

TABLE 3. Characteristics of the boxes used in model calculations. Volume and depth data are from Chinman and Nixon (1985). For sampling station locations and freshwater inputs see Fig. 1.

	Area (km <sup>2</sup> )	Mean Depth (m)	Sampling Stations	Freshwater Inputs
1. Seekonk River	2.80	1.29	1, 2, 3	BR, BV, TM
2. Fox Pt. Reach	3.00	7.03	4, 5	WR, MR, FP
3. Sabin-Nayatt Reach	18.33	3.49	6, 7, 8, 9	PR, EP

Chinman and Nixon (1985). At least two sampling stations were included in each box. Station 10 served as a saltwater endmember.

Salinity in each layer was determined by first averaging high and low tide discrete samples at each station and averaging across stations within a box. Observed concentrations of nutrients were determined similarly. Freshwater input was determined from river flow data furnished by the United States Geological Survey and sewage treatment plant discharge records. Freshwater input and concentrations were taken as the mean of the 3 d preceding each cruise.

Concentrations of ammonia, nitrate + nitrite, total dissolved inorganic nitrogen (DIN), phosphate, dissolved silicon, and particulate carbon and nitrogen were calculated for each cruise, yielding 36 predictions for each constituent equally divided between surface and bottom layers. The agreement between predicted and observed concentrations was assessed by computing the functional regression of predicted (y) on observed (x) (Ricker 1973).

The functional relationship between observed and predicted concentrations provides two pieces of information which bear on the relative importance of external input versus other processes (either external or internal): the  $R^2$  and the slope.

The  $R^2$  of the functional relation is the same whether observed is regressed on predicted or predicted on observed. Thus the  $R^2$  indicates the amount of variability in observed concentrations which can be explained by predicted concentrations. Since predicted concentrations are computed as a function of input and mixing of each layer of each box, by inference, the  $R^2$  measures the amount of variability in observed concentrations which may be due to these processes. The data used in the regressions encompass both temporal (the six cruises) and spatial (the three boxes) variability. We have not tried to distinguish between them. A high  $R^2$  would suggest that if input and mixing produce different concentrations at different times and places, then observed concentrations would also be correspondingly different.

The slope of the regression quantifies these corresponding differences. Again, since predicted concentrations are assumed to result from input

and mixing, the slope may also be interpreted as quantifying the proportion of the observed concentration attributable to these processes.

This interpretation is relatively straightforward when the slope is less than or equal to 1.0. A slope of 1.0 indicates that 100% of the observed concentration can be explained by inputs and mixing. A slope less than 1.0 indicates that predicted concentrations are a fraction of the observed, suggesting addition to the system by some process.

When the slope is greater than 1.0, observed concentrations are less than predicted and loss from the system is indicated. The inverse of the slope measures the fraction of predicted material which is actually observed, and assumed due to input and mixing. The remainder is the fraction lost due to some unquantified process.

## Results

### FRESHWATER INPUT

Total freshwater discharge to the system varied (Fig. 3), being relatively high during the December, March, and April cruises and relatively low during October, June, and August. Rivers were the major source of freshwater, comprising 94–96% of the total discharge during high flow conditions

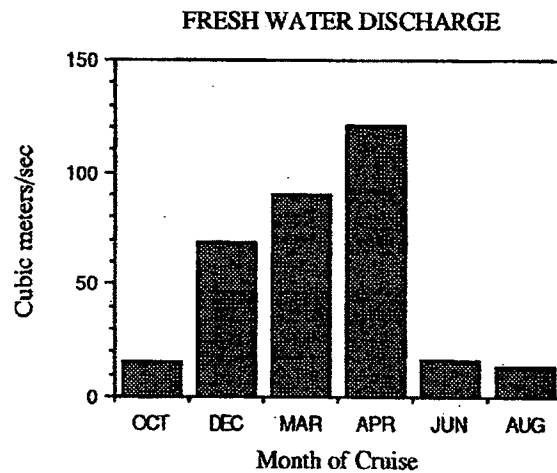


Fig. 3. Mean total freshwater input to the Providence-Seekonk River during the 3 d preceding each cruise.

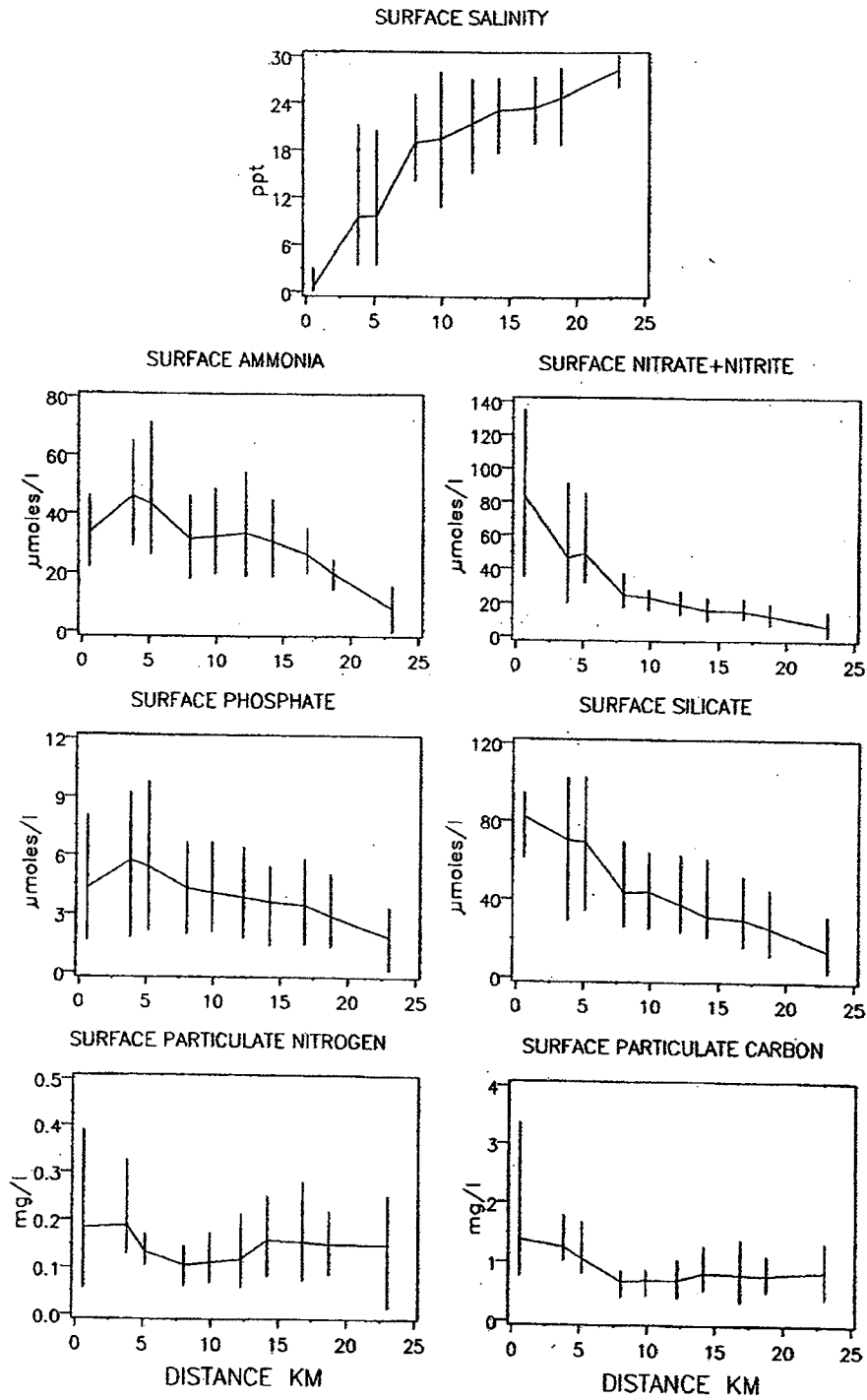


Fig. 4. Mean and range of salinity and nutrient concentrations observed in surface waters (depth = 1.0 m) during the six cruises, versus distance from the Main Street Bridge, Pawtucket, Rhode Island at the head of the Seekonk River.

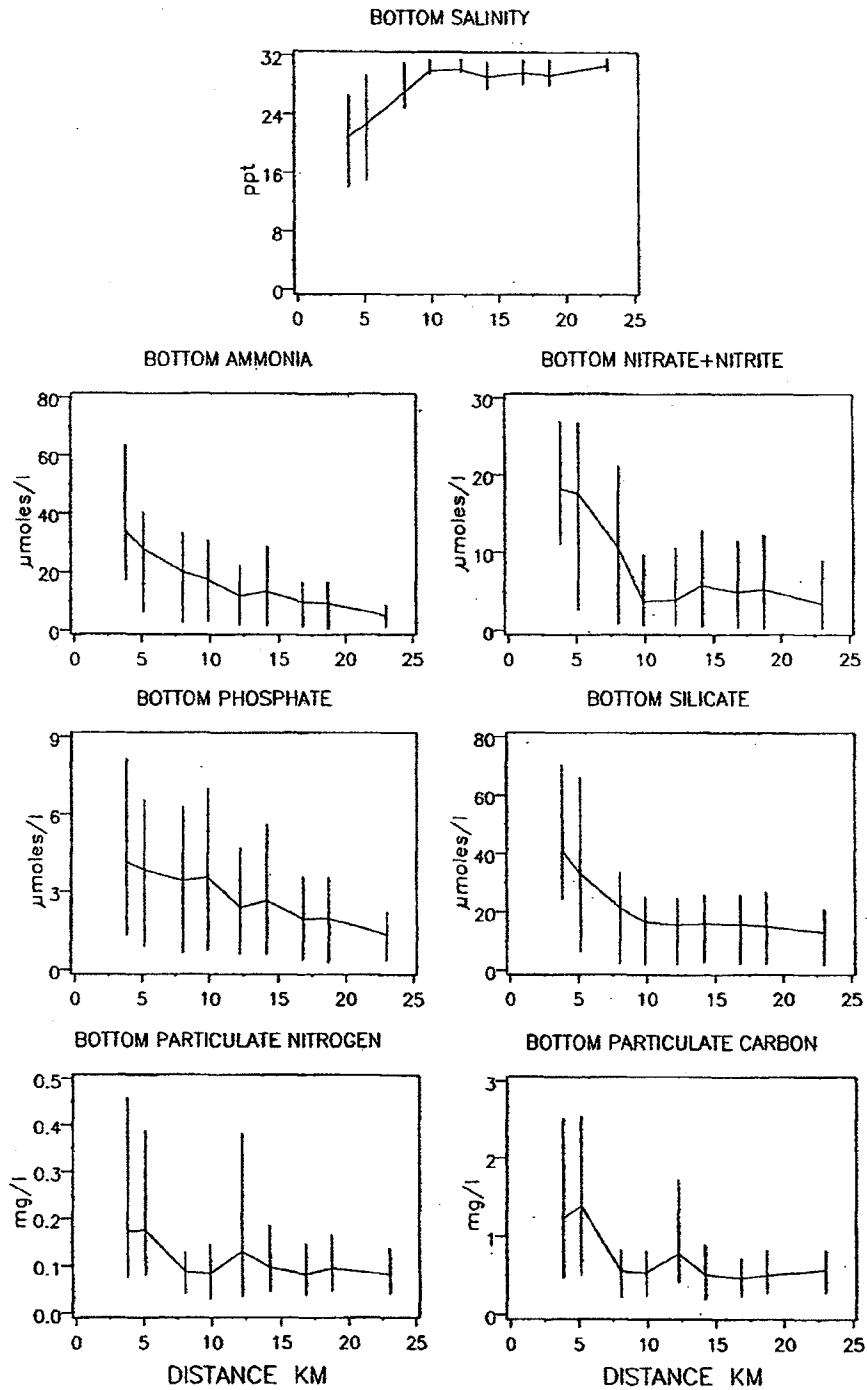


Fig. 5. Mean and range of salinity and nutrient concentrations observed in bottom waters (1.0 m from bottom) during the six cruises, versus distance from the Main Street Bridge, Pawtucket, Rhode Island at the head of the Seekonk River.

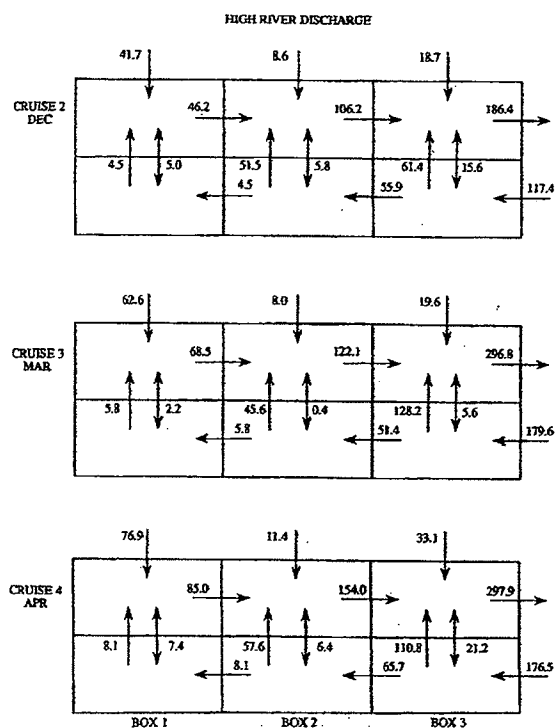


Fig. 6. Transport coefficients ( $\text{m}^3 \text{s}^{-1}$ ) for three cruises (December, March, and April) when freshwater input was high. Arrows correspond to Fig. 2.

and 78–82% during low flow conditions. The Blackstone River entering at the head of the Seekonk was the largest source of freshwater. Second in importance was the Pawtuxet which enters around the middle of the Providence River.

#### CONCENTRATIONS

The salinity of bottom water always exceeded that near the surface (Figs. 4 and 5). Dissolved nutrient concentrations exhibited an opposite trend with surface values being greater than those near the bottom. There was no consistent relationship between surface and bottom concentrations of particulate nitrogen and carbon.

The salinity of surface waters generally increased down the estuary (Fig. 4). Lowest salinities were always observed at station 1 in the Seekonk River and highest salinities at station 10 in upper Narragansett Bay.

Highest concentrations of all nutrients measured in surface waters occurred in the Seekonk River (Fig. 4). The concentration of dissolved species tended to decrease from stations 1 or 2 in the Seekonk River down the estuary. Secondary peaks in concentration, however, were evident especially for ammonia and phosphate.

TABLE 4.  $R^2$  of linear relationships between tidally averaged nutrient concentrations and salinity for each cruise.  $n = 19$  for each cruise. Correlation coefficients were all negative excepting particulate N on cruise 4. If  $R^2 \geq 0.208$  then  $p < 0.05$ .

	Cruise					
	Oct. 1	Dec. 2	Mar. 3	Apr. 4	Jun. 5	Aug. 6
$\text{NO}_2^- + \text{NO}_3^-$	0.990	0.988	0.994	0.990	0.986	0.958
$\text{NH}_4^+$	0.402	0.893	0.874	0.752	0.118	0.292
$\text{PO}_4^{3-}$	0.662	0.016	0.726	0.441	0.295	0.194
Dissolved Si	0.986	0.945	0.996	0.974	0.922	0.956
Particulate N	0.576	0.546	0.508	0.130	0.310	0.008
Particulate C	0.573	0.482	0.830	0.106	0.540	0.037

By contrast surface concentrations of particulate carbon and nitrogen, while behaving similarly to dissolved species in the Seekonk River, tended to increase between the head of the Providence River (station 4) and upper Narragansett Bay (station 10).

Bottom water salinities increased precipitously in the Seekonk River but remained relatively constant in the Providence River (Fig. 5). Highest concentrations of all nutrients occurred in the Seekonk River (stations 1–3). Concentrations declined from the head to the mouth of the estuary, but again secondary peaks in concentration were evident (Fig. 5).

Concentrations of all nutrients were significantly correlated with salinity on most cruises (Table 4). The  $R^2$  of the linear relationship was consistently greater than 90% on all six cruises only for nitrate + nitrite and dissolved silicon.

#### Model Results

##### TRANSPORT COEFFICIENTS

Transport coefficients for the three high and low river discharge cruises are given in Figs. 6 and 7. Up-estuary transport of bottom water from the Fox Pt. Reach (Box 2) to the Seekonk River (Box 1) was small. About 90% (88–96%) of the bottom water entering Box 2 was advected vertically to the upper layer. Given the constricted passage between these boxes (Fig. 1), this result seems intuitively reasonable.

##### NUTRIENT INPUTS

The ultimate sources of nutrients considered in the model were rivers, sewage treatment plants, and bottom water from upper Narragansett Bay. In the model the former two point-sources supply nutrients to the surface layer and the latter represents the initial source of nutrients to bottom water. By way of comparison, fluxes (flow  $\times$  concentration) from these sources are given for two representative cruises in Table 5.

Point-source inputs of dissolved inorganic nitrogen were an order of magnitude greater than the

TABLE 5. Nutrient inputs (flow × concentration) to the Seokk-Providence River from point sources and bottom water from upper Narragansett Bay. Units are moles s<sup>-1</sup>.

	High Flow Cruise 3 March		Low Flow Cruise 5 June	
	Point Sources	Bottom Water	Point Sources	Bottom Water
NH <sub>3</sub> <sup>+</sup>	6.31	0.21	4.82	0.84
NO <sub>2</sub> <sup>-</sup> + NO <sub>3</sub> <sup>-</sup>	4.28	0.09	1.54	0.13
PO <sub>4</sub> <sup>-3</sup>	0.36	0.10	0.34	0.16
Dissolved Si	10.76	0.30	2.00	1.54
Particulate C	13.49	4.14	5.64	3.37
Particulate N	1.71	0.64	0.80	0.50

contribution of upper Narragansett Bay bottom water. Both sources contributed significantly to the input of PO<sub>4</sub>, particulate carbon, and particulate nitrogen. The relative importance of dissolved silicon input varied with freshwater discharge. During high flow point-source input dominated, while during low flow conditions the two sources were roughly equivalent.

PREDICTED AND OBSERVED CONCENTRATIONS

As an internal check of the model, mean salinities were predicted in each layer, substituting salinities for concentrations in the equations given in Table 2. Functional regressions of predicted on observed salinities for both layers yielded slopes equivalent to 1.0 and intercepts not statistically different from 0.0. Correlation coefficients exceeded 0.999 in both cases (Table 6).

TABLE 6. Model results: slopes and intercepts of functional regressions of predicted on observed concentrations in surface and bottom layers. Errors are the 95% confidence interval. (\*) slope does not overlap 1.0 (\*\*) intercept does not overlap 0.0. DIN = NH<sub>4</sub><sup>+</sup> + NO<sub>2</sub><sup>-</sup> + NO<sub>3</sub><sup>-</sup>. % of concentration attributable to inputs and mixing calculated as described in text. Units are μmols l<sup>-1</sup> for nutrients and ‰ for salinity.

	Slope	Intercept	R <sup>2</sup>	% Due to Inputs and Mixing
<b>Surface layer</b>				
Salinity	1.00 ± 0.001	0.00 ± 0.02	1.000	—
DIN	1.29 ± 0.15*	-11.16 ± 11.32	0.950	78
NH <sub>4</sub> <sup>+</sup>	1.74 ± 0.59*	-16.88 ± 21.06	0.583	57
NO <sub>2</sub> <sup>-</sup> + NO <sub>3</sub> <sup>-</sup>	0.98 ± 0.08	0.85 ± 3.07	0.979	100
PO <sub>4</sub> <sup>-3</sup>	1.48 ± 0.29*	-1.25 ± 1.44	0.858	68
Dissolved Si	1.20 ± 0.14*	-4.80 ± 7.92	0.948	83
Particulate N	1.77 ± 0.73*	-0.07 ± 0.11	0.399	56
Particulate C	1.77 ± 0.68*	-0.42 ± 0.64	0.469	56
<b>Bottom layer</b>				
Salinity	1.00 ± 0.009	-0.01 ± 0.23	0.999	—
DIN	0.91 ± 0.08*	0.01 ± 3.01	0.970	91
NH <sub>4</sub> <sup>+</sup>	0.78 ± 0.13*	0.32 ± 3.10	0.905	78
NO <sub>2</sub> <sup>-</sup> + NO <sub>3</sub> <sup>-</sup>	1.05 ± 0.12	0.36 ± 1.54	0.952	100
PO <sub>4</sub> <sup>-3</sup>	0.84 ± 0.12	0.05 ± 0.49	0.921	84
Dissolved Si	0.95 ± 0.07	0.58 ± 2.08	0.978	100
Particulate N	0.44 ± 0.20*	0.05 ± 0.03**	0.288	44
Particulate C	0.37 ± 0.16*	0.34 ± 0.16**	0.333	37

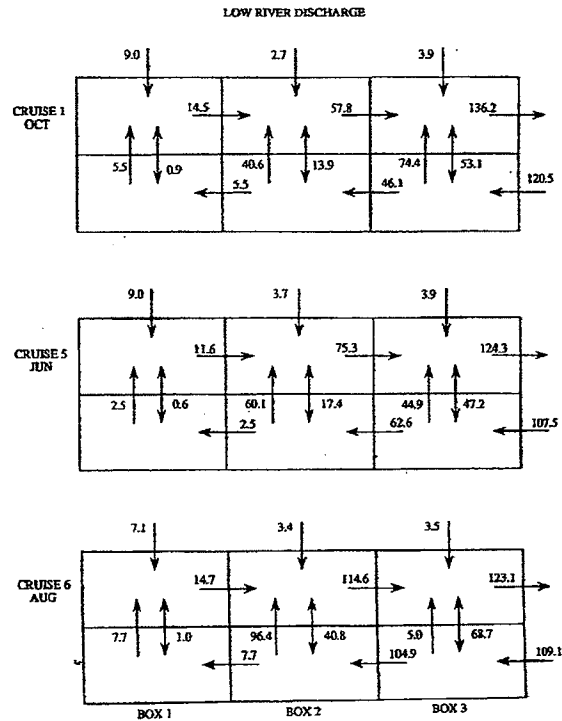


Fig. 7. Transport coefficients (m<sup>3</sup> s<sup>-1</sup>) for three cruises (October, June, and August) when freshwater input was low. Arrows correspond to Fig. 2.

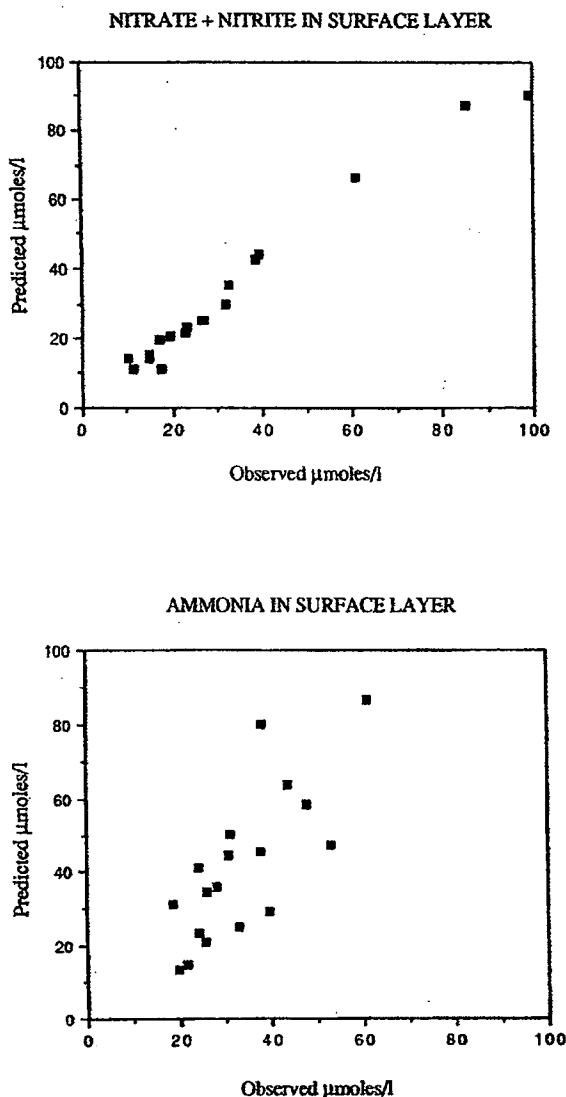


Fig. 8. Relationship between predicted (y) and observed (x) concentrations of nitrate + nitrite and ammonia in surface waters. Predicted concentrations were calculated from the box model.

Functional relationships between predicted and observed nutrient concentrations were all statistically significant at  $p < 0.05$  (Table 6). Slopes of the regression were thus all different from zero. Nonzero intercepts were found only for particulate nitrogen and carbon in the bottom layer.  $R^2$  values of regressions were generally high, signifying little scatter in data points about the regression line. Regressions for particulate carbon and nitrogen and ammonia in surface water had particularly low  $R^2$  values. Results for ammonia and nitrate + ni-

trite in surface waters are given in Fig. 8 as examples of relationships with high and low  $R^2$  values.

The concentrations of nitrate + nitrite in surface waters and dissolved silicon and nitrate + nitrite in bottom waters could be explained entirely by the model, as a function of inputs and mixing (slopes = 1.0). Concentrations of the remaining dissolved and particulate nutrients in surface waters were less than predicted by the model (slopes greater than 1.0), suggesting loss by unaccounted for processes. By contrast, concentrations of the remaining dissolved and particulate nutrients in bottom waters were greater than predicted (slopes less than 1.0), suggesting enrichment by unaccounted for processes.

Judging from the regression slopes, inputs and mixing processes in surface layers produced concentrations of dissolved constituents which achieved 57–100% of their potential value. Loss processes reduced these potential concentrations by some 0–43%. In bottom waters, inputs and mixing processes explained between 78–100% of observed concentrations of dissolved constituents. Other processes increased observed concentrations, and must account for the remaining 0 to 22%.

#### NET FLUX OF NITROGEN

Net fluxes of dissolved inorganic (DIN) and particulate nitrogen were calculated from point-source inputs and longitudinal fluxes between the lower Providence River (Box 3) and upper Narragansett Bay. The data (Table 7) revealed no trends in retention or export for either DIN or particulate nitrogen which may be explained by changing seasons or river flow conditions.

Integrating these fluxes over the year (Table 8) indicated that about 96% of the DIN and 95% of the particulate N entering the system was exported. Of the total, perhaps 5% was retained or lost in some other form (e.g., dissolved organic or gaseous).

Owing to lack of data for other than dissolved forms of phosphorus and silicon, useful budgets for these nutrients could not be constructed.

#### Discussion

##### SALINITY AND NUTRIENT CONCENTRATIONS

Spatial variability of nutrient concentration in the Seekonk-Providence River was at least in part a function of salinity. Excepting nitrate + nitrite and dissolved silicon, correlations with salinity were weak. Low association between salinity and nutrient concentration was not always caused by significant curvature of the relationship but more often

TABLE 7. Net flux of dissolved (DIN =  $\text{NH}_4^+ + \text{NO}_2^- + \text{NO}_3^-$ ) and particulate nitrogen through the system. Input = contribution from point sources and bottom water from upper Narragansett Bay. For net flux (+) denotes export, (-) denotes retention. Units are moles  $\text{s}^{-1}$ .

	Cruises					
	Oct.	Dec.	Mar.	Apr.	Jun.	Aug.
<b>DIN</b>						
Input						
Point source	5.05	8.00	10.58	9.39	6.36	4.58
Bottom water	2.05	1.81	0.30	0.21	0.97	0.70
Export	8.06	10.42	9.85	10.20	4.93	4.25
Net	0.96	0.61	-1.03	0.60	-2.40	-1.03
<b>Particulate N</b>						
Input						
Point source	0.84	1.09	1.71	1.58	0.80	1.12
Bottom water	0.69	0.34	0.64	1.73	0.50	0.90
Export	1.13	1.04	1.73	3.38	2.00	1.61
Net	-0.40	-0.39	-0.62	0.07	0.70	-0.41

by scatter of the data points. The Seekonk-Providence River system is relatively narrow and shallow. Lateral inputs may be expected to significantly influence observed distributions. Under such conditions, property vs. salinity plots are ineffectual at distinguishing conservative and nonconservative behavior of constituents within the estuary (Fisher et al. 1988).

#### BOX MODEL

We chose to use a box model to facilitate interpretation of nutrient distributions. Since lateral inputs are taken into account, conservative and non-conservative behavior within the estuary can be distinguished.

Salinity in the Seekonk-Providence River did not change gradually, rather there were precipitous changes in surface waters between the Seekonk and Providence rivers (Fig. 4). In bottom waters this discontinuity was displaced somewhat downstream (Fig. 5). Estimating hydrodynamic exchanges from a continuous curve model (e.g., Kaul and Froelich 1984; Smith et al. 1989) did not seem warranted. The changes in pattern of salinity distribution imply a step function which can be reasonably represented with a box model (Smith et al. 1989).

The delineation of boxes in the model is thus an important consideration. Boundaries should encompass spatial zones of regular salinity change and separate zones with different patterns of change. Boxes 1 and 2 (stations 1-5) of the model separate regions of rapid salinity change in the Seekonk and upper Providence River from the lower Providence River (stations 6-10) where changes were more gradual.

The box model is two-dimensional rather than one-dimensional. This two-layer configuration is commensurate with the nearly 100 vertical profiles

of salinity taken during the six cruises. These profiles conform to the characterization given by Pilson (1985b) for Narragansett Bay and are consistent with the net circulation pattern represented in the model.

#### PREDICTED AND OBSERVED NUTRIENT CONCENTRATIONS

Nutrient concentrations predicted by the model were all linearly related to observed concentrations. The strength of these relationships, as indicated by the  $R^2$  values, was generally high, but in some cases (particulate nutrients and ammonia in surface waters) it was not. Given the modest nature of the data used in the model (surface and bottom samples) the statistical significance of the relationships was gratifying and suggests that our data are sufficient to provide a first-order picture of the Seekonk-Providence River region.

Aside from  $\text{NO}_2^- + \text{NO}_3^-$  (which everywhere behaved according to model prediction) and dissolved silicon in bottom waters, both dissolved and particulate nutrients were depleted in surface waters and enriched in bottom waters relative to the model. Processes responsible for these deviations can only be surmised (Taft et al. 1978), but would appear to be internal to the system, as timing of the cruises minimized potential effects of nonpoint-

TABLE 8. Annual nitrogen budget for the Seekonk-Providence River derived by integrating data in Table 8. Units are  $10^6$  moles  $\text{N yr}^{-1}$ . Input = point sources + bottom water.

	Input	Export	Percent Input Exported
DIN	267	257	96
Particulate N	62	55	90
Total	329	312	95

source inputs (rainfall, runoff, etc.) and major point sources were measured.

For dissolved substances in surface waters, precipitation, adsorption (e.g.,  $\text{PO}_4^{3-}$ , dissolved silicon), and biological fixation into particulate matter may be invoked as explanations (Fanning and Pilson 1973; Burton and Liss 1976; Aston 1978; Kamatani and Takano 1984). It is interesting to note that while  $\text{NO}_2^- + \text{NO}_3^-$  behaved as predicted, ammonia did not. The latter is preferred by phytoplankton (McCarthy et al. 1975) and this proclivity might explain the contrasting behavior of these two forms of nitrogen.

In bottom waters the relative enrichment of  $\text{PO}_4^{3-}$  and  $\text{NH}_4^+$  may well be explained by remineralization either in the water itself or through flux from sediments fueled by diagenesis. Remineralization can significantly affect water column concentrations (Nixon 1981; D'Elia et al. 1983; Pilson 1985a; Anderson 1986).

Both dissolved silicon and nitrate + nitrite concentrations behaved as predicted in bottom waters. Efflux of the latter from sediments in Narragansett Bay is small (Kelly et al. 1985) and ammonia is the initial end product of nitrogen regeneration (Kaul and Froelich 1984). The fact that dissolved silicon was not enriched relative to prediction was surprising given the significant flux of this material from Narragansett Bay sediments (Nixon 1981) and other estuarine sediments as well (D'Elia et al. 1983; Kamatani and Takano 1984).

Both particulate carbon and nitrogen were depleted in surface waters and enriched in bottom waters relative to the model predictions. Sinking from surface layers (e.g., Officer 1980) and resuspension of bottom sediments (Oviatt and Nixon 1975) may account for this pattern.

#### INTERNAL PROCESSES VS. EXTERNAL INPUTS AND MIXING

Much of the variability in and absolute magnitude of dissolved nutrient concentrations could be attributed to external inputs and subsequent mixing with lower Narragansett Bay water. Excepting ammonia in surface waters, the model explained better than 85% (see  $R^2$  values) of the variability in dissolved nutrient concentrations. For particulate phases, this percentage was substantially lower. The slopes of the predicted on observed regressions indicated that some 60 to 100% of dissolved and 40 to 60% of particulate nutrient concentrations appear to be maintained by external inputs and mixing.

The comparisons between observed and predicted concentrations from which these estimates were made encompass both temporal and spatial variation. As such they should be viewed as rep-

resenting an average condition. There were too few data to dissect these sources of variation.

As a practical matter, the preponderant dependence of dissolved nutrient concentrations in the Seekonk-Providence River on external supply suggests that control of point sources would substantially improve water quality in this already degraded region. These conclusions, based on field data, agree with earlier manipulative experiments conducted in the MERL mesocosms (Oviatt et al. 1984).

#### ESTUARINE FUNCTION AND FLUSHING TIME

The relative contribution of internal and external factors to dissolved nutrient concentrations varies spatially in Narragansett Bay. As shown in this study and an earlier mesocosm experiment (Oviatt et al. 1984), dissolved nutrient concentrations in the Seekonk-Providence River are subject to external control. This condition contrasts with circumstances in lower Narragansett Bay where nutrient cycles may be largely driven by activities internal to the system (Pilson 1985a).

This apparent regional difference in functioning of the bay may in part depend on flushing time. The freshwater in Narragansett Bay is replaced every 26 d (range 10 to 40 d; Pilson 1985b). Estimates for the Seekonk-Providence River (3–10 d; Spaulding 1987) are considerably shorter. The extent to which a substance can be acted upon before it is washed out of the system depends on the relationship between the chemical or biochemical reaction rate and the flushing time (Officer 1980). The intensity of any internal biogeochemical signature should vary inversely with flushing time (Smith et al. 1989) and this appears to be the case for Narragansett Bay.

#### NITROGEN BUDGET

The preliminary nitrogen budget for the Seekonk-Providence River indicates that annually about 95% of the total nitrogen (DIN + particulate) entering the system is exported to upper Narragansett Bay. The fate of the unaccounted nitrogen (5%) is unknown. Burial, denitrification, or export as dissolved organic nitrogen represent potential sinks. On an areal basis the Seekonk-Providence River apparently removes  $0.71 \text{ mole N m}^{-2} \text{ yr}^{-1}$ . Nixon et al. (1986) prepared bay-wide budgets for a variety of materials including nitrogen. We did not distinguish between loss processes but our estimate would include both denitrification and burial in the sediments. Nixon et al. (1986) estimate that these two processes account for some  $0.55 \text{ mole N m}^{-2} \text{ yr}^{-1}$  over the whole bay. A somewhat greater areal removal rate in the Seekonk-Providence River, as compared with the whole bay,



concur with available data. First, total nitrogen concentrations in the sediments are high in the Providence River and decrease down the bay, indicating greater net sedimentation in the Seekonk-Providence River (Oviatt et al. 1984; Seitzinger et al. 1984). Second, although denitrification in sediments was not demonstrably greater than in the rest of the bay, its rate in the Providence River has probably been underestimated (Seitzinger et al. 1984). Either or both of these processes could result in a greater areal removal rate.

We can now at least provisionally put the Seekonk-Providence River in perspective with respect to Narragansett Bay as a whole. This region holds somewhat over 3% of the water yet receives about 60% of the bay's external nitrogen input. Although the effects of internal processes on dissolved nutrient concentrations are clearly evident, they do not appear as important as in the lower bay. Rather external inputs predominantly control concentrations.

As expected, the apparent loss of nitrogen from burial and denitrification on an areal basis seems greater than in the rest of Narragansett Bay. Certainly because of its smaller area and perhaps because of its higher flushing rate the Seekonk-Providence River removes some 12% of the total nitrogen annually lost in Narragansett Bay and 3% of the total annual input.

Although considerable dilution of nutrient input occurs in this region, the Seekonk-Providence River does not buffer lower Narragansett Bay against high nitrogen loading. Under the conditions which we observed, the Seekonk-Providence River acted as a conduit passing nitrogen on to Narragansett Bay.

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