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# A SYNOPTIC VIEW OF A COASTAL PLAIN ESTUARY*

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ABSTRACT

During October, 1972 the Patuxent River Estuary was monitored intensively and synoptically over two tidal cycles to determine the spatial and temporal patterns of various hydrodynamic, chemical and biological features. Forty-one depths at eleven stations along nine transects were sampled simultaneously at hourly intervals for salinity, temperature, dissolved oxygen, chlorohyll a, particulate nitrogen, nitrate, nitrite, total kjeldahl nitrogen, ammonia, particulate carbohydrate, dissolved organic carbon, total hydrolizable phosphorous, dissolved inorganic phosphorous, suspended sediment, particle size distribution, and zooplankton. Tidal velocity was continuously monitored at each depth by recording current meters. Riverine input and meteorological conditions were relatively stable for two weeks preceeding the deployment.

This communication describes the calculation of the intrinsic rates of change of the observed variables from their measured distributions in the Estuary. The steady-state, one-dimensional equation of species continuity is employed to separate the advection and tidal dispersion of a hydrodynamically passive substance from its intrinsic rate of change at point. A new spatial transform is introduced for the purpose of interpolation and extrapolation of data.

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The intrinsic rate of change profiles reveal a region of heavy bloom activity in the upper estuary and a secondary bloom near the point in the River that most of the suspended material settles out. The changes in ammonia and nitrates are highly correlated to the productivity patterns. Phosphorous rates are less closely correlated to productivity. The perturbations that the Chalk Point steam electric power plant have on the heat and oxygen balances are easily discernible.

## INTRODUCTION

Practically every ecologist who has planned a field study has had to grapple with the limitations finite manpower and equipment impose upon his ability to adequately sample his system over its spatial and temporal domains. Marine and estuarine ecologists are particularly limited by the size and accessibility of their study areas from viewing the manifold physical, chemical and biological processes synoptically. While the developing technology of remote sensing is beginning to alleviate this difficulty, there is still no substitute for in situ sampling through the water column and over its areal extent.

In the study described below the investigators have amassed a set of data on key physical, chemical and biological variables taken simultaneously over a net of stations along the Patuxent River Estuary, a tributary estuary of the Chesapeake Bay. The objectives behind such a data acquisition are threefold:

1. To serve as a data set for the purpose of calibrating a combined physical - chemical - biological model yet to be developed.
2. To enable the authors to estimate the magnitude of the rates of various processes as they occur along the Estuary.
3. To provide a reference set of data that investigators without recourse to synoptic data collection may use to evaluate their own hypothesis about estuarine ecosystem dynamics.

An opportunity to embark upon such an ambitious task occurred in the fall of 1972 during the acquisition of prototype data for the U.S. Army Corps of Engineer's Chesapeake Bay Study. The Chesapeake Biological Laboratory and the Chesapeake Bay Institute of the Johns Hopkins University were under contract to the Corps to deploy current meters and research vessels to measure tidal velocities and salinities in the mid-portion of the Bay.

To monitor the stations prescribed by the Corps in the Bay stem and major tributaries usually required several deployments of the available manpower. The Patuxent Estuary, however, was small enough to cover in a single deployment, yet large enough to serve as a replica of most estuarine processes.

The study called for the deployment of thirty-four meters at eight stations on six "transects" along the axis of the Estuary. The current meters (Braincon #1301 Histogram Recording Current Meters) recorded tidal speed and direction automatically every ten minutes. The salinity beside each meter was to be measured with an induction salinometer lowered from a shipboard at hourly intervals for thirteen hours of three consecutive daylight periods.

With all of the vessels and men deployed for this study it appeared to the authors that, for relatively little extra effort, a host of chemical and biological variables could be measured simultaneously with the currents and salinities. The result would be a "snapshot" of the Estuary giving detailed information about a complex of phenomena for a short period of time.

As extra manpower and equipment would be needed for such a survey beyond that of the two participating organizations, assistance was solicited from neighboring research groups in the Bay. The response was overwhelming. Nine research institutions volunteered boats, equipment and manpower to the effort. With the consent of the Corps the program was expanded to cover forty depths of eleven stations on nine transects along the Estuary.

Some of the details concerning the study area, sampling location, variables measured and data reduction are given in the following sections. Later, the authors present the analysis of the process rate profiles and attempt to relate these magnitudes to mechanisms occurring at various reaches of the Estuary.

## STUDY AREA

The Patuxent River is a significant tributary of the Chesapeake Bay some 160 km in length and draining some 2494 $km^2$, all within the State of Maryland. The River rises some 48 km west of the city of Baltimore and flows southeast and south through the Piedmont Plateau to the fall line 90 km above the mouth. While the upper 32 km of this river is protected as a source of drinking water for the Washington Metropolitan Area, approximately 200 million liters per day of treated sewage enter the next 56 km. The region from

90 km to 48 km above the mouth is tidal, fresh-brackish water and is characterized by a narrow channel meandering through broad, marshy flats. The lower 40 km of the Estuary is a drowned river valley characterized by partially-mixed, two-layer flow, except near the mouth where occasional three-layer phenomena have been reported.

The study area is confined to the lower 72 km of the Estuary ending at a point where the Western Branch sub-tributary joins with the main stream. Eleven stations were established at nine distances along the river as shown on Fig. I. The coordinates of each station are listed in Table I. along with the depth in meters at which each current meter was suspended. The vertical spacing between the sensors was nominally 3 meters.

The lower four stations were sampled only for tidal current, salinity and temperature, whereas stations P-03-01 through P-07-01 were sampled for the full set of physical, chemical and biological data as described below.

The study period was from 0600 on 17 October through 0700 on 18 October, 1972 with samples taken at hourly intervals over the two tidal cycles and one diurnal period.

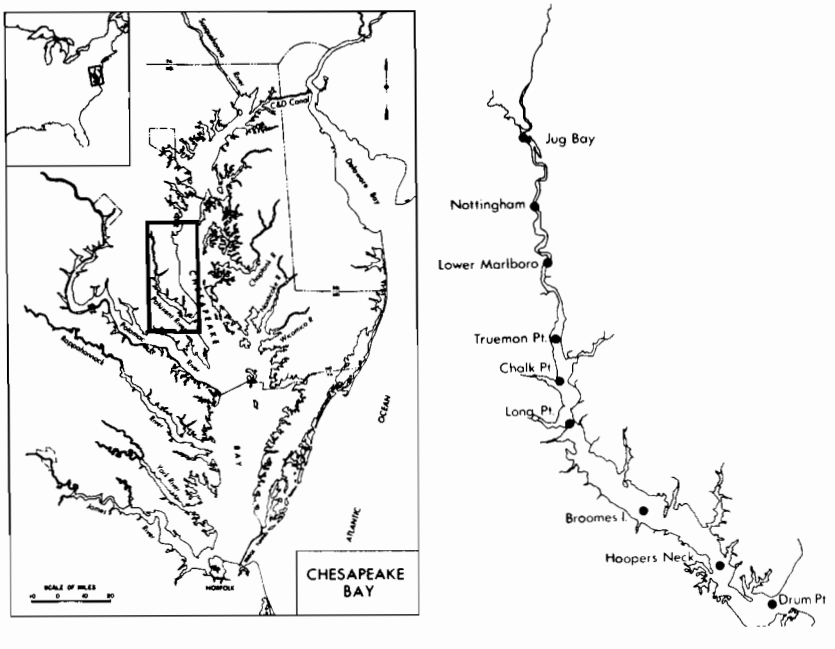


Fig. I. Stations on the Patuxent River Estuary

TABLE 1

Station location and depths

| Station Designation | KM | Longitude | Latitude (N) | Depths (M) |
|---|---|---|---|---|
| P-01-01 | 0.0 | 76° 25' 17" | 38° 18' 43" | 0.6, 3.7, 6.7, 9.8, 12.2 |
| P-01-02 | 0.0 | 76 25 17 | 38 18 55 | 0.6, 3.7, 6.7, 9.8, 12.8, 15.9 |
| P-02-01 | 10.0 | 76 29 33 | 38 20 50 | 0.6, 3.7, 6.7 |
| P-02-02 | 10.0 | 76 29 08 | 38 21 00 | 0.6, 3.7, 6.7, 9.8, 12.8, 15.9, 18.9, 21.5 |
| P-03-01 | 22.6 | 76 35 07 | 38 24 42 | 1.2, 3.7, 6.7 |
| P-04-01 | 33.4 | 76 39 55 | 38 29 38 | 1.2, 3.7, 6.7, 9.8 |
| P-04-02 | 39.3 | 76 40 32 | 38 32 30 | 1.2, 3.7 |
| P-05-01 | 43.6 | 76 40 44 | 38 34 46 | 1.2, 3.7 |
| P-05-02 | 53.3 | 76 41 03 | 38 39 23 | 1.2, 3.7, 6.7 |
| P-06-01 | 61.3 | 76 42 02 | 38 42 33 | 1.2, 3.7, 6.7 |
| P-07-01 | 71.8 | 76 42 53 | 38 46 40 | 1.2 |

SAMPLING PROCEDURE

At each hour beginning on the hour the following sequence of sampling procedures was carried out at each of the seven stations for every depth at which a current meter was moored:

1. Conductivity and temperature were measured in situ by lowering an induction coil and thermocouple apparatus (Inter-Ocean 503A CST or Beckman RS-5 salinometer).

2. Dissolved oxygen was measured in situ at three stations equipped with the Inter-Ocean CST-DO units and from the remaining stations by immersing a YSI dissolved oxygen cell into freshly pumped water from the proper depth.

3. Approximately eight liters of water was pumped from the required depth and immediately processed as described below.

4. Zooplankton were filtered from 30 liters of water pumped from the prescribed depth through a 72 micron plankton net.

5. During the daylight hours Secchi disc extinction depths were read.

Aliquots of the water collected in step 3 above were immediately filtered and processed as follows:

Chlorophyll - Mg $CO_3$ was added to a 100-200 ml (exact amount recorded) aliquot and filtered through a GF/C glass fiber filter. The filtered material was immediately frozen for subsequent analysis in the laboratory.

Particulate Nitrogen - 100-200 ml of water was filtered on a different Millipore system and the GF/C filter and material were dehydrated for later analysis.

Particulate Carbohydrate - 100-200 ml was filtered through a GF/C filter which had been fired to remove any carbon. The residual material was frozen for later analysis.

Dissolved Nitrogen and Phosphorous - Two Whirl-Pax bags were filled with 75-100 ml of filtrate from the two preceeding filtrations and frozen for later chemical analysis.

Total Phosphorous and Organic Carbon - Unfiltered samples of 50-75 ml volume were frozen to be analyzed later.

Suspended Sediment - About 50-100 ml was filtered on a "tared" 47 mm Millipore filter to be dehydrated and weighed in the laboratory.

## ANCILLARY COOPERATIVE STUDIES

In addition to the baseline measurements outlined above the schedules of three other Patuxent studies being conducted by cooperating institutions were altered to be cotemporaneous with the Patuxent synoptic survey.

Heinle and Flemer (1976) were directing monthly observations of mass transfer between a section of marsh and the Patuxent River channel. The subject marsh was within the synoptic survey area and the sampling protocol was very similar to that described above. Therefore, the 24-hour marsh study took place simultaneous with the synoptic survey.

The Philadelphia Academy of Natural Sciences, likewise, was conducting monthly cruises to measure the gross and net photosynthesis along the River by the oxygen-bottle method. Relative numbers of phytoplankton and bacterial taxa were also determined alongside the various stations of the synoptic survey while the study was underway (Mountford et. al. 1972).

The National Aeronautics and Space Administration facilities at Wallops Island and Langley, Virginia realized an opportunity to acquire ground-truth data from the synoptic operations and arranged to fly two C-147 and one C-130 missions to take black and white, color IR photographs and multi-spectral scans of the Patuxent during the daylight hours of the deployment (Ohlhorst, 1976).

The U.S. Coast and Geodetic Survey was also maintaining four automatic recording (six-minute interval) tidal height gauges along the Patuxent as part of the Corps' Chesapeake Bay Study.

CHEMICAL ANALYSIS OF SAMPLES

Immediately upon the termination of the deployment the samples were sorted and sent to the laboratories of five of the cooperating institutions. The Chesapeake Biological Laboratory performed the analysis for chlorophyll a, particulate carbohydrate and particulate nitrogen; the Department of Biology of the American University analyzed the samples for particulate and dissolved carbon; the Maryland State Water Resources Administration determined the values of total and dissolved phosphorous; and the Annapolis Field Office of the U.S. Environmental Protection Agency effected the measurement of ammonia, kjeldahl nitrogen, nitrate and nitrite. The sedimentology division of the Smithsonian Institution's Museum of Natural History weighed the sediment samples.

Active chlorophyll a was determined fluorometrically with a Turner Model 111 fluorometer (Yentsch and Menzel, 1963 and Holm-Hansen et. al., 1965). A specific absorption coefficient of 12.8 was used in the primary spectrophotometric calibration.

The Dumas method of high temperature oxidation was used to determine particulate nitrogen. Analysis were carried out on a Coleman Model 29A Nitrogen Analyzer equipped with a Model 29 combustion tube and syringe.

Particulate carbohydrate was determined by the anthrone reaction as described in Strickland and Parsons (1972).

Particulate and dissolved fractions of organic carbon were measured according to the methods described by Menzel and Vacarro (1964).

The remaining fractions of phosphorous and nitrogen were measured on Technicon Auto Analyzers according to Methods for Chemical Analysis of Water and Wastes published by the U.S. Environmental Protection Agency (1974).

The single reagent ascorbic acid reduction method (pp. 249-255) was used to obtain dissolved orthophosphorous, while the total hydrolyzable phosphorous values were the results of the colorometric ascorbic acid reduction method (pp. 256-263).

Total kjeldahl nitrogen values resulted from the automated phenate method (pp. 182-186); ammonia from the automated colorometric phenate method (pp. 168-172); and both nitrite and nitrate from the automated cadmium reduction method (pp. 207-212).

In summary, the tidal speed and direction were recorded at each depth at ten-minute intervals. Other variables measured each hour at the forty depths include salinity, temperature, dissolved oxygen,

suspended sediment, chlorophyll *a*, particulate nitrogen, particulate carbohydrate, nitrate, nitrite, ammonia, total kjeldahl nitrogen, total hydrolyzable phosphorous, dissolved orthophosphorous, particulate organic carbon, dissolved organic carbon and zooplankton density.

Other variables observed on an opportunistic basis include gross and net photosynthesis, phytoplankton taxa and relative numbers, insolation, coliform counts, river flow and tidal height. Meteorological data from the Patuxent River Naval Air Station near the mouth of the Estuary are probably available, but have not been assembled to date.

All processed data is available to the public through the National Oceanographic Data Center*.

## ESTIMATION OF PROCESS RATES

The primary objective of the Patuxent Synoptic Study as cited in the introduction is to enable the development of a combined physical - chemical - biological model of a coastal plain estuary. Ideally, if one is to set about modeling a system of such complexity, it is useful to develop a preliminary model based on fragmentary empirical data and other *a priori* estimates. Such an initial model is often a substantial aid in prescribing a data acquisition scheme.

Unfortunately, the opportunistic and *ad hoc* nature of this study did not allow for such preliminaries, and the authors must begin the modeling process after the data collection. The model structure (especially the chemical and biological sub-models) will thus be guided by the results of the initial data manipulations. The entire modeling procedure will then take on much of the nature of a *posteriori* modeling as described elsewhere (Ulanowicz et. al., 1975 and 1978).

Under this approach the structure of the reaction kinetics results from comparing the rates at which species (inorganic, organic, and living) are appearing and disappearing with the amounts present. The data acquisition scheme described above will result in information on the stocks of the species. The rates at which they are intrinsically changing, however, is confounded by the association advection and dispersion in the Estuary. The remainder of this presentation will be devoted to the estimation of the process rates and the qualitative behavior evinced by the results.

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The separation of the intrinsic rates from the hydrological transport requires a statement of mass balance. Since data was acquired from a string of single stations along the estuary, it is natural to begin with a one-dimensional mass balance, i.e., all variables are averaged over a cross-section of the estuary.

Since concentrations and velocities are available at frequent intervals, it is possible to state the equation of species conservation at various times during the tidal cycle. To do so, however, would yield results with little statistical significance. Therefore, a one-dimensional, tidally-averaged equation of species continuity is chosen to begin with:

$$A \frac{\partial C}{\partial t} = \frac{\partial}{\partial x} (CQ) - \frac{\partial}{\partial x} (KA \frac{\partial C}{\partial x}) + R \qquad (1)$$

where C is the tidally-averaged concentration
Q is the cumulative freshwater input up to point x
A is the local cross-sectional area
K is the longitudinal dispersion coefficient
R is the rate of appearance or disappearance of C
x is the distance upstream
t is the time

Now the middle of October, 1972 was a propitious time to perform the synoptic study, since the U.S. Geological Survey records indicate that riverine input to the lower estuary was virtually constant for the two weeks preceeding the observations. Hence, the River was, most likely, as close to tidally-averaged steady-state conditions as one could hope to achieve. During the measurement period a meteorological high pressure front did pass through the area causing a net loss of water from the Estuary, but the effect of this short-term phenomenon upon the steady-state gradients was probably small. Henceforth, the Estuary will be assumed at steady-state, and equation (1) can thus be solved for the "reactions term" as:

$$R = K \frac{d}{dx} (A \frac{dC}{dx}) + A \frac{dC}{dx} \frac{dK}{dx} - C \frac{dQ}{dx} - Q \frac{dC}{dx} \qquad (2)$$

Each term on the right-hand-side of equation (2) can be reasonably estimated - the concentration profiles are known from the measurements, the freshwater input profile can be evaluated with minor assumptions from USGS data, the areas are available from bathymetric charts, and the dispersion coefficient profile can be calculated from the observed salinities. There are, however, a number of numerical details associated with these estimates which should be discussed.

To begin with the values for the concentrations at a station are averaged over the station depths. In this averaging each point reading is weighted according to the fraction of the cross-sectional area associated with the particular depth. The resultant station values are subsequently averaged over the two tidal cycles (and one diurnal period) of the study. Each variable then has one "steady-state" value associated with each station at which measurements were taken. The calculated steady-state values are listed in Table II.

The longitudinal distances between stations are greater than is desirable, with distances of over 10 km separating the biological stations. Furthermore, the lower 22 kilometers were not covered by the chemical and biological sampling program. A rational method of interpolation and extrapolation of the variables and their derivatives is therefore, in order. Reasoning heuristically that longitudinal mixing becomes greater (in the absolute sense) as the Estuary cross-section increases, it would follow that longitudinal gradients are dampened as the Estuary widens. The cross-sectional area thus becomes a weighting factor for the existing gradients, and it is convenient to define a new independent variable, $\lambda$, characterizing longitudinal distance as:

$$d\lambda = \frac{dx}{A(x)} \tag{3}$$

or equivalently:

$$\lambda = \int_0^x \frac{dx}{A(x)} \tag{3a}$$

This transformation of the independent variable has the advantage that the transformed descriptions of advection and dispersion become independent of estuary geometry, i.e., equation (2) becomes:

$$AR = K \frac{d^2C}{d\lambda^2} + \frac{dC}{d\lambda}\frac{dK}{d\lambda} - C\frac{dQ}{d\lambda} - Q\frac{dC}{d\lambda} \tag{4}$$

Straightforward linear extrapolation of C ($\lambda$) and its derivatives into the downstream range gave more plausible results than similar efforts using several different non-linear regression schemes on C (x). The areas used in this transform are graphed in Figure 2.

Encouraged by the utility of this transform, the author proceeded to estimate C($\lambda$) and its two derivatives by the simplest means possible. Concentrations at any longitudinal distance were

TABLE II

Averaged concentrations

| Species (Units) | 22.6 (KM) | 33.4 | 39.3 | 43.6 | 53.3 | 61.3 | 71.8 |
|---|---|---|---|---|---|---|---|
| Salinity (MG/L) | 11810 | 10430 | 7640 | 6340 | 1410 | 300 | 203 |
| Chlorophyll -A ( G/L) | 10.25 | 7.464 | 16.85 | 22.46 | 40.20 | 68.50 | 8.715 |
| Ammonia | 0.081 | 0.130 | 0.100 | 0.153 | 0.114 | 0.075 | 0.759 |
| Nitrate-Nitrite (MGA/L) | 0.166 | 0.174 | 0.101 | 0.118 | 0.224 | 0.717 | 2.150 |
| Kjeldahl Nitrogen (MGA/L) | 0.567 | 0.502 | 0.629 | 0.507 | 0.416 | 0.609 | 1.387 |
| Dissolved Ortho Phosphate (MG/L) | 0.026 | 0.052 | 0.055 | 0.019 | 0.058 | 0.071 | 0.767 |
| Total Phosphorous (MG/L) | 0.052 | 0.134 | 0.114 | 0.100 | 0.070 | 0.262 | 1.187 |
| Dissolved Organic Carbon (MG/L) | 3.192 | 3.483 | 3.196 | 3.190 | 4.278 | 4.962 | 3.562 |
| Particulate Carbon (MG/L) | 2.210 | 2.088 | 1.881 | 2.438 | 3.527 | 4.015 | 2.290 |
| Suspended Material (MG/L) | 18.651 | ----- | 35.507 | 68.486 | 52.380 | 44.034 | 30.00 |
| Dissolved Oxygen (MG/L) | 9.42 | 9.34 | 8.98 | 8.62 | 10.80 | 12.11 | 7.13 |
| Heat Content (KCAL/LITER) | 16.83 | 16.38 | 15.69 | 16.02 | 15.12 | 14.62 | 13.89 |

approximated by linear interpolation of the two nearest stations. The derivatives at the mid-point between two stations were estimated by the difference quotient of the concentration change and the interval of $\lambda$. Derivatives at other points were acquired by linear inter polation and extrapolation. Second derivatives were calculated by a repeat application of the derivative scheme.

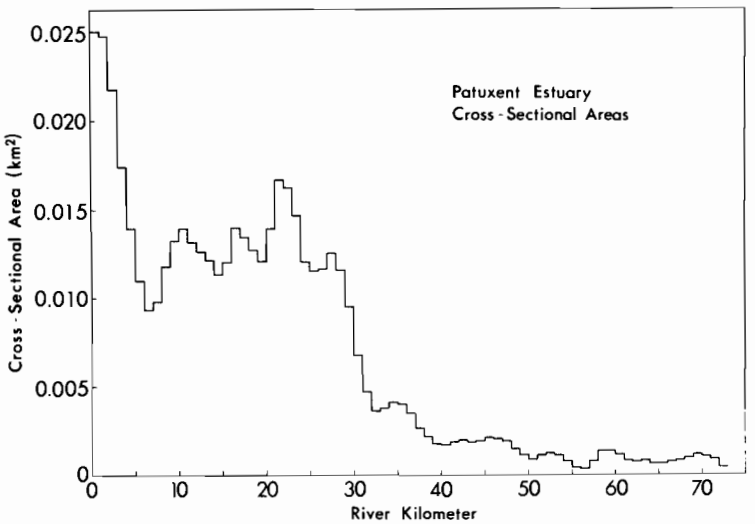



Fig. 2. Patuxent estuary cross-sectional areas.

Over 40% of the area of the Patuxent watershed lies adjacent to the study area, making it impractical to consider that all of the freshwater input occurs at the head of the model. By pro-rating the input according to area, one estimates that Q increases from about 4.75 $M^3$/sec at the head of the Estuary to around 8.10 $M^3$/sec at the mouth. Now observation of the watershed reveals that most of the feeder streams run perpendicular to the longitudinal axis of the Estuary and their mouths are evenly dispersed along both banks. An appropriate assumption, therefore, is that the rate of accumulation of freshwater input, $dQ/dx$, is nearly continuous along the main River axis and proportional to the width of the watershed at that point. Figure 3a shows the schematic representation of the watershed adjacent to the study area. Figure 3b below it illustrates the cumulative riverine input at any point in the Estuary. Under the above assumptions Q varies almost linearly along the region of interest.

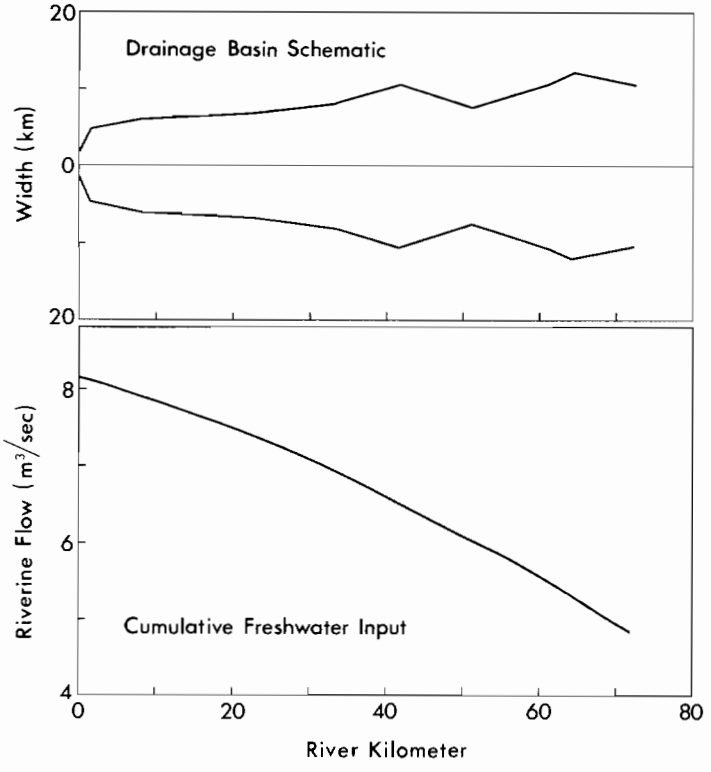



Fig. 3. (a) Drainage basin schematic showing width as a function of distance upstream (b) Cumulative freshwater input as calculated along the estuary

The only remaining terms from equation (4) to be estimated are K and $dK/d\lambda$. They may be calculated from the observed salinity profile. Salt, being a conservative substance, should have a zero intrinsic rate of change. There is a source term for salt, however, which arises from the input of residual salinity ($C_r$) associated with the freshwater input. Equation (4) is then written as:

$$\frac{d}{d\lambda}\left(K \frac{dC}{d\lambda} - CQ\right) = -C_r \frac{dQ}{d\lambda} \tag{5}$$

$$\text{or } \frac{d}{d\lambda}\left[K \frac{dC}{d\lambda} - (C-C_r)Q\right] = 0 \tag{5a}$$

Assuming that advection balances dispersion at steady-state allows one to estimate K as:

$$K = (C - C_r)Q\left(\frac{dC}{d\lambda}\right)^{-1} \tag{6}$$

and subsequently calculate:

$$\frac{dK}{d\lambda} = \left[\frac{d}{d\lambda}(CQ) - C_r\frac{dQ}{d\lambda} - K\frac{d^2C}{d\lambda^2}\right]\left(\frac{dC}{d\lambda}\right)^{-1} \tag{7}$$

To avoid the possibility of a negative value of K resulting from noise in the derivatives of the salinity, the salinity was approximated by the implicit function:

$$(S - .17)^{1.04776}\ [\lambda + 814.04(S-.17) - 10794] = 3255.7$$

where S is the salt content in parts per thousand and $\lambda$ is measured in reciprocal kilometers. Figure 4 shows the measured and approximated salinities.

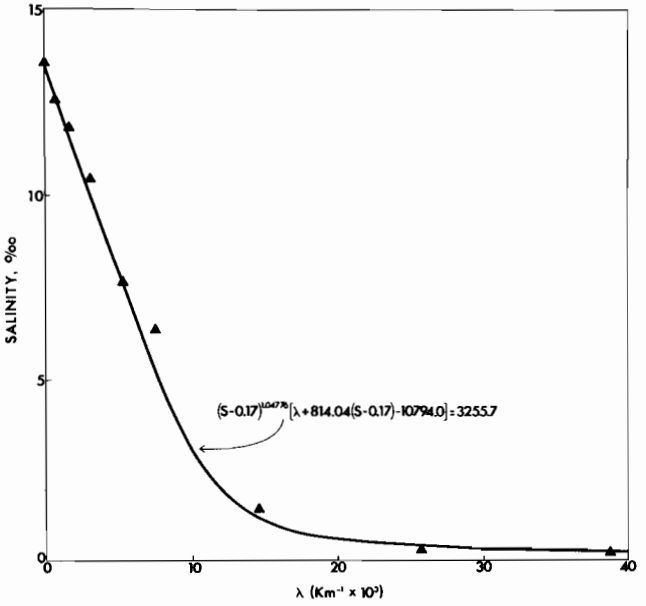



Fig. 4. Salinity as a function of reduced longitudinal coordinate (river month = 0.0).

The longitudinal variation of the dispersion coefficient is depicted in Figure 5. Qualitatively, the variation is similar to that obtained from the Escaut Estuary by Wollast (1973) and discussed by Ronday (1975). The dispersion coefficient declines upstream to a minimum near the point at which the Estuary narrows and rises thereafter to values higher than those found in the lower estuary.

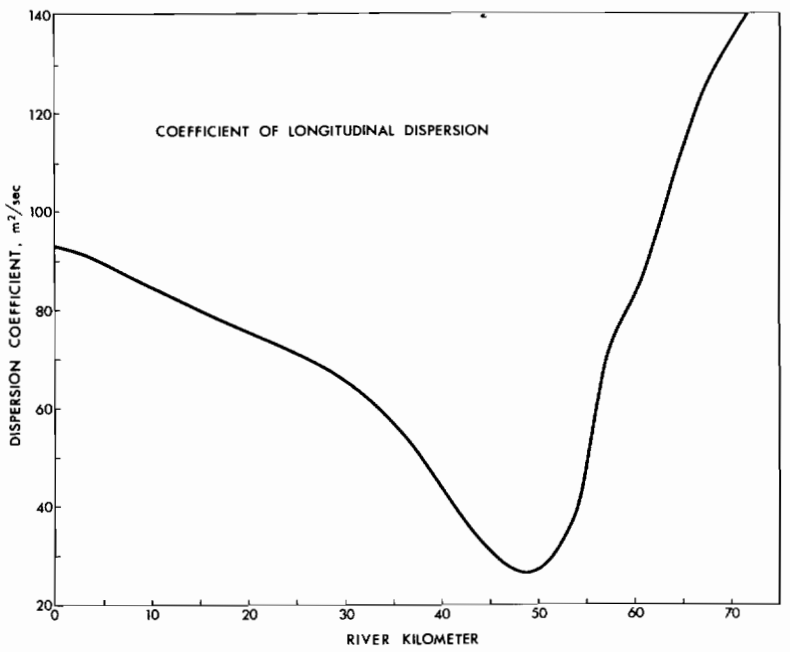



Fig. 5. Calculated coefficient of longitudinal dispersion.

Now Q, K and their derivatives have been estimated independently of the outlined interpolation scheme. A useful test of how compatible the interpolation estimates are with the assumptions used on Q and K would be to calculate the reaction rates of the salt as if it were a reactive substance. Performing such a balance yields a total gain of 0.41 metric tons of salt per day for the entire Estuary. This is an inconsequential fraction of the 5.7 million metric tons of salt present in the Estuary.

DISCUSSION OF THE INTRINSIC RATES OF CHANGE

The calculated profiles for the rates of change are depicted in Figure 6. A positive value for the rate of change indicates a source of the given material and a negative value denotes a sink. The reader will notice that the term "reaction" has been avoided where possible so as not to infer a priori the mechanism contributing to a given source or sink. Other mechanisms besides chemical or biological reactions which might contribute to the intrinsic rates of change include inputs associated with freshwater inflows and adsorption onto sedimenting material.

Chlorophyll a is often used as an indicator of primary productivity of an aquatic ecosystem. The appearance of chlorophyll a is then, indicative of an algal "bloom". A very significant bloom is observed in the upper estuary (60-72 km), and a secondary bloom is observed along the range from 39 to 45 km (Figure 6a). A sewage treatment plant introduces nutrients into the Western Branch which enters the mainstream of the River about two kilometers above the study area. It is reasonable to assume that the observed bloom is in response to this nutrient addition. The secondary bloom is coincident with the initial disappearance of suspended material and is possibly the result of light no longer being limiting to productivity. Chlorophyll a is lost in the remainder of the Estuary presumably due to herbivorous uptake. On balance the Estuary as a whole is a source of approximately 0.04 metric tons of chlorophyll per day.

It is of primary interest to follow the behavior of the nutrient species to see how they relate to the observed patterns of phytoplankton growth and death.

The most striking correlation to the productivity is exhibited by ammonia, Figure 6b. Its rate of change is practically inversely proportional to that of chlorophyll a. With the exception of a small reach of the Estuary (53-57 km), the appearance of one microgram of chlorophyll a is accompanied by the disappearance of approximately ten microgram atoms of ammonia (and vice-versa).

Nitrate and nitrite also exhibit close correlation to the primary production patterns (Figure 6c). The loss of these species is slightly heavier than that of ammonia in the upper estuary (> 45 km) and the inverse correlation with primary production breaks down more drastically in the stretch from 47-57 km. In the lower estuary nitrates appear on almost a mole-for-mole basis with ammonia.

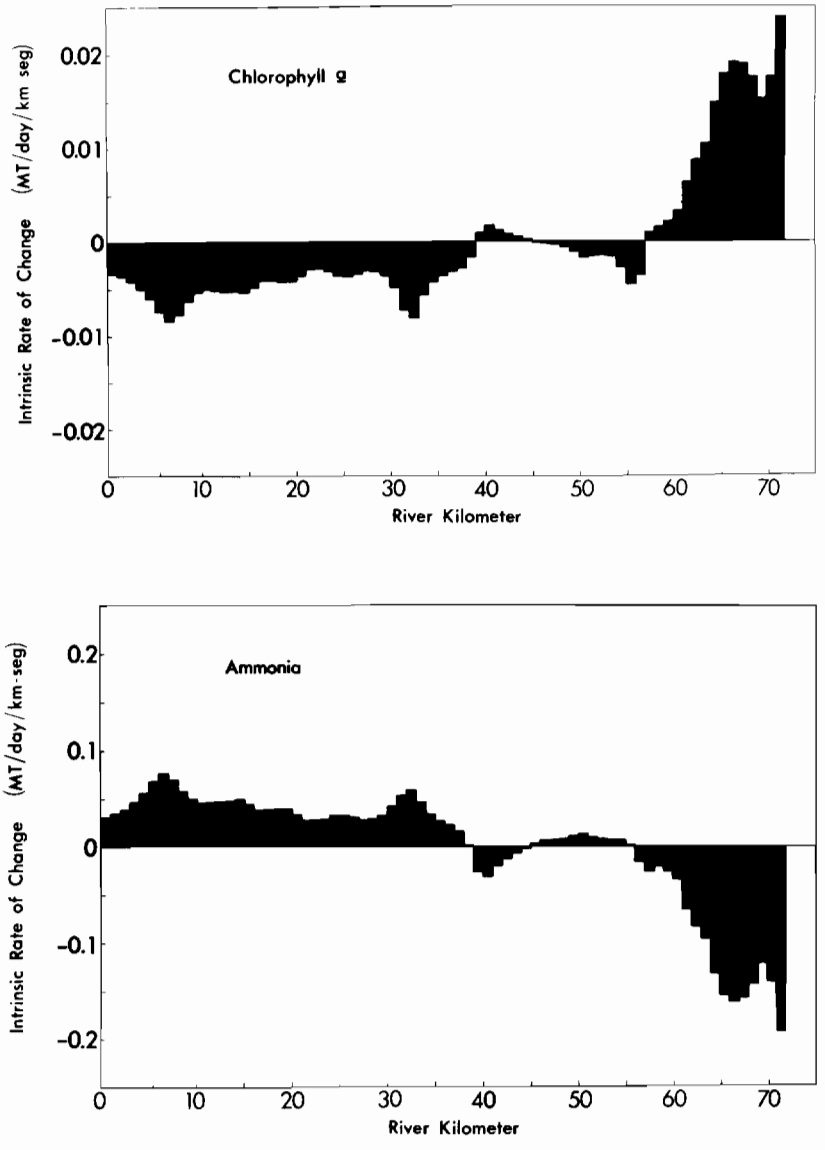
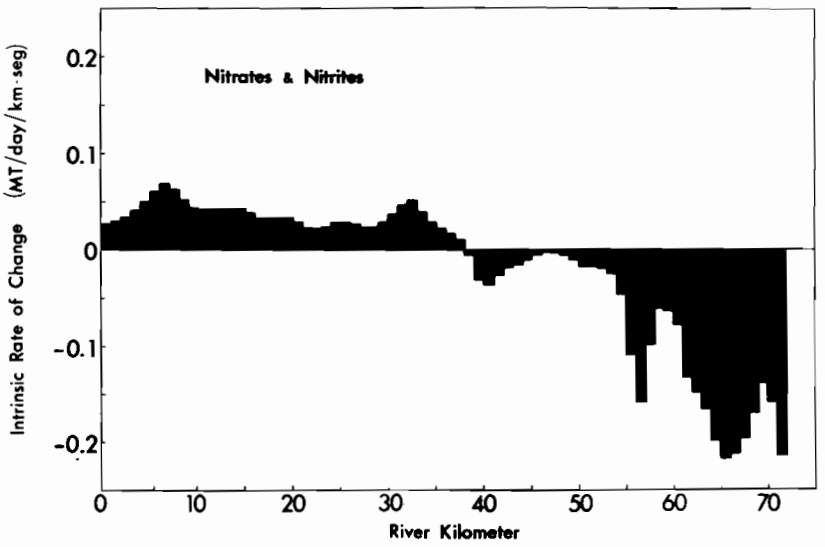
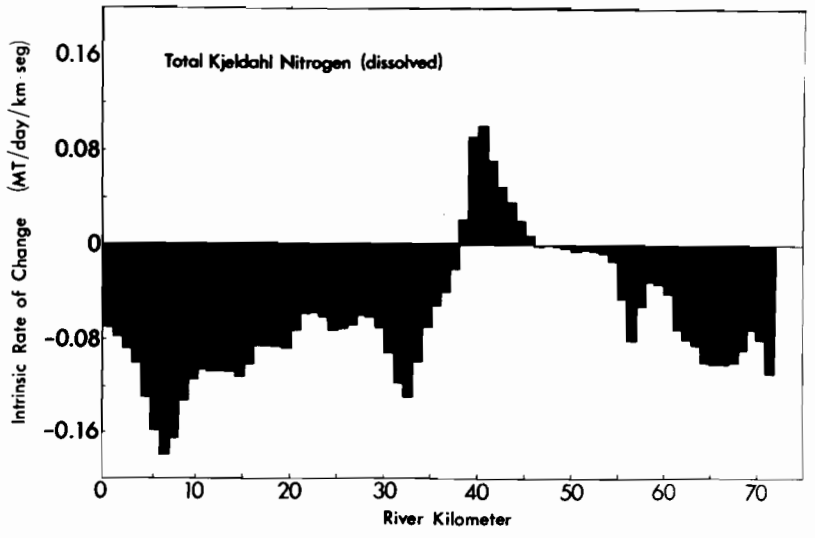
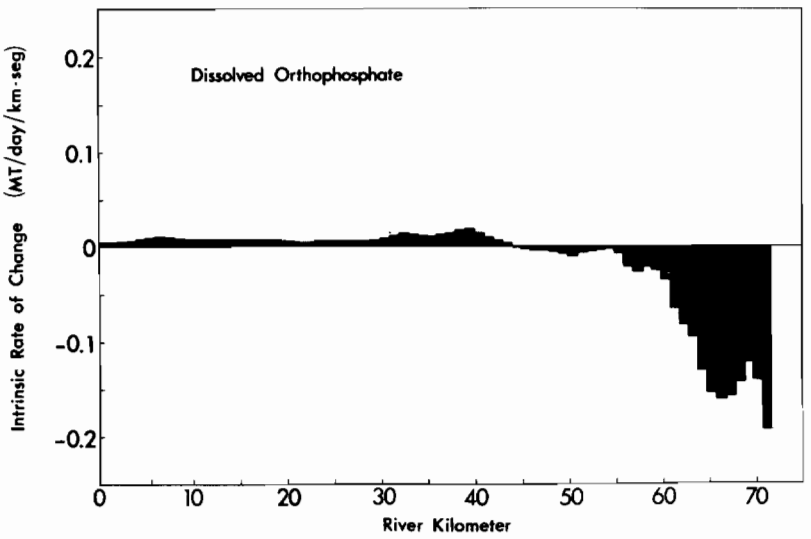
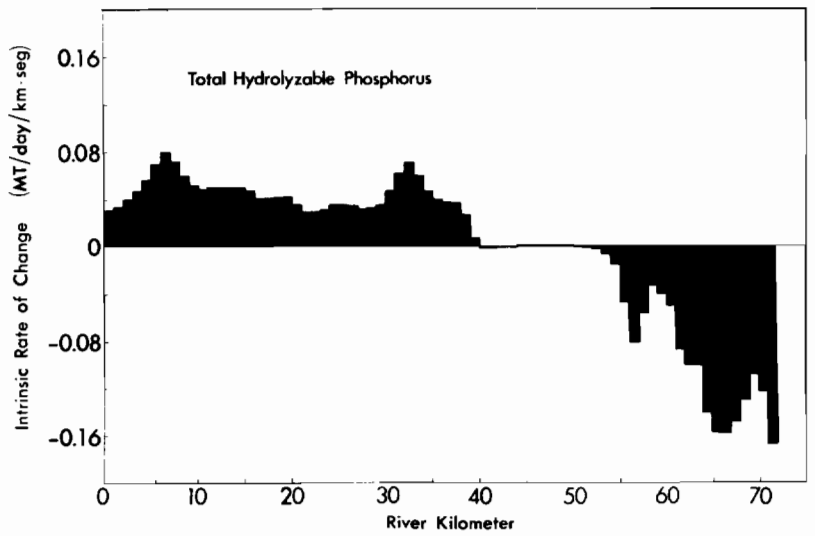


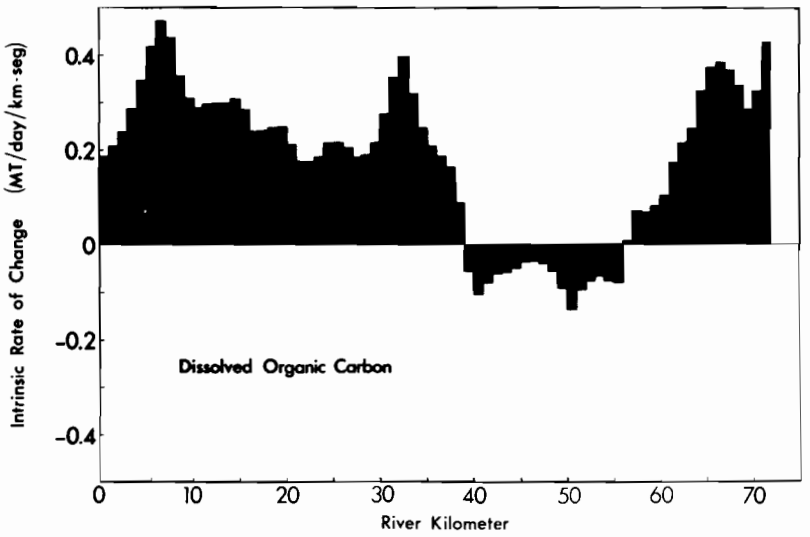

Fig. 6. Daily rates of appearance (+) or disappearance (-) of various substances for kilometer sequents of the Patuxent River Estuary.

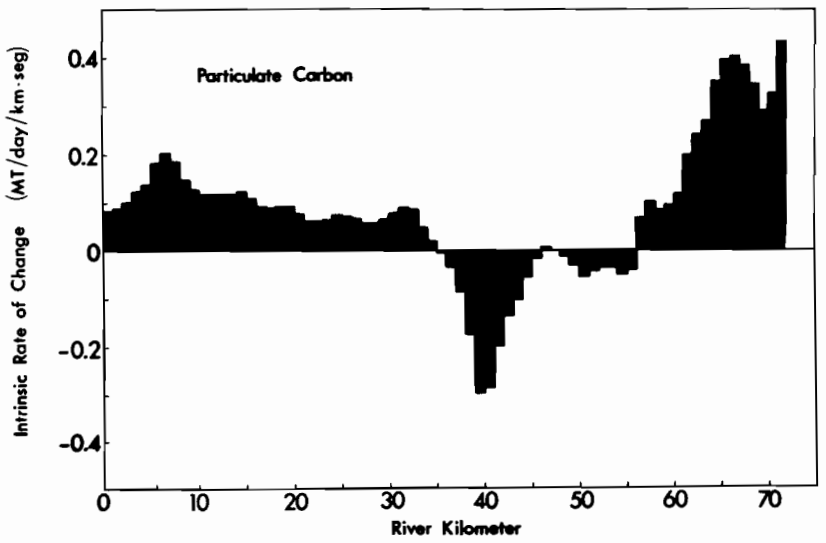

Nitrates & Nitrites
Intrinsic Rate of Change (MT/day/km-seg)
0.2
0.1
0
-0.1
-0.2
0
10
20
30
40
50
60
70
River Kilometer

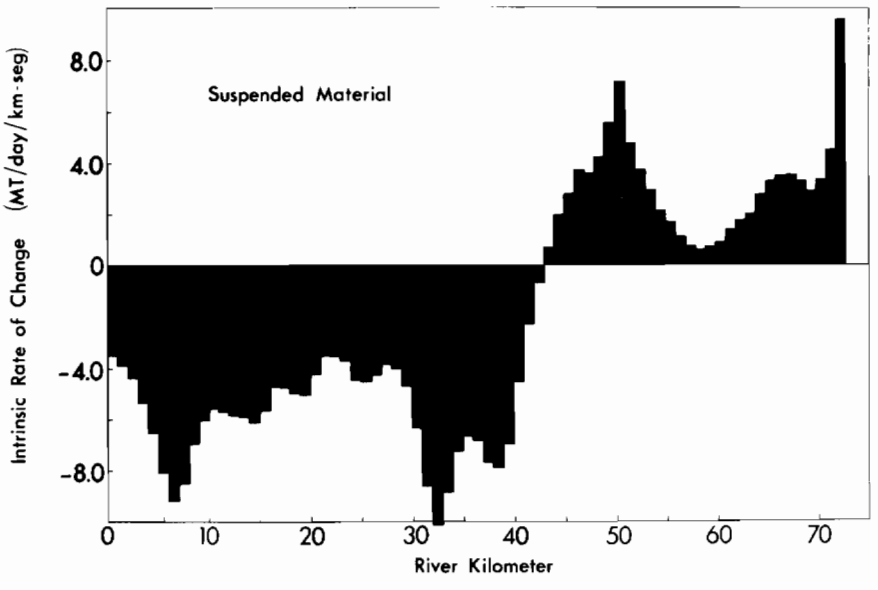

Total Kjeldahl Nitrogen (dissolved)
Intrinsic Rate of Change (MT/day/km-seg)
0.16
0.08
0
-0.08
-0.16
0
10
20
30
40
50
60
70
River Kilometer

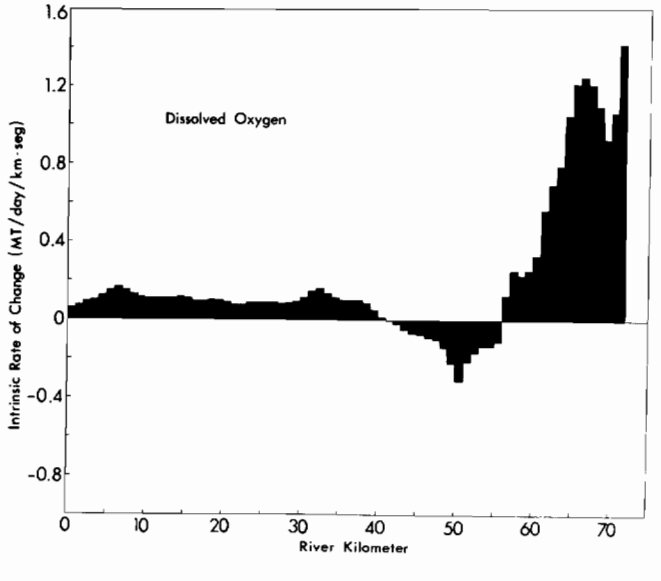

Dissolved Orthophosphate
Intrinsic Rate of Change (MT/day/km·seg)
0.2
0.1
0
-0.1
-0.2
0
10
20
30
40
50
60
70
River Kilometer

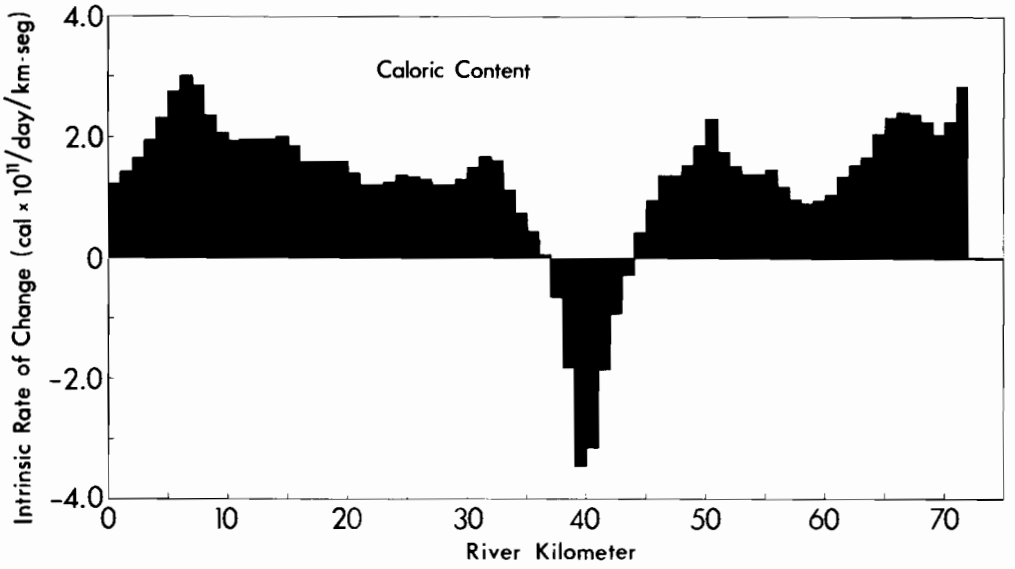

Total Hydrolyzable Phosphorus
Intrinsic Rate of Change (MT/day/km·seg)
0.16
0.08
0
-0.08
-0.16
0
10
20
30
40
50
60
70
River Kilometer


Intrinsic Rate of Change (MT/day/km-seg)
0.4
0.2
0
-0.2
-0.4
Dissolved Organic Carbon
0
10
20
30
40
50
60
70
River Kilometer


Intrinsic Rate of Change (MT/day/km-seg)
0.4
0.2
0
-0.2
-0.4
Particulate Carbon
0
10
20
30
40
50
60
70
River Kilometer


Suspended Material
Intrinsic Rate of Change (MT/day/km-seg)
8.0
4.0
0
-4.0
-8.0
0
10
20
30
40
50
60
70
River Kilometer


Dissolved Oxygen
Intrinsic Rate of Change (MT/day/km-seg)
1.6
1.2
0.8
0.4
0
-0.4
-0.8
0
10
20
30
40
50
60
70
River Kilometer


Caloric Content
Intrinsic Rate of Change (cal x 10^11/day/km-seg)
4.0
2.0
0
-2.0
-4.0
0
10
20
30
40
50
60
70
River Kilometer

Total (kjeldahl) nitrogen is lost throughout the entire length of the Estuary (see Figure 6d) with the exception of the reach from 38-45 km. The gain in total nitrogen coincides with the secondary bloom of phytoplankton just below the sediment trap.

There is loss of all species of nitrogen from the Estuary as a whole. Cumulative loss of total nitrogen amounts to about 4.7 metric ton atoms per day with 1.9 metric ton atoms of nitrate-nitrite and about 0.5 metric ton atoms of ammonia disappearing from the study area each day.

Phosphorous appears to be less correlated to productivity than was the case with the nitrogen species. Dissolved orthophosphate (see Figure 6e) was lost from the upper Estuary (>45 km) with heavy disappearance above 60 km. The lower Estuary hosted a small gain in the same species. Apparently, the dissolved phosphorous does not remain long in the water column after its addition from the Western Branch.

Total phosphorous (Figure 6f) behaves similarly, except that there is significantly more phosphorous gained in the lower Estuary (presumably in the particulate form). Total phosphorous is almost conserved over the whole range with a loss of only 0.4 metric ton atoms occurring per day. Dissolved phosphorous, in apposition, is lost at the rate of 1.7 metric ton atoms per day.

There are several hypotheses which might explain the observed patterns of phosphorous behavior. The phosphorous lost in the upper Estuary is likely due to adsorption to the suspended sediments. There does not appear to be any uptake of dissolved phosphorous in the region of the secondary bloom. The source of phosphorous in the lower Estuary is in question. It could originate in the main stem of the Bay, or it could conceivably be regenerated from the sediments.

Dissolved and particulate carbon (see Figures 6g, h) follow similar patterns. Both are accreted in the upper regions (>55 km) and the lower Estuary (<35 km), but the forms are lost in the transitional region. The bloom and detrital contributions from the marsh are likely sources of carbon in the upper reach. Metabolic products could possibly explain the source of carbon in the lower Estuary. The disappearance of chlorophyll *a* in the lower Estuary does not imply the absence of carbon fixation in these regions. It simply states that losses (e.g. consumption by grazers) exceeds production by growth. The productivity of the lower Estuary is

revealed by the carbon figures. Over 20 metric ton atoms of carbon are produced each day by the study area with 13.5 ton atoms appearing in the dissolved phase and 6.7 ton atoms in the particulate form.

The calculations reveal (Figure 6i) that 150 metric tons of suspended material are lost to the system each day with most of that figure probably going to the sediments. The upper region where suspended material is accreted is well demarcated from the lower region (<43 km) where sedimentation dominates.

The bloom appears to be a net producer of oxygen, even when averaged over the diurnal period. The marked contribution of oxygen from the bloom dominates Figure 6j. Immediately downstream of the bloom area is a region (41-56 km) of oxygen depletion. The region of depletion is probably a combination of the Streeter - Phelps oxygen sag and the lowered oxygen solubility associated with the warmer water in the vicinity of the power plant out fall (km 46). The lower Estuary exhibits a gradual recovery from the sag.

The assumption of steady-state is probably weakest when made upon the thermal structure of the Estuary. During the Autumn the upper River is dominated by the cooler runoff water, whereas the lower Estuary is kept warmer by exchange with the heat reservoir of the Bay. Traveling with a parcel of river water, one would observe a warming trend as one proceeded downriver. Figure 6k shows that this is indeed what is observed throughout most of the Estuary, with the notable exception of a region downstream of the power plant effluent (37-43 km) where the excess heat from the power plant is being dissipated.

## FUTURE WORK

The logical next step in the modeling process is the correlation of the calculated rates of change with the observed concentrations (or prescribed functions thereof) to culminate in a kinetic scheme for the chemical and biological species. This would result in a complete steady-state, tidally averaged model of the Patuxent kinetics. Using the kinetic scheme thus derived it would be interesting to release the assumption of steady-state and see how the derived model would respond to changes in riverine flow and nutrient input. With any degree of success in this endeavor, the next progression would be to a one-dimensional dynamic model which could be calibrated to the hourly data. The parameters derived from the tidally-averaged model should provide a convenient starting point for the calibration of the dynamic model.

No matter how complete the Patuxent model may become, its applicability will always be limited to the fall season unless it can be calibrated against data from other seasons. Hence, there is a desire on the part of the authors to repeat such synoptic surveys during other seasons of the year.

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REFERENCES

Environmental Protection Agency. 1974. Methods for Chemical Analysis of Water and Wastes. EPA-625-16-74-003 Office of Technology Transfer, Washington, D.C.

Heinle, D. R. and D. A. Flemer. 1976. Flows of Materials between Poorly Flooded Tidal Marshes and an Estuary. Mar. Biol. 35:359-373.

Holm-Hansen, O., C. J. Lorenzen, R. W. Holmes, and J. D. H. Strickland. 1965. Fluorometric determination of chlorophyll. J. Cons. Perm. Int. Explor. Mer. 30:3-15.

Menzel, D. W. and R. F. Vacarro. 1964. The measurement of dissolved organic and particulate carbon in seawater. Limnol. Oceanogr. 9:138-142.

Mountford, K., R. S. Mullen, and R. S. Shippen. 1972. Patuxent River Primary Productivity Profiles and Surface Phytoplankton Data. Benedict Estuarine Laboratory, Benedict, Maryland. Unpublished Manuscript.

Ohlhorst, C. W. 1976. Analysis of Six Broad Band Optical Filters for Measurement of Chlorophyll-a and Suspended Solids. NASATMX-339 National Aeronautics and Space Administration, Langley, Virginia.

Ronday, F. C. 1975. Etude de l'envasement et de la variation longitudinale du coefficient de dispersion dans des estuaires partiellement stratifiés. Annales des Travaux Publics de Belgique, No. 4.

Strickland, J. D. H. and T. R. Parsons. 1972. A Practical Handbook of Seawater Analysis. Fish. Res. Bd. Can., Ottawa.

Ulanowicz, R. E., D. A. Flemer, D. R. Heinle, and C. D. Mobley. 1975. The A-Posteriori Aspects of Estuarine Modeling. pp. 602-616 in Vol. 1, L. E. Cronin (ed.), Estuarine Research, Academic Press, New York.

Ulanowicz, R. E., D. A. Flemer, D. R. Heinle and R. T. Huff. 1978. The Empirical Modeling of an Ecosystem. Ecol. Modelling, 4 (in press).

Wollast, R. 1973. Origine et mécanismes de l'envasement de l'estuaire de l'Escaut. Service d'Oceanographie chimique. Insitut de Chimie Industrielle. Universite Libre de Bruxelles et Laboratorie de Recherches Hydrauliques - Bogerhout. Ministere des Travaux Publics de Belgique.