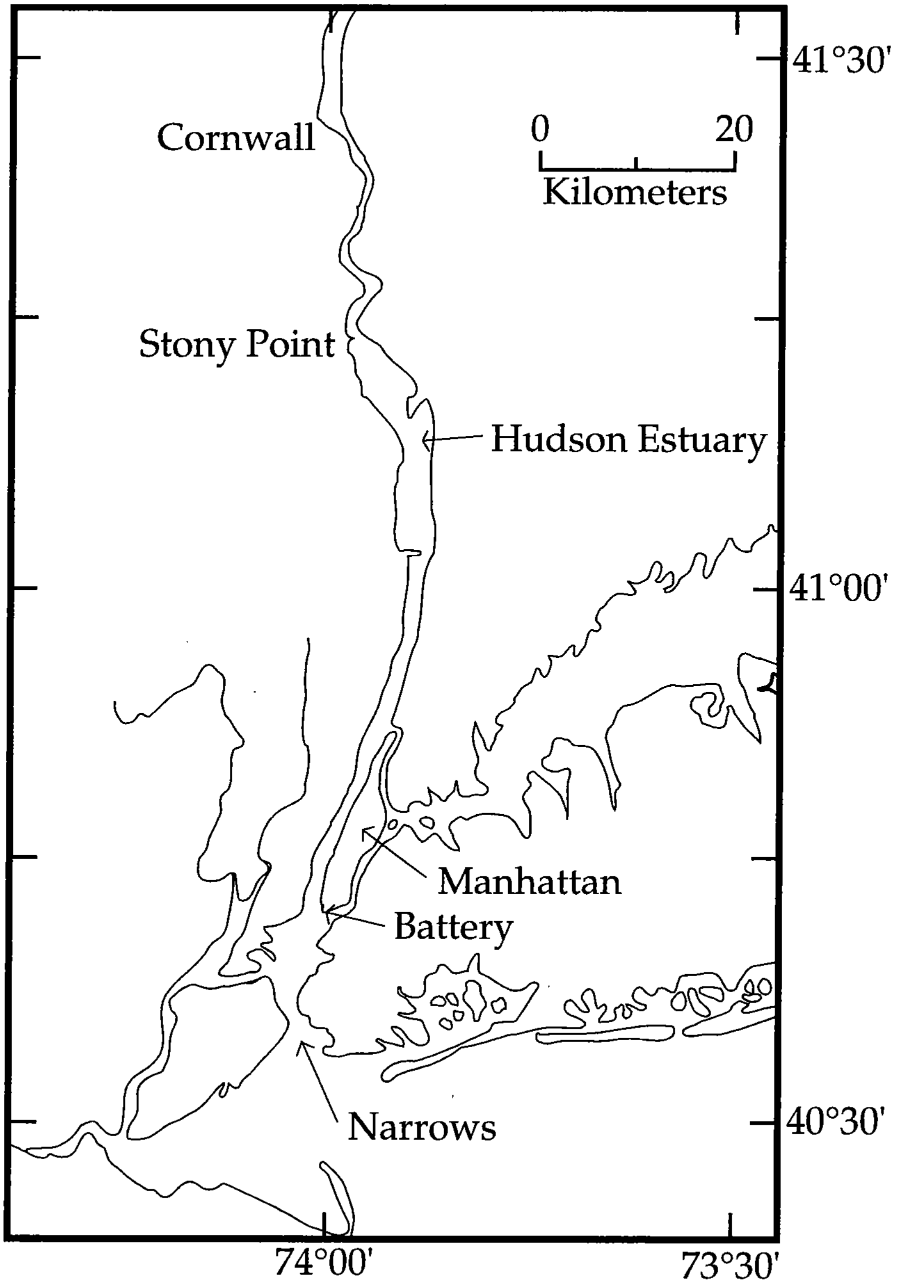
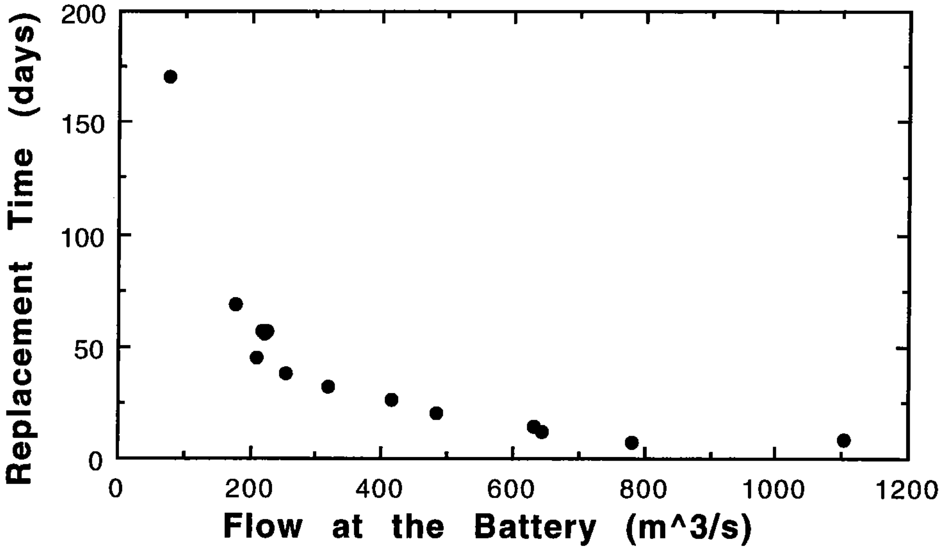

41°30'
Cornwall
0
20
Kilometers
Stony Point
Hudson Estuary
41°00'
Manhattan
Battery
Narrows
40°30'
74°00'
73°30'

Fig 1


Replacement Time (days)
200
150
100
50
0
0
200
400
600
800
1000
1200
Flow at the Battery (m^3/s)

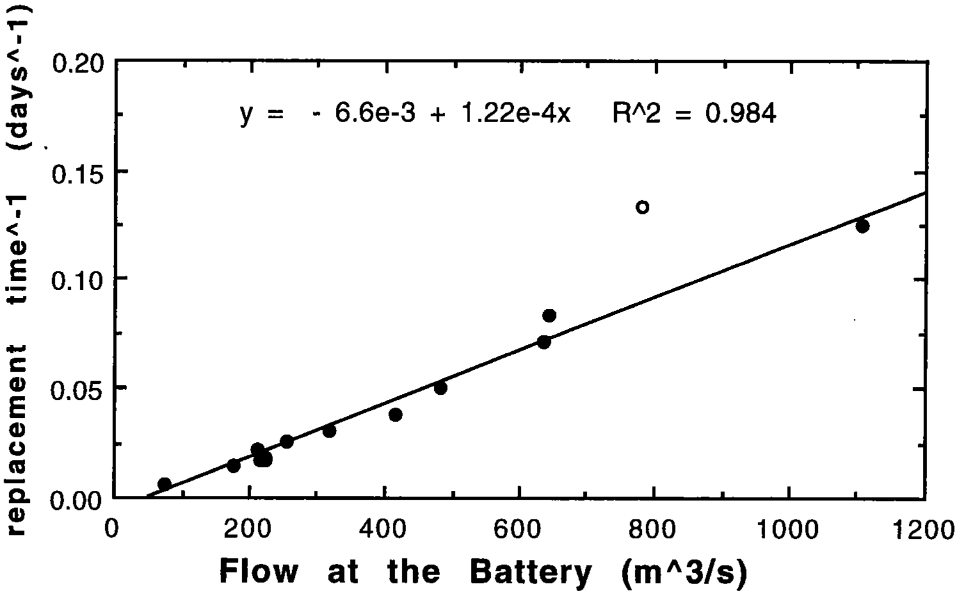

replacement time^-1 (days^-1)
0.20
0.15
0.10
0.05
0.00
y = - 6.6e-3 + 1.22e-4x R^2 = 0.984
0
200
400
600
800
1000
1200
Flow at the Battery (m^3/s)

Fig 2

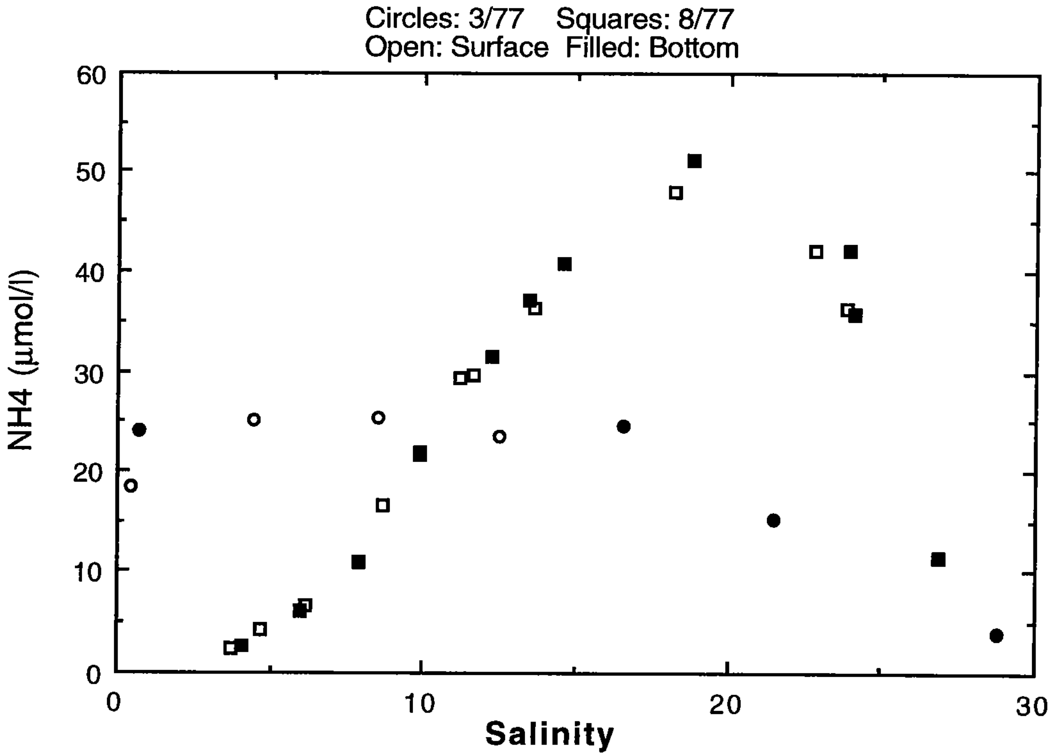

Circles: 3/77 Squares: 8/77
Open: Surface Filled: Bottom
NH4 (µmol/l)
60
50
40
30
20
10
0
0
10
20
30
Salinity

Fig 3

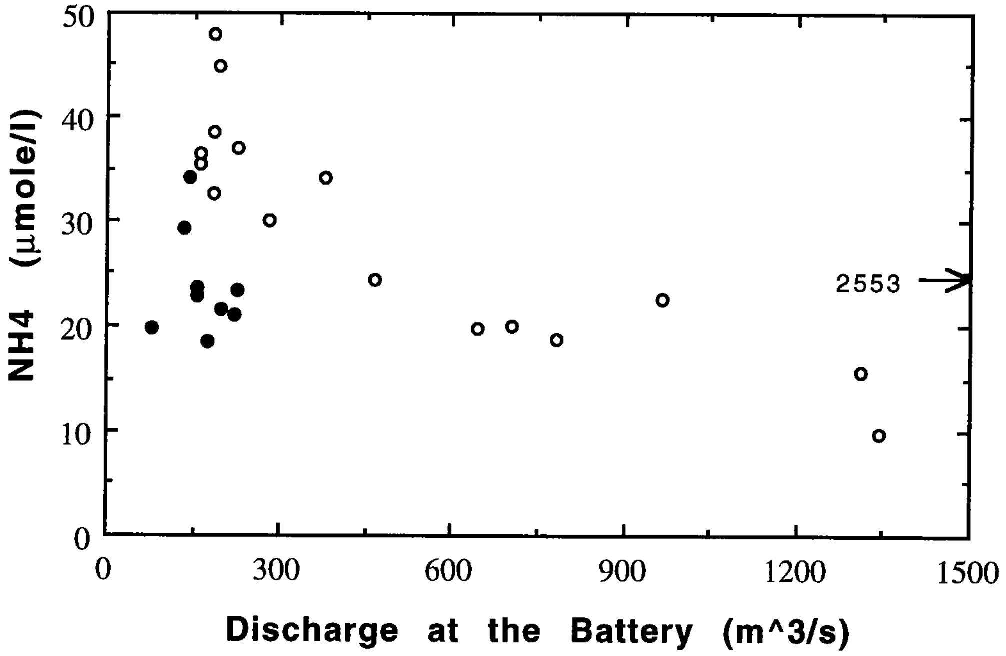
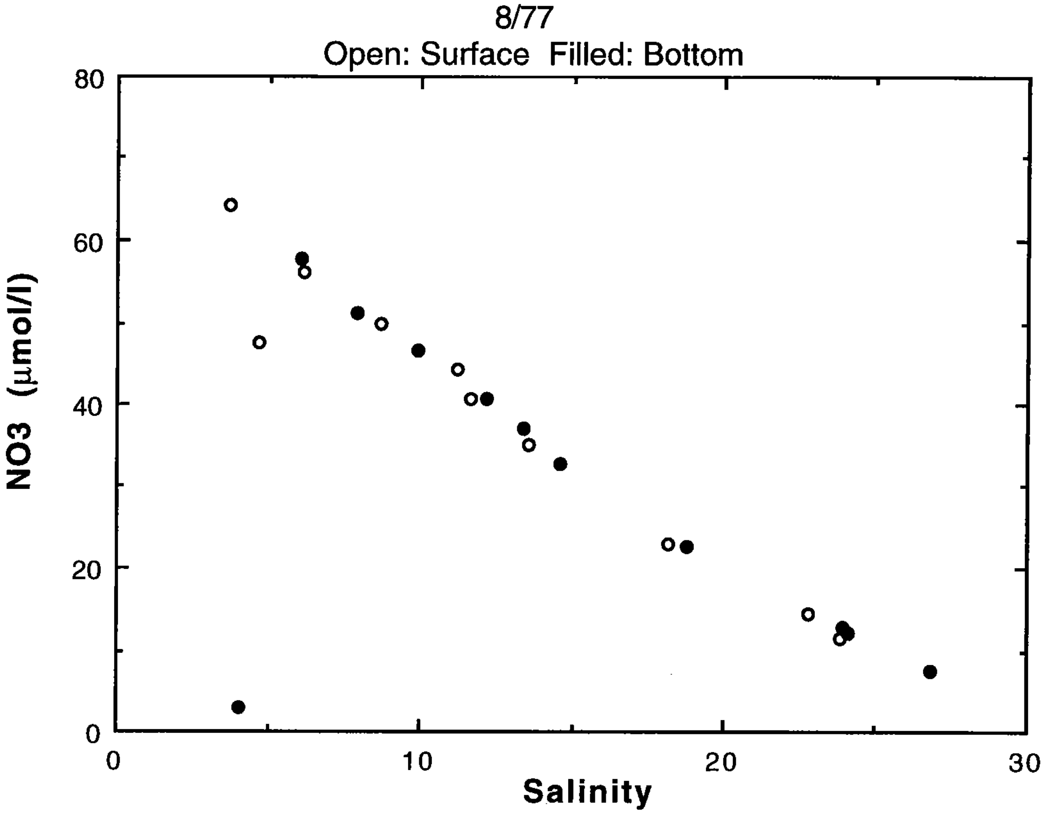

NH4 (µmole/l)
50
40
30
20
10
0
2553
0
300
600
900
1200
1500
Discharge at the Battery (m^3/s)

Fig 4



8/77
Open: Surface Filled: Bottom

Fig 5

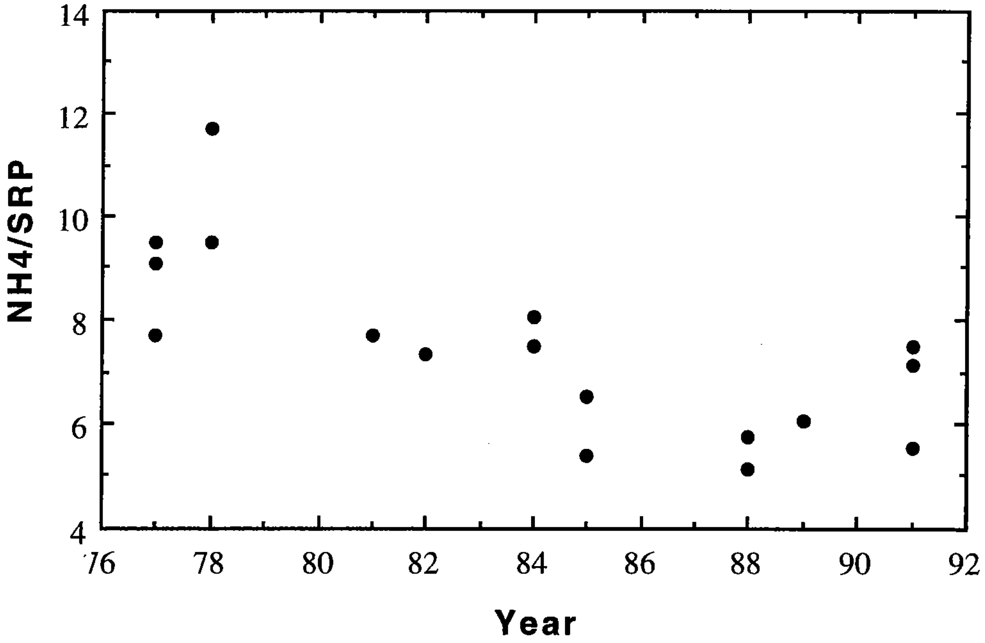

14
12
10
8
6
4
NH4/SRP
76
78
80
82
84
86
88
90
92
Year

Fig 6

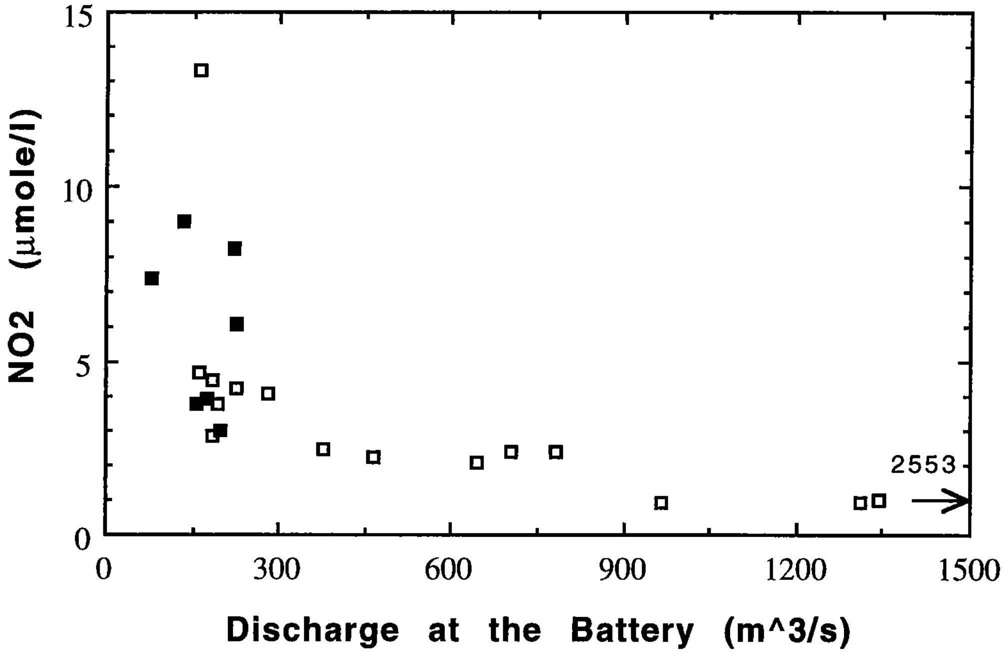

15
10
5
0
NO2 (μmole/l)
2553
0
300
600
900
1200
1500
Discharge at the Battery (m^3/s)

Fig 7