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Variability and transport of suspended sediment, particulate and dissolved organic carbon in the tidal freshwater Hudson River

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Abstract. Measurements of suspended matter, particulate organic carbon and dissolved organic carbon were made over a three year period at stations spanning ~ 150 km of the tidal freshwater Hudson River. Suspended matter concentrations varied from year-to-year and were not related to freshwater discharge. The increase in suspended matter with depth in vertical profiles suggests that, during medium to low flow conditions, resuspension of bottom sediments was as important a source of sediment as loadings from tributaries. Particulate organic carbon showed significant variability among stations, and both autochthonous primary production and detrital organic matter are contributing to POC standing stocks. Dissolved organic carbon represented over half of the total organic carbon in the water column and showed little variation among stations.

Examining downstream changes in transport showed that there was significant production of both suspended matter and POC within the study reach during the ice-free season. Tributary loadings within the study reach do not appear to be the cause of these increases in downstream transport. Dissolved organic carbon behaved conservatively in that there was no evidence for net production or net consumption within the river.

The spatial/temporal patterns and analyses of transport suggest that suspended matter and POC, but not DOC, were controlled to a significant extent by processes occurring within the river and were not simply related to loadings from outside.

Introduction

High concentrations of suspended inorganic and organic particles are a persistent feature of many large rivers and the upper reaches of most estuaries (Postma 1967; Schubel & Carter 1984; Smith et al. 1987). Fluctuations in suspended matter influence several important biological and chemical processes in these systems. Phytoplankton biomass can be predicted from light extinction (Wofsy 1983) and primary production can be modelled knowing phytoplankton biomass, light penetration and depth of mixing (Cole & Cloern 1984, 1987), indicating that light rather than

nutrients limit phytoplankton growth in these systems. In the Hudson estuary, primary production is strongly light-limited (Cole et al., in press), so seasonal or spatial vaiations in suspended sediment will control rates of primary production. Filter-feeding organisms can also be inhibited by high concentrations of suspended matter (Threlkeld 1986; Koenings et al. 1990). Filter-feeders must expend energy rejecting non-nutritive particles or cease feeding under conditions of high turbidity. The organic component of suspended matter may be an important food resource for estuarine or nearshore animals. For instance, it has been shown that suspended sediments can stimulate heterotrophic activity in shallow coastal waters (Wainwright 1987) and some filter-feeders can survive on suspended detrital particulate organic carbon (Stuart et al. 1982).

Chemical processes in the water column are affected by adsorption/desorption reactions with particles. The partitioning between dissolved and particulate phases influences the availability of nutrients and can change the probability of export from the system. In particular, phosphorous sorption to suspended matter may either increase the loss of P to permanent burial (Caraco 1986) or act as a reservoir of P which may be available to water column organisms (Fox et al. 1986). Resuspension or deposition of particles influences sediment geochemistry by altering pore water gradients and transporting particles to environments of differing redox conditions and/or solute concentrations.

Many pollutants are associated with benthic or suspended sediments (Olsen et al. 1984; Williams et al. 1978), so modelling the transport of these pollutants requires knowledge of suspended matter distributions (Uncles et al. 1986). In the case of the Hudson, upstream deposits of PCB-contaminated sediments are transported downriver as suspended matter (Limburg et al. 1985). Moreover, effects of toxic compounds on planktonic organisms are strongly affected by the supply and removal of suspended particulate matter from the water column.

Dissolved organic matter is a major component of material budgets for large rivers (Lewis & Saunders 1989) and also represents an important component of total material transport (Schlesinger & Melack 1981; Meybeck 1982; Moeller et al. 1979). Additionally, dissolved organic carbon (DOC) can be a significant growth substrate supporting bacterial growth in river water (Meyer et al. 1987) and therefore may be important in supporting higher trophic levels. Adsorption of inorganic and/or organic pollutants to certain components of DOC may change their transport or bioavailability (e.g. Wershaw et al. 1969).

Large rivers are clearly important in supplying materials to the world's oceans. However, the significance of transformations occurring within the river during transport have not been considered in detail. Such transfor-

mations will influence the nature of materials delivered to the oceans and thereby influence the effect of river inputs on coastal or land-margin ecosystems. In this paper, we address the question of the relative importance of external loadings versus autochthonous processes (internal transformations) in governing distributions and fluxes of suspended matter, particulate and dissolved organic carbon in the Hudson River estuary.

Methods

Site description

This study focussed on the tidal freshwater portion of the Hudson River Estuary, ranging from Haverstraw Bay in the south (river kilometer (RKM) 65) to Castleton in the north (RKM 228, Fig. 1). The salt front (0.1 g Cl/L) extends as far as RKM 150 during exceptionally low discharge periods (Cooper et al. 1988). The study reach is north of the turbidity maximum zone as reported by Coch and Bokuniewicz (1986).

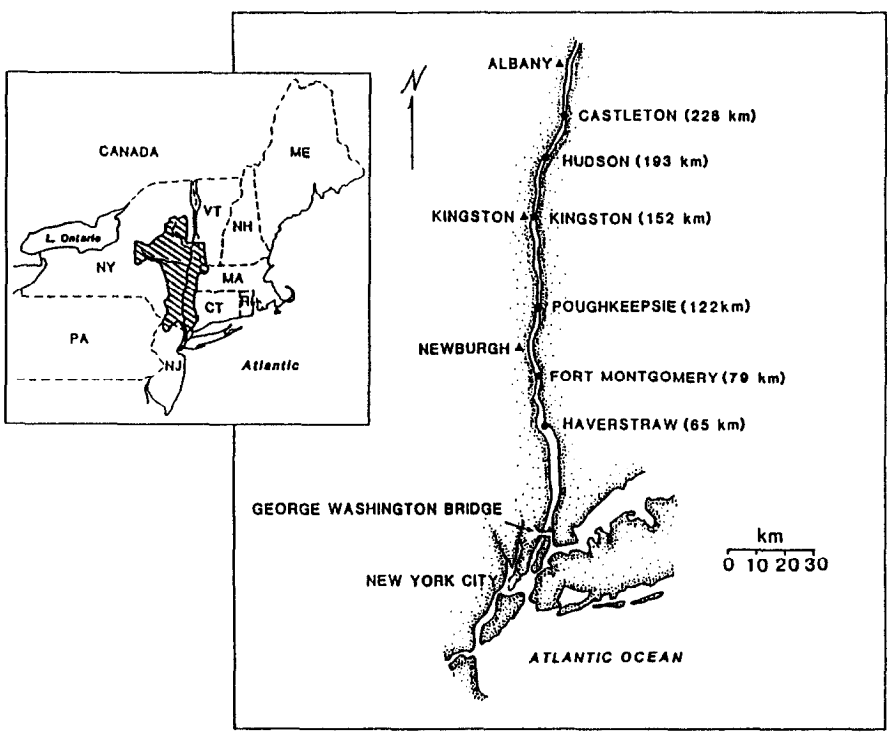


Fig. 1 Map showing Hudson drainage and sampling locations.

The study reach varies considerably in physiography, including narrow deep sections (mean depth >20m, above Fort Montgomery, Fig. 1) and broad shallow reaches (mean depth 5—10m) at the northern and southern ends (depths derived from Table 8 in Gladden et al. 1988). The tidal range is about 1.1 m over this entire region, and tidal velocities can exceed 1 m/s. Annual average freshwater discharge at the head of the tidal portion is 382 m^3/s (United States Geological Survey (USGS) data 1958—1988) ranging from 180 to 619 m^3/s. All discharge data used in our analyses were obtained from USGS in Albany, NY. Discharge is recorded at Green Island in Troy, NY above the tidal portion of the estuary, but below the confluence with the Mohawk River, the major tributary to the Hudson. Data for water year 1989 are provisional at time of preparation of this paper.

Sample collection and frequency

Sampling effort was divided between frequent (bi-weekly) trips to stations near Kingston and Poughkeepsie, NY and less frequent transects along the north-south axis of the estuary from Haverstraw Bay to Castleton, NY (Fig. 1). Stations along the North-South axial transect were sampled twice in 1987, eight times in 1988, and four times in 1989. All water samples were collected with a peristaltic pump into polypropylene bottles. Three bottles were collected from a given depth. For most trips to the Kingston and Poughkeepsie stations, samples were collected from three depths (0.5, 2.5, 5 m and 0.5, 5, 10 m, respectively). For stations along the transects, collections were made only from 0.5 m depth.

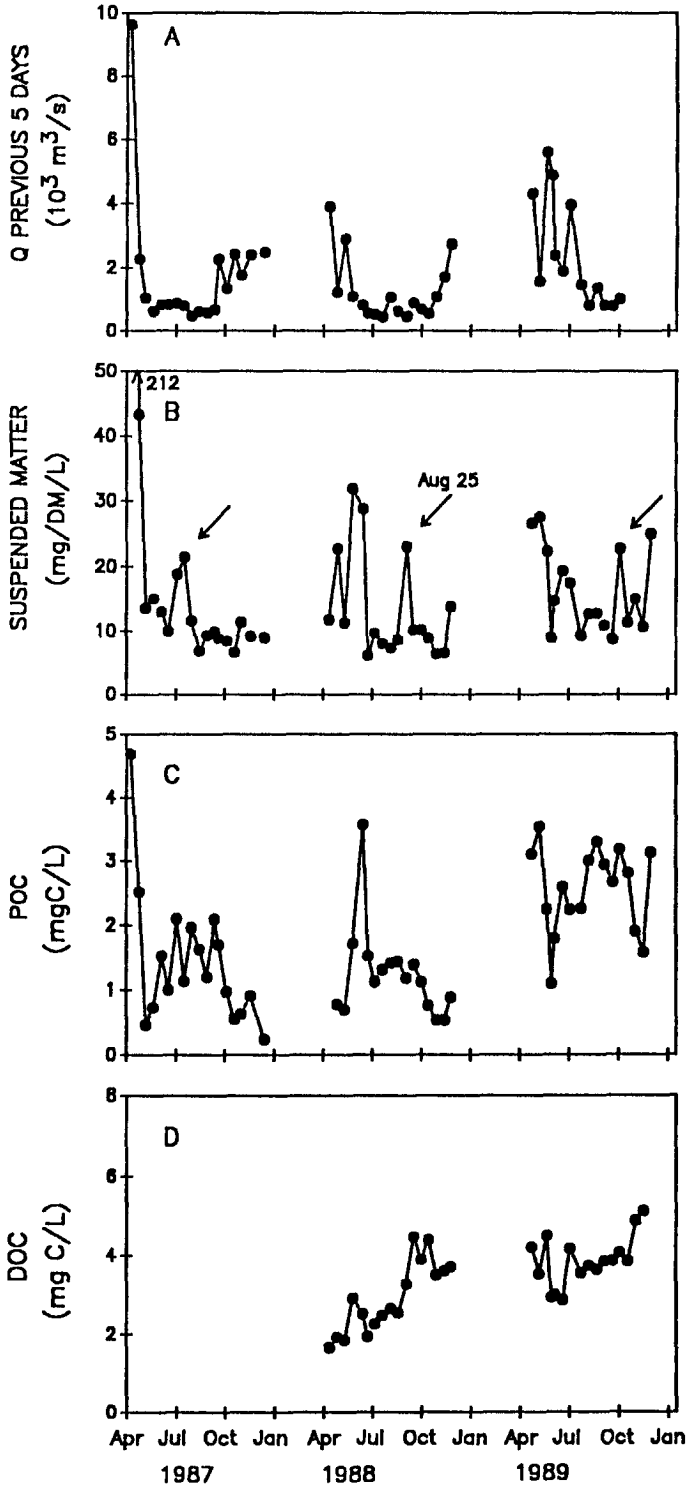
Sample analyses

Upon return to the laboratory, three filters for determination of total suspended matter and particulate organic matter were prepared from each bottle. 100—400 mL were filtered through pre-combusted, weighed glass fiber filters (Whatman 934AH, nominal pore size 1.5 μm). Filters were dried overnight at 70 °C, reweighed to estimate total suspended matter and then combusted at 450 °C for 4 h and weighed again. Organic matter was estimated from the weight loss on ignition; organic carbon was assumed to be 45% of ash-free dry weight (AFDW) (Whittaker & Likens 1973). A subset of our samples was also analyzed for particulate organic carbon (POC) with a Carlo Erba NA1500 Nitrogen/Carbon Analyzer to

determine whether loss of water from clays during ignition was causing overestimates of organic carbon (Dankers and Laane 1983). The relationship between values obtained from the two techniques was highly significant ($p < 10^{-5}$) with a correlation coefficient of 0.74 and no apparent systematic bias. Chlorophyll a was measured on samples collected on Gelman AE glass fiber filters after methanol extraction and grinding. Chlorophyll concentrations were determined on a fluorometer, corrected for phaeopigments and calibrated against Chl a from Sigma Chemical Co., St. Louis, MO, USA. To separate total POC into a living algal component and a detrital carbon component, we assumed a carbon/Chl a ratio of 30 (Parsons et al. 1984) to estimate algal carbon and estimated detrital carbon by difference. This procedure underestimates the importance of detritus because chl a will persist for at least several days in dead algae and several weeks in vascular plant detritus from the Hudson River (Bianchi & Findlay, 1991).

In 1988, dissolved organic carbon (DOC) was determined on settled but unfiltered, preserved water samples. In 1989, DOC was determined on unpreserved filtrates from the same samples used for seston analysis. A cross-calibration of these methods using the same water sample showed values within 5% of each other. However, because of these differences in sample preparation between 1988 and 1989, we do not consider between-year differences in DOC nor do we combine data from the two years. DOC was measured with an ASTRO 2001 TOC Analyzer, using persulfate and UV oxidation at 70°. Possible interference with DOC oxidation by chloride ions was examined by adding known amounts of NaCl to Hudson water and glucose standards such that the range in conductivity was the same as the range in conductivity observed in field samples. Measured DOC concentrations in field samples were corrected for potential interference based on conductivity of each sample.

We examined source/sink relationships for suspended matter, POC and DOC in the estuary. Material fluxes were calculated as concentration (g/m^3) times discharge (m^3/s). The increase in water discharge moving downstream was calculated from the proportional addition of water entering from tributaries (Giese and Barr 1967) upstream of each station. A conservative material will increase or decrease in flux through each cross-section in proportion to changes in water flux through the cross-sections, whereas the flux of nonconservative materials will depart from water flux (Meade et al. 1985). To estimate how materials changed across the entire reach of our study (160 km), we regressed fluxes for water, suspended material, POC, and DOC against distance. Differences between water flux and material flux allowed us to assess whether materials were conserved, produced, or consumed in the estuary.


A
Q PREVIOUS 5 DAYS
(10^3 m^3/s)
B
212
Aug 25
SUSPENDED MATTER
(mg/DM/L)
C
POC
(mgC/L)
D
DOC
(mg C/L)
Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan
1987
1988
1989

Results

Temporal patterns

Seasonal patterns at the station with the best temporal coverage (Kingston, 17—18 observations each year) showed that peak concentrations of total suspended matter were sometimes associated with spring floods (Fig. 2A), but also occurred later in the year (Fig. 2B). Suspended matter concentrations ranged 20-fold, from <10 mg dry weight (DW) per L to 212 mg DW/L. There was no significant difference in suspended matter concentration among years (analysis of variance (ANOVA), $p = 0.5$). The annual average suspended sediment concentration in the Hudson (16.9 mg/L) was close to the 25th percentile (18.4 mg/L) for rivers of the United States (Smith et al. 1987).

To examine short-term fluctuations in suspended matter, we occupied a site near Kingston over a low-high-low tidal cycle on two dates in 1987. Near-surface current velocity (Fig. 3A, C) and suspended matter (Fig. 3B, D) were measured every half hour. There was relatively little variation in suspended matter on both dates (Fig. 3), and concentrations were not related to either the absolute magnitude of velocity or the rate of change of velocity. In October, a small boat followed a drogue deployed at time zero such that a water mass could be repeatedly sampled as it was advected upriver. Neither the stationary boat nor the drogue boat detected significant fluctuations in suspended matter over this particular tidal cycle. The meteorological conditions during both these tidal studies were not such that we would have predicted resuspension to occur.

Particulate organic matter showed maximum values in either the spring or during mid- to late summer in all three years (Fig. 2C). There were significant differences in POC concentration among years (ANOVA, $p < 0.001$), with 1989 having higher concentrations (2.55 mg C/L) than 1987 (1.45 mg C/L) or 1988 (1.20 mg C/L). Detrital material was always a significant component of POC, with an average contribution of 63.3% (± 23.4 standard deviation (SD) $n = 57$) ranging from 50 to 80% of total POC (Table 1). The contribution of detrital POC was highest at the northern and southern extremes of our sampling region.

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Fig. 2 Concentrations of total suspended matter (*B*), particulate organic carbon (*C*) and dissolved organic carbon (*D*) in surface water of the Kingston station over the period 1987 to 1989. Arrows in (B) indicate times of high suspended matter concentration that do not correspond to periods of high discharge.

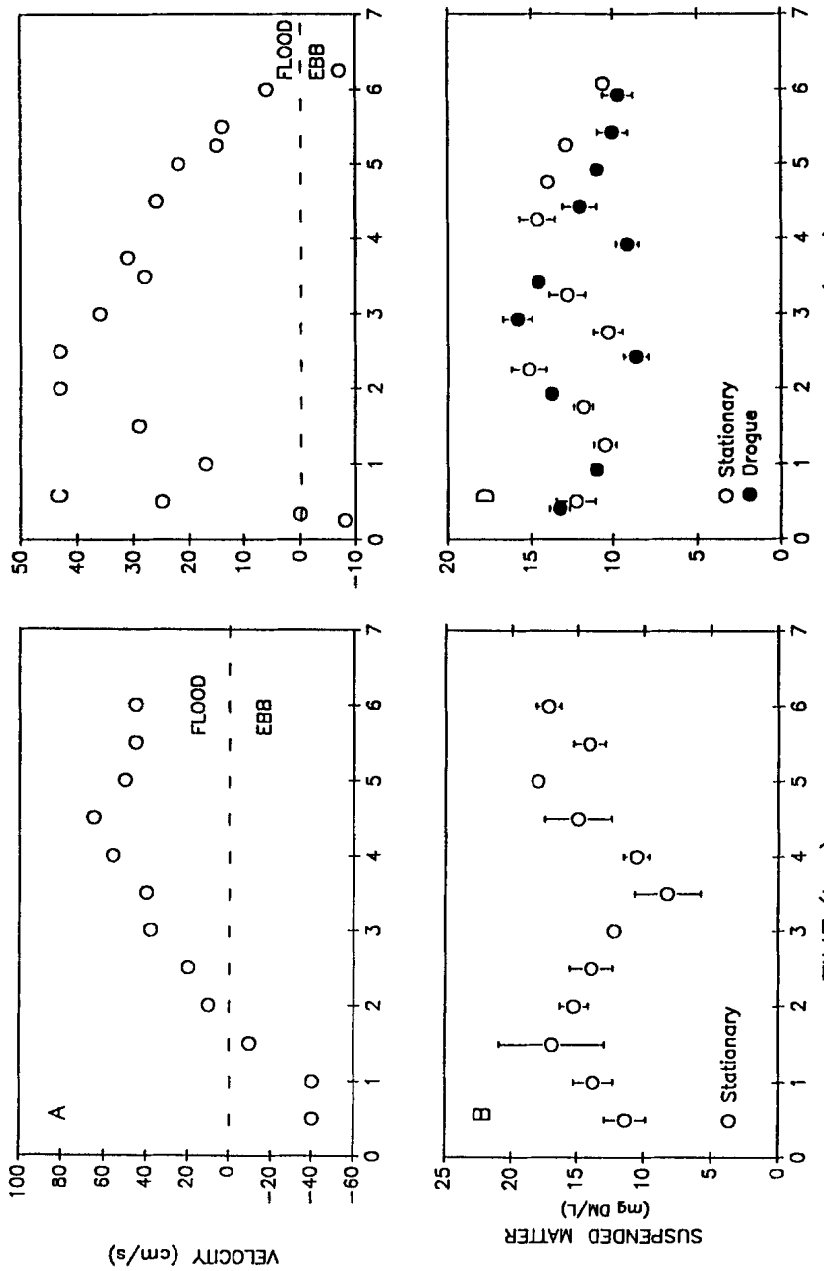

Fig. 3 Variation in current velocity (*A*, *C*) and suspended matter (*B*, *D*) (mean ± SD, $n = 3$) in surface waters near Kingston in June and October 1987. In both June and October, samples were collected from a stationary boat; in October, a drogue was released at time = 0 so that a water mass could be sampled as it was advected upriver.

Table 1. Proportion of detrital particulate organic carbon in Hudson estuary POC. Values are means of all observations in 1988.

Station	1	2	3	4	5	6
River Km	228	193	152	122	79	65
Detrital POC (%)	75.6	49.3	50.2	64.8	79.6	74.9

Addition of NaCl to samples singificantly reduced the apparent DOC concentraction in Hudson water samples, but had only a slight effect on DOC recovered from glucose standards (Fig. 4). Field data for DOC were corrected based on the conductivity measured at the time of water sampling. Dissolved organic carbon concentrations showed gradual but significant (regression analysis, $p < 0.05$) increases during the course of 1988 and 1989 (Fig. 2D).

Vertical patterns

Vertical variations in total suspended matter and particulate organic

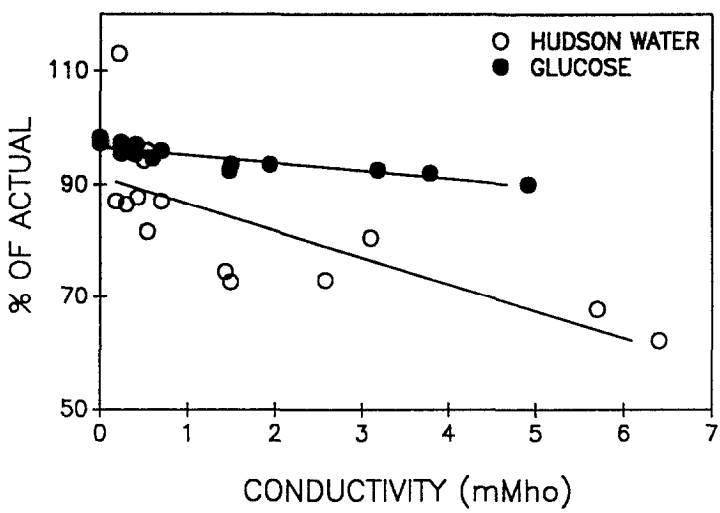

Fig. 4 Effect of NaCl (conductivity) on recovery of DOC from glucose standards and a known sample of Hudson River water from Kingston.

matter were examined by first normalizing the concentrations in a particular profile to the maximum concentration observed in that profile on that sampling date. This procedure removes the confounding effect of seasonal variation in absolute concentrations of material. Normalized vertical profiles at both Kingston and Poughkeepsie showed significantly higher concentrations of both total dry mass and POC at depth (ANOVA, $p \ll 0.05$ for all cases, Fig. 5). For Kingston, the shallower station, concentrations increase steadily with depth, and concentrations of total suspended matter and POC at 5 m were 50—100% greater than surface values. At Poughkeepsie, the deeper station, surface and mid-water concentrations were similar, while concentrations at 10 m were 10—20% greater than surface values (Fig. 5).

The vertical profile coinciding with the August 1988 peak in suspended matter (Fig. 2B) seen at Kingston, show very high near-bottom concentrations of suspended matter on this date (Fig. 6). Profiles before and after this particular date showed much lower concentrations and near homogeneity with depth (Fig. 6).

Spatial patterns

Total suspended matter did not vary among stations (ANOVA, $p = 0.5$, Fig. 7A). There was no consistent location for the maximum in suspended matter concentrations for the eight transects sampled in 1988 (data not shown). If the turbidity maximum (reported to occur between RKM 40 and 80, Coch and Bokuniewicz 1986) were migrating into our study reach, we would have expected to see the location of highest suspended matter concentration move progressively northward as freshwater input decreased from spring to fall. Our detailed time series (Fig. 2B—2D) was collected at RKM 147, so it seems unlikely that either intrusion of the turbidity maximum or "diffusion" (*sensu* Postma 1967) was responsible for the high suspended matter events.

POC was significantly ($p = 0.005$) different among stations, with highest concentrations of particulate organic carbon at Haverstraw Bay (Fig. 7B). DOC was not significantly different among stations (Fig. 7C). Apparent concentrations decreased from North to South, but correcting these DOC values for chloride inhibition removed the trend. Samples for DOC collected on one occasion from the upper (non-tidal) Hudson and the Mohawk River (the major tributary to the Hudson) showed concentrations between 4.5 and 5.0 mg C/L, while concentrations in the northern

reaches of the tidal Hudson were 5.6 to 6.1 mg C/L. Apparently, at least in this one instance, upstream supply of DOC is not the only factor influencing concentrations observed in the tidal freshwater Hudson.

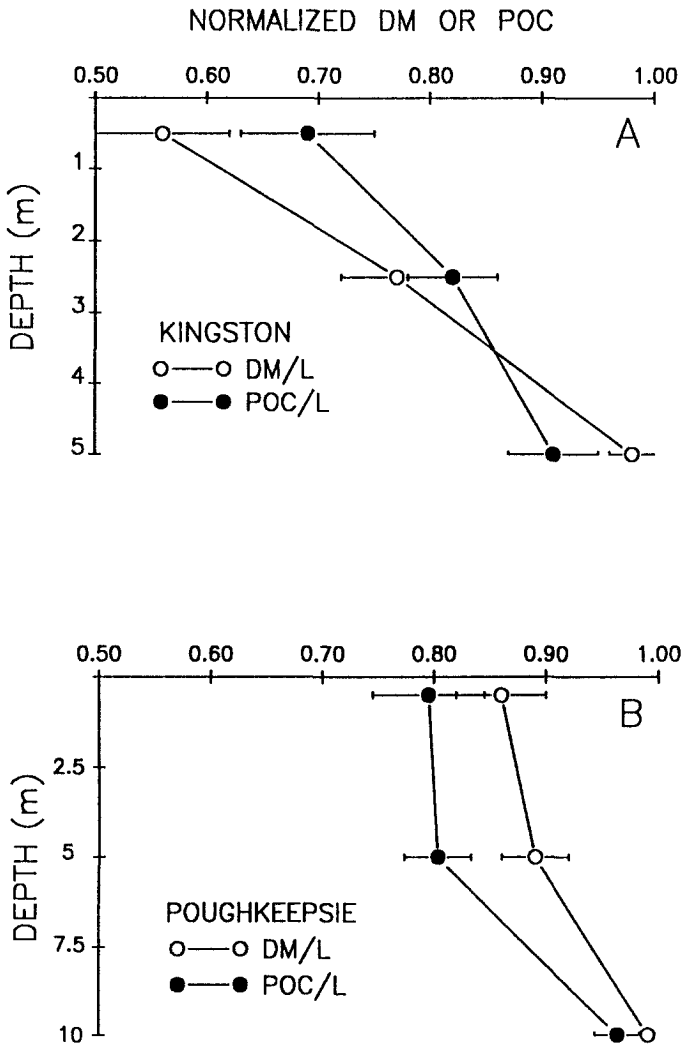

Fig. 5 Vertical distribution of suspended matter and POC at two stations. Data have been normalized to the maximum concentration in a particular profile (see text). Error bars are 1 SE.

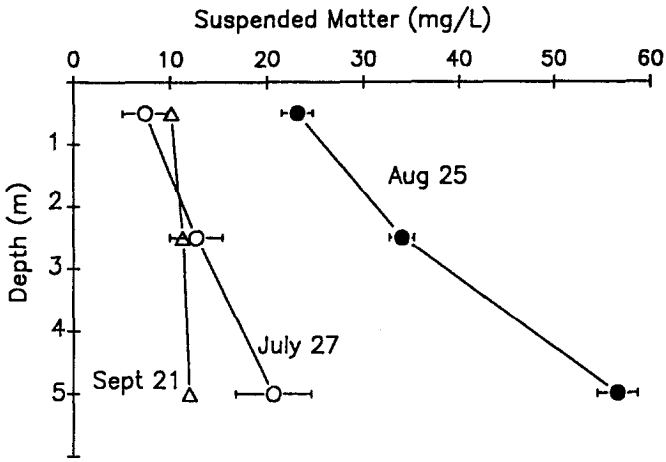

Fig. 6 Vertical profiles of suspended matter (mean ± SD, n = 3) before, coincident with, and after the peak in suspended matter observed on August 25, 1988 (see Fig. 2B).

Relationships with discharge

Suspended matter at the Kingston station was related to discharge ($p < 0.05$) (Fig. 8A) only if the observation from Apri l7, 1987 was included. Removal of this datum resulted in a non-significant relationship ($p = 0.24$) explaining only 3% of the variability in suspended matter. The same result was obtained for the relationship between POC and discharge (Fig. 8B, all points, $p = 0.04$, without April 1987, $p = 0.95$). Considering each year separately showed non-significant relationships in 1988 and 1989 for both suspended matter and POC. As expected, 1987 was only significant if the April 7th observation was included. Apparently, much of the variation in suspended matter and POC observed in the ice-free season was not simply due to inputs to the river associated with high runoff periods. For example, in Fig. 2B, we indicate high-suspended matter concentrations that do not correspond to high-discharge events. Dissolved organic carbon showed no significant relationship with discharge (Fig. 8C) using data from 1988 and 1989 either together or separately. No data were available from 1987.

Discussion

Estimating the total flux of materials from the land surface to the oceans

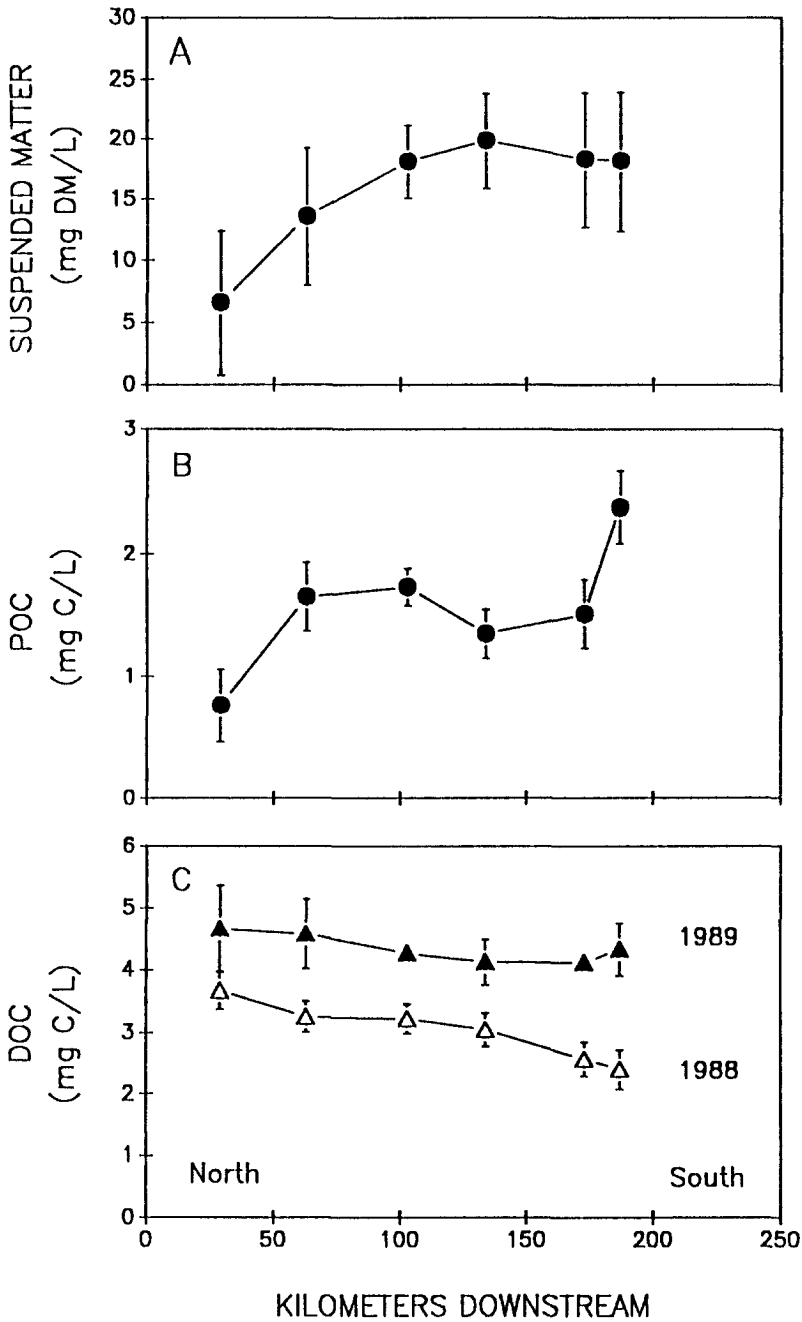

Fig. 7 Spatial variability in suspended matter (*A*), POC (*B*) and DOC (*C*) among stations in the Hudson Estuary. Values are means (± 1 SE) across all sampling dates except for DOC where 1988 and 1989 data were not combined.

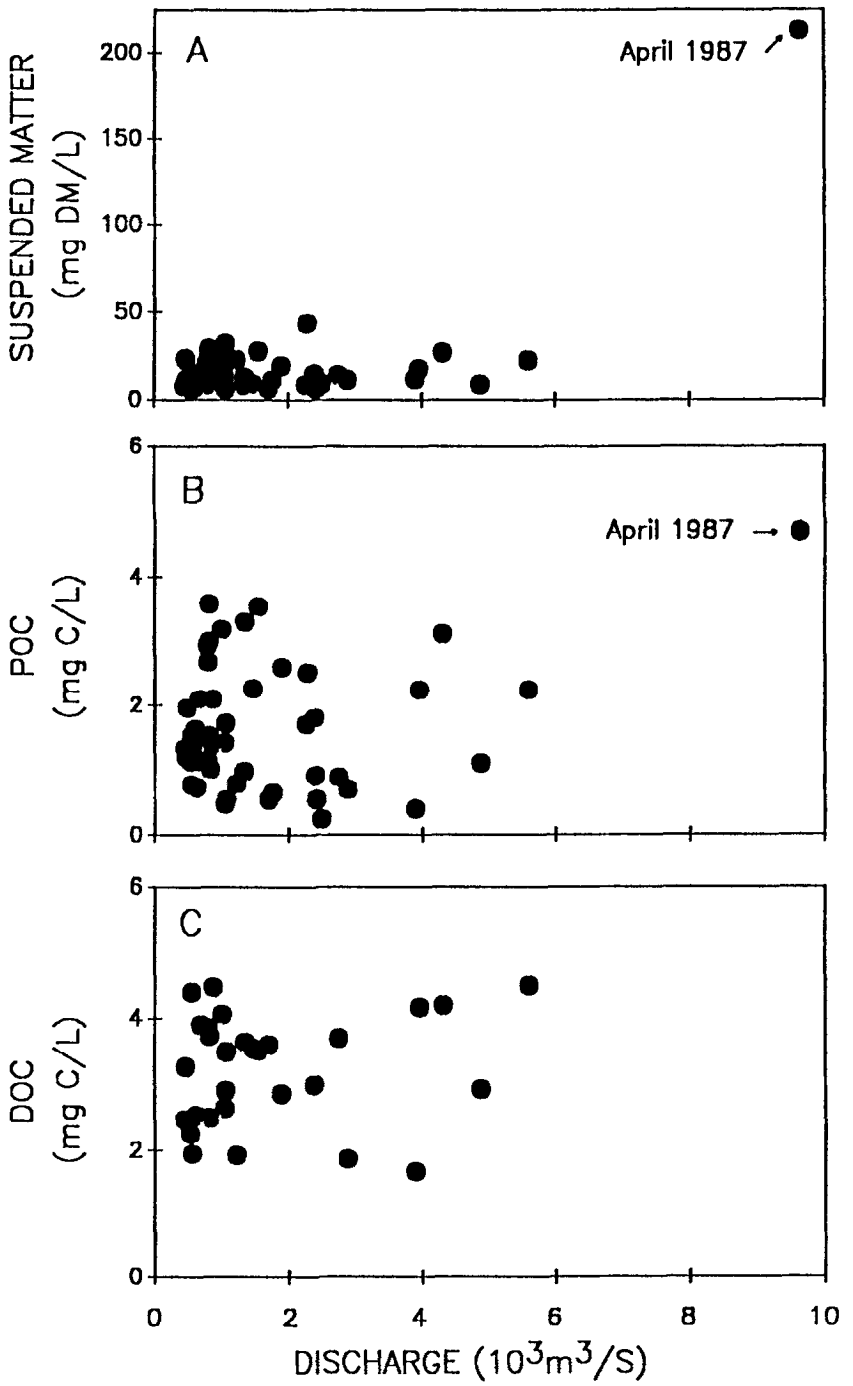

Fig. 8 Relationship of suspended matter (*A*), POC (*B*) and DOC (*C*) with discharge summed over the previous five days.

has been the focus of many studies of suspended matter (Schlesinger & Melack 1981; Mulholland & Watts 1982; Milliman & Meade 1983; Degens & Ittekkot 1985; Ittekkot 1988). There is little doubt that the combination of high discharge and high suspended matter concentrations during spring runoff or major storms is responsible for the bulk of transport (Ellsworth 1986). In our case, however, we wanted to examine more detailed spatial and temporal scales because interactions between suspended matter and biological or chemical processes probably occur on the scale of weeks and kilometers.

In the Hudson, several lines of evidence suggest that much of the variability in suspended matter concentrations, particulate organic carbon and dissolved organic carbon was not simply due to freshwater input to the system. Apparently, processes occurring within the Hudson estuary were responsible for much of the variation in these parameters. First, we did not find consistently significant relationships between suspended matter and discharge, and there were clear peaks in suspended matter concentration that did not correspond to high discharge or storms (Fig. 2B). Second, the increases in suspended matter with depth (Figs. 5 and 6) suggest that resuspension of bottom sediments is a significant source of suspended matter in the water column (Richards 1982), as previously suggested for the Hudson by Bokuniewicz & Arnold (1984). Field observations suggest that a south wind generates sufficient turbulence to resuspend material from shallow regions. If significant resuspension occurs, it provides a mechanism for increasing the turbidity of the system even during low discharge periods and facilitates the movement of sediment-associated pollutants into the water-column food web.

The kilometer-scale variability in POC indicates relatively rapid production or consumption of particulate organic carbon by either biological or physical processes. POC may be supplied by resuspension of benthic organic matter, *in situ* primary production or input from fringing wetlands and tributaries. As for total suspended matter, the vertical profiles suggest supply of POC from the bottom and, based on the greater vertical variation, this input would appear to be more important in the shallower regions. There was a strong positive relationship between POC and suspended matter ($p < 0.001$, Fig. 9A), suggesting that processes supplying suspended matter also supply POC. In the Hudson estuary, resuspension of bottom sediments would supply detrital POC to the water column and result in a positive relationship between total suspended matter and POC.

Dissolved organic carbon is an important component of total organic carbon in the water column of the Hudson estuary. Plotting DOC versus POC (Fig. 9B) shows that essentially all the points fall above the 1:1 line.

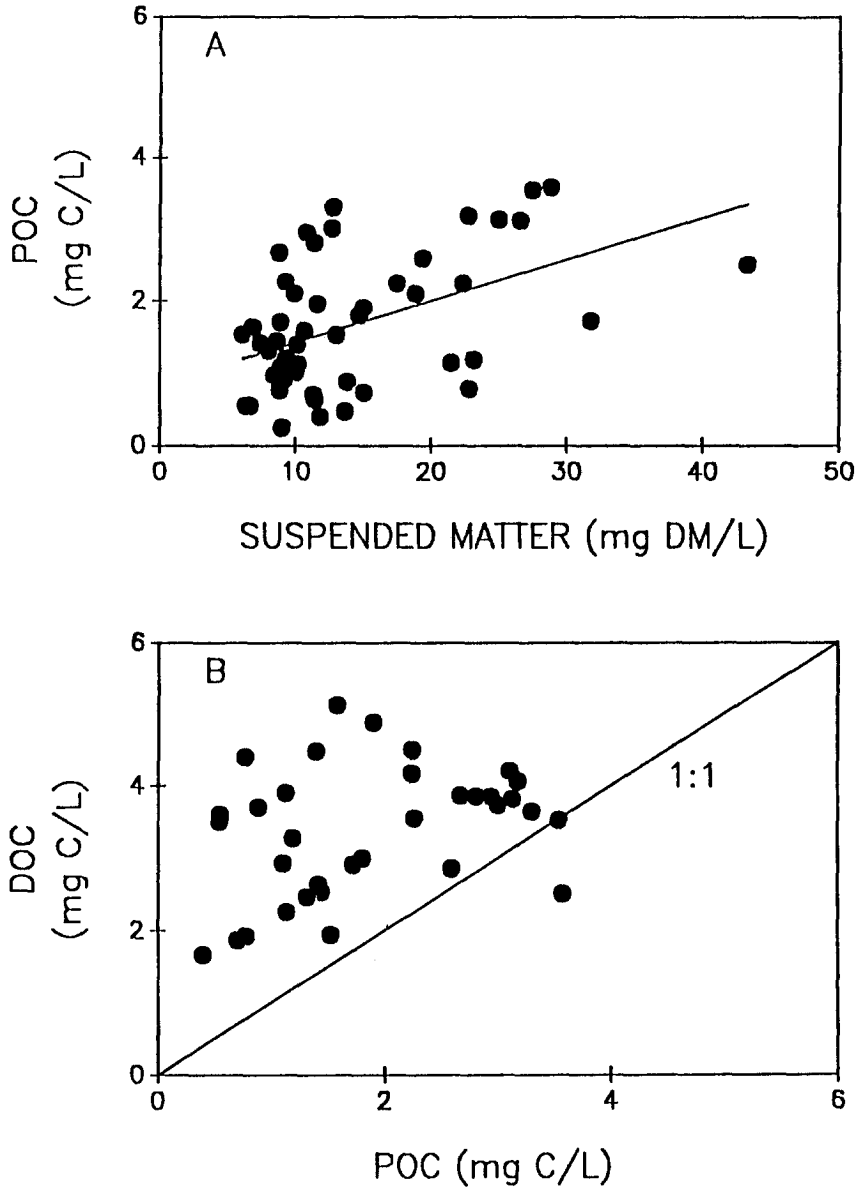

Fig. 9 Relationship between POC and total suspended matter ($p < 0.05$) (*A*) and between DOC and POC ($p > 0.05$) (*B*) for the surface waters near Kingston.

There was not a significant relationship between DOC and POC, nor was there a seasonal pattern in the relative contribution of DOC and POC to the total organic carbon pool.

DOC concentration seems to be at least partially under the control of processes occurring within the Hudson estuary, rather than simply being a function of loadings from the surrounding watershed. The lack of a relationship between DOC and discharge (Fig. 8C) and the increase in concentrations from spring to fall (Fig. 2D), when freshwater inputs were declining, suggests that external supply was not the only control on DOC concentration. It is, however, possible that the seasonal increase in DOC is an inverse dilution effect, with greatest dilution occurring during the spring and declining over the course of the summer. If the seasonal increase in DOC is due to a net production of DOC, then release from phytoplankton, macrophytes, bottom sediments or inputs from fringing wetlands are all reasonable sources of DOC.

Using the changes in fluxes in downstream cross-sections to evaluate source/sink relationships for suspended matter showed significant (regression analyses, $p < 0.05$) increases from north to south (Fig. 10B). The percentage increases over the study reach were 368% in 1988 and 157% in 1989, both of which are greater than the increase in water flux (31%, Fig. 10A). These large increases indicate either significant contribution of materials from tributaries or production of suspended matter within this portion of the estuary. We do not believe tributaries are the major source because the major tributary (Wallkill/Rondout, contributing over 50% of the total tributary input) enters between the Kingston and Poughkeepsie stations, but suspended matter did not increase markedly over this stretch in either year (Fig. 10B). This is further evidence that the proximate source of these materials is not tributary loadings but generation within the estuary. Ultimately, tributary loadings probably provide the bulk of sediment to the estuary, but it seems that medium scale variability in space and time is a function of internal processes. Regressions of POC flux against distance downriver (Fig. 10C) showed that there was a weak relationship ($p = 0.078$) in 1988 but a more significant relationship ($p = 0.02$) in 1989. The percentage increases in POC flux (276% in 1988 and 123% in 1989) were again much greater than the increase in water flux, indicating that generation of POC within the study reach was the most likely mechanism. As was the case for suspended matter, there were two major increases in POC flux, one near River Km 30 and one near River Km 130. Again, the major tributary inflow occurs near River Km 70, reiterating the lack of correlation between tributary inputs and increases in mass flux of POC.

In contrast to suspended matter and POC, DOC seems to behave conservatively, showing no significant relationship between net flux and position in 1988 (Fig. 10D). Either production and consumption were in

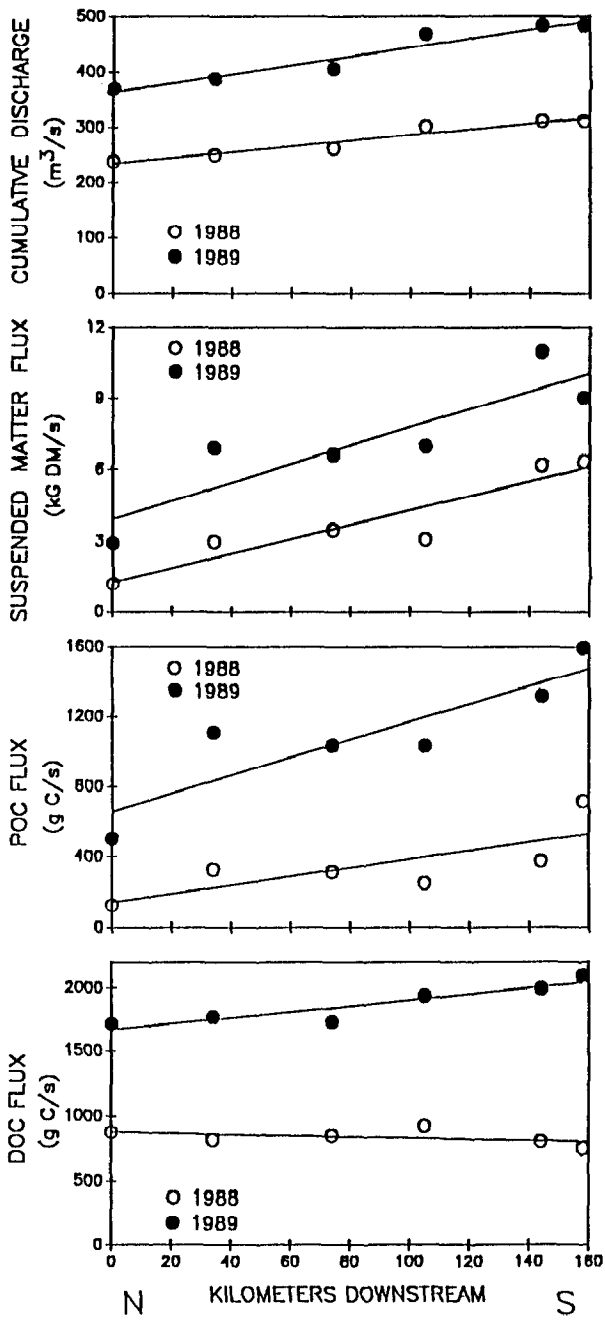

Fig. 10 Downstream changes in total flux of water and different materials through cross-sections located at sampling points. Concentrations are averages for 1988 and 1989. Note that kilometer 0 is at the head of the study reach.

close balance, or there were no significant processes acting to remove or produce DOC within the Hudson estuary. In 1989, there was a significant relationship between net flux and distance, but the total change in flux (21%) was less than the net increase in water flux (31%), indicating that tributary additions would be more than sufficient to explain the downstream increase in DOC flux.

In summary, examination of medium-scale temporal and spatial variability in suspended matter and POC points to the importance of within-system sources and sinks of these materials in the Hudson Estuary. We have shown that, at the time and space scales most significant to biological processes, the Hudson estuary is not simply being driven by external loadings. Processes occurring within the Hudson ecosystem are important if not predominant in governing medium-scale distributional patterns and dynamics. Detailed, close-interval measurements, conducted within the Hudson River Estuary, rather than measurements of upstream or tributary loadings, will be necessary to understand and/or predict suspended and dissolved material distributions and dynamics.

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