1967

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Proceedings of

THE NATIONAL SYMPOSIUM ON ESTUARINE POLLUTION

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August 23 to 25, 1967

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NUTRIENT ASSIMILATION IN A VIRGINIA TIDAL SYSTEM

By Morris L. Brehmer[1]

INTRODUCTION

Over-enrichment leading to environmental degradation and the production of aquatic nuisance conditions have destroyed the multi-use potential of several coastal tidal systems in the United States. The Middle and South Atlantic and the Gulf Coast drainage basins are especially vulnerable to this type of destruction because of their hydraulic characteristics. Many are drowned pre-Pleistocene river valleys having a large basin capacity relative to the fresh-water inflow. This results in a horizontal-boundary type estuary[2] characterized by higher salinities on the left side (looking downstream) and the absence of a sharp salinity gradient from surface to bottom of the water column. The surface waters have a net downstream movement and the bottom waters have a net upstream movement with a theoretical level of no net motion near mid-depth. The time of passage or net non-tidal movement in the fresh-water tidal section is almost directly related to the inflow rate at the most downstream physical barrier and to the basin capacity.

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[2] Pritchard, D. W., "Salinity Distribution and Circulation in the Chesapeake Bay Estuarine System," Journal of Marine Research, Vol. 11, No. 2, 1952, pp. 106-123.

Degradation of these systems usually occurs during the summer months when fresh-water flow rates are minimal and when primary productivity rates are high. The conditions produced are characterized by extremely high phytoplankton levels which make the water aesthetically undesirable and which are capable of reducing the dissolved oxygen in the water to sub-minimal levels during the period of darkness. It is also thought that over-enrichment may produce changes in the composition of the phytoplankton in which the dominant forms may be unicellular green algae which do not serve as a satisfactory food supply for marine filter-feeding animals.

This study was initiated and carried out to determine the levels of enrichment in the tidal James River and in the Nansemond, a tributary of the James. The biotic and abiotic assimilation of the nutrients was determined and the phytoplankton response evaluated.

THE JAMES RIVER SYSTEM

The James River is the most southerly major tributary of the Chesapeake Bay system. It is approximately 400 miles in length and has a drainage area of over 10,000 square miles. The drainage basin includes parts of four physiographic provinces--the Coastal Plain, Piedmont, Blue Ridge, and Ridge and Valley. The mean fresh water as measured at the Richmond gaging station is approximately 7,500 c.f.s., with recorded extremes from 329 to 325,000 c.f.s.[3]

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[3] Virginia Department of Conservation and Economic Development, Division of Water Resources, "Notes on Surface Water of Virginia," 1960, 88 p. (mimeo).

The James River is tidal from its mouth at Hampton Roads to Richmond, a distance of approximately 90 nautical miles. The average salt-water intrusion extends to Jamestown Island, 35 miles upstream from the mouth. During periods of extremely high run-off, the fresh water may extend down to a point 20 miles from the mouth, and during drought conditions, measurable quantities of dissolved solids of marine origin may be found at Jordan Point, 64 miles from the mouth. The salinities ranged between 20 and 24 ‰ at a station 4 miles (Fig. 1, J-4) from Chesapeake Bay during the period of investigation.

The mean tidal range is approximately 2.6 feet at Hampton Roads and 3.2 feet at Richmond. The tidal current velocities range between 0.8 and 1.5 knots, with surface ebb velocities usually slightly higher than surface flood velocities. The opposite is true for the velocities of the deeper waters. The system has two high and two low tides each 24-hour period.

The tidal James is approximately 5 miles wide in the Hampton Roads area but decreases to 0.1 mile in the upper reaches. Although dredging is required in many areas to maintain a 40-foot navigation channel in the Hampton Roads area and a 25-foot channel to Richmond, depths to 90 feet are recorded.

The Nansemond River is a small, 16-mile tributary emptying into Hampton Roads eight miles upstream from the mouth. The fresh-water discharge into the Nansemond is modified by impoundments on the tributary streams. The water held in the reservoirs is used by the cities of Norfolk and Portsmouth and, after use, is discharged as waste water into the Elizabeth River system, another tributary of the lower James.

A relatively small amount is used by the city of Suffolk and discharged through a sewage treatment plant located 15.5 miles from the mouth. The modified fresh-water discharge pattern produces a salt-water environment from the mouth to the first dam at all times except during periods of high run-off. The salinities at a station 2 miles upstream (N-2) from the confluence with the James ranged between 11 and 20 ‰, and the salinities at a station 15 miles from the mouth ranged between 0.4 and 12 ‰ during the study period.

This system was chosen for the second part of the investigation because the modified fresh-water discharge patterns result in flushing rates which are more comparable to those of the upper tidal James, but the Nansemond represents an estuarine environment, whereas the James presents a tidal fresh-water environment.

SOURCES OF ENRICHMENT

Nutrient enrichment of the estuarine and tidal James is largely confined to three areas--the lower section near the mouth where effluents from the cities of Hampton Roads are discharged, the Hopewell area, and the upper section below Richmond. The upper tidal region has the lowest assimilation capacity because of the basin capacity to fresh-water discharge ratio.

The Metropolitan Richmond area has a population of nearly 500,000. A part of the domestic wastes receives secondary treatment, a part only primary treatment, and approximately 33% is untreated. The BOD loading[4] exceeds the assimilation capacity of the river during low flow conditions. In addition, the city discharges approximately 2.7 metric tons of phosphorus and 8.2 metric tons of nitrogen in various inorganic and organic forms each day. Assuming no buildup due to tidal oscillations, this level of nutrient accrual would result in 30 ug.at P l^{-1} and 200 ug.at N l^{-1} enrichment when the fresh-water discharge at the Fall Line is 1000 c.f.s. The mean low water basin volume in the upper reaches is approximately 6 X 10^8 gallons per mile. Data recorded at a VIMS hydrographic station located 75 miles upstream from the mouth indicated a non-tidal current of 0.75 mile per day during a period when the fresh-water discharge was between 750 and 800 c.f.s.

The city of Hopewell, which is located approximately 30 miles downstream from Richmond, also adds a nutrient loading to the system. The data indicate a significant increase in nitrogen concentrations in the vicinity of the Hopewell industrial and domestic outfalls. Nutrients are added in the Hampton Roads area, but here the dilution capacity is high and the quantities introduced are hardly detectable.

The Nansemond River receives nutrients from sewage treatment plant effluents discharged by the city of Suffolk. This city, with a population of approximately 13,000, discharges approximately 1.5 X 10^{-2} metric tons of phosphorus and 4.5 X 10^{-2} metric tons of nitrogen into the headwaters each day. The sewage treatment plant outfall is located just downstream from a dam, thus eliminating significant upstream transport during flood tide currents.

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[4] O'Connor, Donald J., "Estuarine Distribution of Nonconservative Substances," *Journal of the Sanitary Engineering Division*, ASCE, Vol. 91, No. SA 1, Proc. Paper 4225, February, 1965, pp. 23-42.

The nutrient concentration of a Nansemond River station located 14 miles upstream from the mouth (N-14) and a James River station located 76 miles upstream from the mouth (J-76) were compared (Table 1). The unreactive phosphorus values are included because of the short turnover time for this element. Although the data show a rather high level of variability both within and between months, the oxidized forms of nitrogen and phosphorus are generally within the same range. The data for September and December will be compared in the Discussion.

METHODS

Water samples for analyses were collected monthly at slack before flood tide from a 22-foot outboard boat. The tidal characteristics of the James River system make it possible to occupy all stations at surface slack water. The tidal current correction between the mouth and J-76 is 6:05 hours and the correction from the mouth to N-15 of the Nansemond is approximately 3 hours.

Stations were established at approximately 5-mile intervals in the estuarine James and at 10-mile intervals in the tidal fresh-water portion. The station designations as miles from the mouth were J-4, J-10, J-17, J-29, J-36, J-47, J-57, J-68, and J-76. Stations in the Nansemond were established at 2-mile intervals in the lower portion and at 1-mile intervals in the upper reaches. The station designations were N-2, N-4, N-6, N-8, N-10, N-11, N-12, N-13, N-14, and N-15 (Fig. 1). The sampling stations on the James River were occupied from May 1965 through May 1966, and the stations on the Nansemond River were occupied from July 1966 through June 1967.

Table 1.--Reactive (RP) and Unreactive (UP) Phosphorus and Nitrite and Nitrate Nitrogen at Two Stations on James and Nansemond Rivers.

NANSEMOND N-14 JAMES J-76

PHOSPHORUS (ug.at l^{-1})

Month	RP	UP	TOT.	Month	RP	UP	TOT.
July 1966	7.91	7.56	15.47	July 1965	3.44	2.44	5.88
Aug.	9.94	4.76	14.70	Aug.	6.10	4.50	10.60
Sept.	8.57	4.73	13.30	Sept.	15.00	6.70	21.70
Oct.	8.31	3.29	11.60	Oct.	3.60	2.23	5.83
Nov.	9.12	2.58	11.70	Nov.	12.90	4.90	17.80
Dec.	7.14	5.06	12.20	Dec.	7.54	7.66	15.20
Jan. 1967	10.24	4.16	14.40	Jan. 1966	5.22	6.66	11.88
Feb.	6.36	4.24	10.60	Feb.			
Mar.	1.37	4.83	6.20	Mar.	1.32	2.28	3.60
Apr.	9.89	4.91	14.80	Apr.	1.01	6.19	7.20
May	5.12	7.28	12.40	May	1.24	2.36	3.60
June	7.76	6.54	14.30	June 1965	1.86	3.44	5.30

NITROGEN (ug.at l^{-1})

Month	NO_2^-.N	NO_3^-.N	TOT. N	Month	NO_2^-.N	NO_3^-.N	TOT .N
July 1966	0.20	8.00	8.20	July 1965	0.90	14.00	14.90
Aug.	1.25	20.60	21.85	Aug.	0.11	14.90	15.01
Sept.	1.40	20.70	22.10	Sept.	0.01	2.00	2.01
Oct.	3.10	27.40	30.50	Oct.	0.62	50.70	51.32
Nov.	6.50	32.80	39.30	Nov.	6.50	10.00	16.50
Dec.	5.25	29.60	34.85	Dec.	1.70	42.20	53.90
Jan. 1967	3.20	32.90	36.10	Jan. 1966	2.10	45.00	47.10
Feb.	0.85	29.00	29.85	Feb.			
Mar.	0.15	27.80	27.95	Mar.	0.65	16.20	16.85
Apr.	1.30	17.00	18.30	Apr.	0.68	7.20	7.88
May	1.60	26.80	28.40	May	0.42	11.20	11.62
June	0.05	6.00	6.05	June 1965	0.59	54.00	54.59

Water samples were collected from the surface to the bottom at 6-foot intervals using a submersible pump. Temperature, salinity, pH, alkalinity, and dissolved oxygen profiles were made, and the transparency of the water was recorded. Water samples were collected at 3 feet below the surface and at 3 feet above the bottom for suspended solids (including loss on ignition and fixed residue); soluble reactive, soluble unreactive, particulate reactive and particulate unreactive phosphorus; soluble organic, ammonia, nitrite, nitrate, and particulate organic nitrogen; and chlorophyll "a". Qualitative phytoplankton and primary productivity determinations were made at selected stations[5], [6]. Where possible, samples were fixed or iced and returned to the laboratory for analyses. Accepted gravimetric, titrametric, absorptiometric, and fluorometric methods as described in the literature were utilized for the analyses.

PHYTOPLANKTON RESPONSE

Environmental degradation resulting from over-enrichment is produced by the atypical phytoplankton populations which reduce the aesthetic value and modify the dissolved oxygen levels in the water. Undesirable conditions and fish kills had been reported from the upper tidal James River on several occasions.

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[5] Brehmer, Morris L., and Haltiwanger, Samuel O., "A Biological and Chemical Study of the Tidal James River," Special Scientific Report in Applied Marine Science and Ocean Engineering, No. 6, Virginia Institute of Marine Science, 1966, 32 p. + Appendix (mimeo).

[6] Brehmer, Morris L., and Haltiwanger, Samuel O., "A Biological and Chemical Study of the Nansemond River," (ms).

Phytoplankton biomass, as indicated by chlorophyll "a" levels in the water, increased as water temperatures increased at the fresh-water stations, J-57 and J-76, with the highest values recorded in September (Fig. 2). Dense blooms, surface scum, and shoreline depositions were observed. The estuarine stations, J-17 and J-36, exhibited only a slight increase in phytoplankton biomass in the fall of the year. Environmental degradation was not observed in the lower reaches.

Phytoplankton populations of the Nansemond River displayed a different response pattern to the levels of enrichment described (Fig. 3). With the exception of a bloom at N-14 in June, the population density did not produce aquatic nuisance conditions or environmental degradation. The highest populations were observed during the winter months when water temperatures were minimal.

The composition of the peak phytoplankton populations indicated the difference in response between fresh-water and estuarine environments. Degradation in the upper tidal James River was produced by a blue-green alga, *Anacystis cyanea*, which is typically found in warm, enriched fresh water. The estuarine pulses in phytoplankton standing crop were usually produced by a concentric diatom, *Thalassiosira* sp.

The characteristic increase in the phytoplankton biomass in the estuary is of economic importance to the oyster industry since it coincides with the "fattening" season of the valuable shellfish.

NUTRIENT-PHYTOPLANKTON RELATIONSHIPS

The seasonal abundance pattern of the James River phytoplankton indicated that the organisms in the fresh-water zone reached highest densities in September and then decreased through the winter months. The September data indicate that at Station J-76 the oxidized forms of nitrogen were at minimal levels but that reactive and therefore available phosphorus was present in supra-minimal concentrations. Nitrite and nitrate levels at J-57 located downstream from the Hopewell outfalls increased to high levels, and the phosphorus in the water was combined in unreactive forms (Fig. 4).

The salt water-fresh water transition zone in September was between stations J-47 and J-57. The data therefore indicate that the blue-green algal forms responsible for the aquatic nuisance conditions in the freshwater tidal reach cannot tolerate the unfavorable environment produced by increased levels of dissolved solids and are eliminated.

The mortality and decomposition of such large quantities of phytoplankton would result in the regeneration of the nutrient components into available forms. The data do not indicate that corresponding increases in the phosphorus or oxidized nitrogen forms occurred in the estuarine areas. The surface salinities at J-10, J-22, and J-36 were 19.92, 12.58, and 5.08 ‰, respectively, at the time of sampling, which, assuming near steady-state conditions, would provide a maximum of slightly over 50% dilution with water of marine origin. The reduction in the oxidized forms of nitrogen within this area exceeded 90% and no detectable increase in phytoplankton was noted.

The data for the September sampling period on the Nansemond River indicate that although reactive phosphorus levels were lower, the levels of oxidized nitrogen forms were higher than those measured for the upstream station on the James (Fig. 5). Phytoplankton levels, as indicated by chlorophyll "a" concentrations, did not approach the 50 ugl^{-1} limit which is considered the maximum for aesthetically desirable waters. With the exception of a slight pulse at N-12, a high degree of uniformity existed at all stations from the mouth to the upper reaches.

The immediately or potentially available nutrients in the system decreased by nearly 50% between N-10 and N-14. This reduction in concentration was due in part to dilution by waters of lower nutrient levels which entered the system from Hampton Roads. The surface salinities at N-2, N-10, and N-14 were 20.23, 11.78, and 5.58 ‰, respectively, at the time of sampling.

Nutrient assimilation capacity of estuarine and tidal systems varies seasonally even though fresh-water discharge levels may remain nearly constant. Virginia was within the northeastern United States area which encountered severe drought conditions during the middle 1960's. In 1965, for example, the mean monthly fresh-water discharges as measured at Richmond ranged between 1500 and 1000 c.f.s. from the middle of July through December. The estuary probably approached as near steady-state conditions as could be expected to occur in nature. The data therefore cover low-flow late summer and fall and early winter conditions, all having nearly equal nutrient enrichment and dilution levels.

The December data on the James River show that the nutrients introduced into the system at Richmond and Hopewell are not utilized by fresh-water algal forms (Fig. 6). The oxidized forms of nitrogen were present in quantities far in excess of the minimal levels for phytoplankton reproduction. Reactive phosphorus was measured at all stations. Phytoplankton levels, as indicated by chlorophyll "a" concentrations, showed a progressive increase towards the mouth at Hampton Roads although the maximum level was only 18 ugl^{-1}. Nitrite and nitrate nitrogen levels exhibited a decrease towards the mouth in a pattern similar to those observed in September; however, the decrease was accompanied by an increase in phytoplankton in December.

The Nansemond River enrichment produced a phytoplankton response during December (Fig. 7). The dominant organism, Thalassiosira sp., and the less abundant genera appeared to utilize the excess nutrients in the upper reaches of the river. Nitrite and nitrate nitrogen levels in the lower estuary were nearly comparable to those found in September but the reactive phosphorus levels were minimal.

NUTRIENT-SEDIMENT RELATIONSHIPS

Data from both the estuarine and tidal James and the estuarine Nansemond rivers indicate that the high levels of enrichment in the upstream areas cannot be followed through the system. Theoretically, the nitrogen and phosphorus introduced into the system would be incorporated into planktonic biological material which would serve as a medium of transport with a rate of downstream motion equivalent to the non-tidal current. Organisms carried into a hostile environment would die and settle out on the bottom of the stream bed. The nutrients combined organically would undergo oxidation and mineralization and either be returned to the water column by ionic diffusion or as the result of agitation, or remain incorporated in the sediments. The data did not indicate that significant regeneration of nitrogen or phosphorus was occurring in either system.

A sediment analyses program was initiated to determine the nitrogen and phosphorus levels in the top 1 cm of benthic material. Samples were collected from outside the navigation channel with a grab-type dredge. The contents were carefully discharged into a tray and a top 1 cm core removed. The sample was cooled to 0°C and returned to the laboratory. Sub-samples of the dried sediment were analyzed for ammonia plus organic, nitrite, and nitrate nitrogen and for total reactive and total unreactive phosphorus. The data were calculated as ug g^{-1} dried weight of sample. The data are graphically presented in Figs. 8-11.

Nitrogen levels in the sediments of the James River indicate that unoxidized forms predominate in the benthic deposits. Oxidized forms of this nutrient element are not readily adsorbed on soil particles and are probably lost to the water column by ionic diffusion. The levels found at the ten stations in the estuary and tidal river indicate that increased depositions do occur just downstream from the zone of highest phytoplankton levels but that the concentrations are not as high as would be expected if the plant material formerly in suspension were evenly deposited on the bottom after death. The September data previously presented indicate a reduction in phytoplankton of approximately 90% between Stations J-57 and J-47, whereas the sediment data indicate only a twofold increase in values. The physical aspects of a type B estuary may also contribute to the increase at the head of the estuary since the lower layer has a net upstream current. The head of the estuary represents the area where the energy of the fresh-water inflow is equal to the energy of the upstream salt-water component. This frequently results in higher turbidity levels in the transition zone than in either the estuary or tidal river[7]. High values in this area may be due in part to organic materials of estuarine origin.

Nitrogen levels in Nansemond River sediments did not indicate that a twofold increase existed at any point in the estuary but the values from Station N-6 to N-14 were variable. A significant increase in all forms was evident in the vicinity of N-10 and the unoxidized level increased at N-14. The normal reduction in total nitrogen in the water column from the head to the mouth cannot be accounted for in the sediment data.

Unreactive and reactive phosphorus levels in the top 1 cm of James River sediments did not indicate that large quantities of this nutrient were being removed from the biocycle by incorporation into benthic deposits. The highest levels were found in the vicinity of the transition zone but the increase was less than twofold. The high value at J-76 can probably be attributed to mineralized settleable solids originating from untreated wastes discharged by the city of Richmond.

Unreactive phosphorus levels were highest just downstream from the area which supported the highest phytoplankton populations. Its fate after oxidation of organic matter cannot be determined from the data.

Sediment phosphorus data from the Nansemond River indicate a gradual decrease in both reactive and unreactive forms from the head to the mouth. The source of the phosphorus is at the head of the river. The distribution

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[7] Brehmer, Morris L., "Turbidity and Siltation as Forms of Pollution," Journal of Soil and Water Conservation, Vol. 20, No. 4, 1965, pp. 132-133.

is probably the result of the net upstream current in the bottom water layer providing energy to retain clays and organic material at the head of the estuary. This mode of action is substantiated by the nearly equal values and proportions of reactive and unreactive phosphorus found in the James River near the mouth of the Nansemond.

DISCUSSION

Estuarine and tidal water pollution is a serious problem in most coastal areas. Water quality degradation may result from 1) organic loadings which exceed the assimilation capacity, 2) bacterial contamination, and/or 3) over-enrichment with the production of aquatic nuisance conditions and sub-minimal oxygen levels during periods when respiration consumption rates exceed photosynthetic production rates. The first two sources of pollution can largely be eliminated by utilizing modern treatment methods; however, a technique is not available for economically removing nitrogen and phosphorus from multi-million gallons of effluent per day. Compounding the problem is the fact that many cities are located at the head of the tidal system where the assimilation capacity for all three types of pollutants is the lowest.

Methods alternative to nutrient removal have been proposed. These include low-flow augmentation which merely increases the assimilation capacity by dilution and the piping of treated effluents directly to the ocean or to the estuary where natural assimilation capacities are greater. The latter solution is viewed with skepticism by estuarine scientists because it would represent a type of "water piracy" which would completely change the salinity regime and hydraulic characteristics of the system during low-flow conditions. These changes can be evaluated with hydraulic model studies. However, it is not possible to model the biological response or the nutrient assimilation capacity of estuarine and marine waters.

The data presented from the two systems studied indicated that the assimilation capacities of tidal fresh-water and tidal estuarine systems differ as the result of differences in biological responses. Tidal fresh-water reaches having poor flushing characteristics support a flora which is more characteristic of a lake than a stream, even though the maximum currents may approach 2 knots. During the summer months, introduced available nutrients are rapidly incorporated into phytoplankton cellular material and removed from solution. The data indicated that the density of the summer phytoplankton population was limited by available nitrogen since the chlorophyll "a" levels increased significantly when a second source was added to the system. Blue-green forms responsible for the aquatic nuisance conditions (chlorophyll "a" levels exceeding 50 ugl^{-1}) could not tolerate even low salinities and a 90% reduction in chlorophyll was measured within a 10-day "time of passage" from the area of highest concentration. Nutrient regeneration and a second biological response could not be followed through the estuary. Higher nutrient assimilation capacities during the winter months appear to be due primarily to the absence of fresh-water algal forms that can utilize the available nitrogen and phosphorus. Reactive phosphorus and nitrite-nitrate nitrogen were present in significant quantities after water temperatures dropped below 10°C but aquatic nuisance conditions did not develop.

Nutrients discharged at the head of the tidal system may either remain in ionic form and remain as a part of the aqueous solution, enter the biological cycle and be either temporarily or permanently combined into organic material, or be removed abiotically from solution through the production of insoluble compounds or by adsorption on particulate matter in suspension. The latter possible method of nutrient removal from the water column was investigated through sediment analyses.

Although the nutrient content of the top 1 cm of dried sediments was 10^3 to 10^4 higher than usually measured in the water column, the data did not establish that an area existed which served as a nutrient sink. It is unlikely that nutrient-bearing particles would be so evenly distributed over 72 miles of estuary and tidal river that no more than a twofold concentration over the mean level could be found at any point.

Nutrients introduced directly into waters having a measurable salinity produced an increase in the standing crop of phytoplankton but did not degrade the environment through an extended zone. The phytoplankton response was the most general during the winter months when diatoms dominate the population.

Many unmeasurable variables affecting phytoplankton response to environmental factors produce uncertainties in predicting population levels that may develop in estuarine systems. For example, dense "red tides" developed in the relatively unenriched lower York River during the summers of 1963, 1964 and 1965 but none were observed in 1966 or 1967. "Red tides" were not observed in the two systems studied during the period of investigation even though both receive heavy enrichment. It appears to be possible, however, to predict that aquatic nuisance conditions will develop in tidal fresh water during periods of low run-off and high water temperatures.

The absence of a "zone of regeneration" and an apparent "loss" of nutrients in both tidal and estuarine systems cannot be explained from the data. An undetermined quantity would be incorporated into sessile and rooted plants which are found in marshes bordering the streams. These may be released and flushed from the systems during periods of heavy rainfall and never enter the stream's biological cycle. Catadromous and anadromous species of fish would utilize the systems transport quantities of nitrogen and phosphorus from the fresh-water and estuarine reaches to the ocean. Man's harvest of seafood also serves as a means of nutrient removal. The estuarine James River has an annual harvest of approximately 3 million bushels of oysters per year. Assuming that none of the nutrients re-enter the system, the calculated annual phosphorus removal by this activity is approximately 46 metric tons. However, this is equivalent to only 17 days enrichment by the Metropolitan Richmond area.

Estuarine and tidal systems are valuable natural resources. Although probably best known for their roles as avenues of commerce, they are used for seafood production, recreation, industrial water supply, domestic water supply, irrigation, and for the assimilation of the byproducts of man's activities. They are unique biological systems in that they represent the link between the marine and fresh-water environments. Environmental degradation in one short section may affect populations not only upstream and downstream from that section but also in contiguous oceanic waters.

For example, the destruction of striped bass spawning areas in the Jamestown Island area would modify population levels in the entire estuary, in Chesapeake Bay and its tributaries, and in the Atlantic Ocean as far north as Cape Cod.

The data presented indicate that estuaries and tidal rivers are vulnerable to degradation by over-enrichment. Economical methods for the removal of nutrients from wastewater must be developed if these systems are to retain their characteristics as truly multi-purpose natural resources.

CONCLUSIONS

During low fresh-water discharge periods, the tidal fresh-water James River receives nutrient loadings exceeding the assimilation capacity. Environmental degradation results from the development of atypical phytoplankton populations which produce aesthetically undesirable waters and modify dissolved oxygen levels. Available nitrogen and phosphorus are incorporated into blue-green algal forms and transported downstream at a rate equivalent to the non-tidal flow. Available nitrogen appeared to be the limiting factor during the summer months since a second pulse in phytoplankton developed after the water mass passed a downstream nitrogen source.

A 90 per cent reduction in phytoplankton standing crop occurred after the water mass became brackish. Neither regeneration of nutrients nor a second phytoplankton response was measured in the estuarine reach. Sediments did not appear to be serving as a nutrient trap, since only a twofold increase in phosphorus and nitrogen was found in the sediments in the transition zone.

No aquatic nuisance conditions were detected during the winter months even though nutrient accrual and dilution rates were comparable to the summer values. The oxidized nutrient forms in the water column increased but it appeared that no phytoplankton species present in the population could develop bloom conditions.

Comparable nutrient levels in low to medium salinity waters did not produce environmental degradation in an extended section of the river. "Red tide" conditions did not develop during the period of investigation.

The data indicate that water containing dissolved solids of marine origin can assimilate higher nutrient levels than fresh water without producing aquatic nuisance conditions.

SUMMARY

Nutrient assimilation and phytoplankton response was measured in the James River estuary and tidal river and in the Nansemond estuary.

The assimilation capacity of the tidal fresh-water reaches increased as the water temperatures decreased in the fall. The most extensive estuarine phytoplankton response was measured during the winter months.

ACKNOWLEDGMENTS

This investigation was partially supported with funds provided through Public Health Service Contract No. PH 86-65-86 and Federal Water Pollution Control Administration Contract No. WA66-12.

The author wishes to thank Messrs. S. O. Haltiwanger, W. I. Simmonds, J. R. Greene, and the several graduate students who contributed to the program.

Contribution No. 255 from the Virginia Institute of Marine Science, Gloucester Point, Virginia.

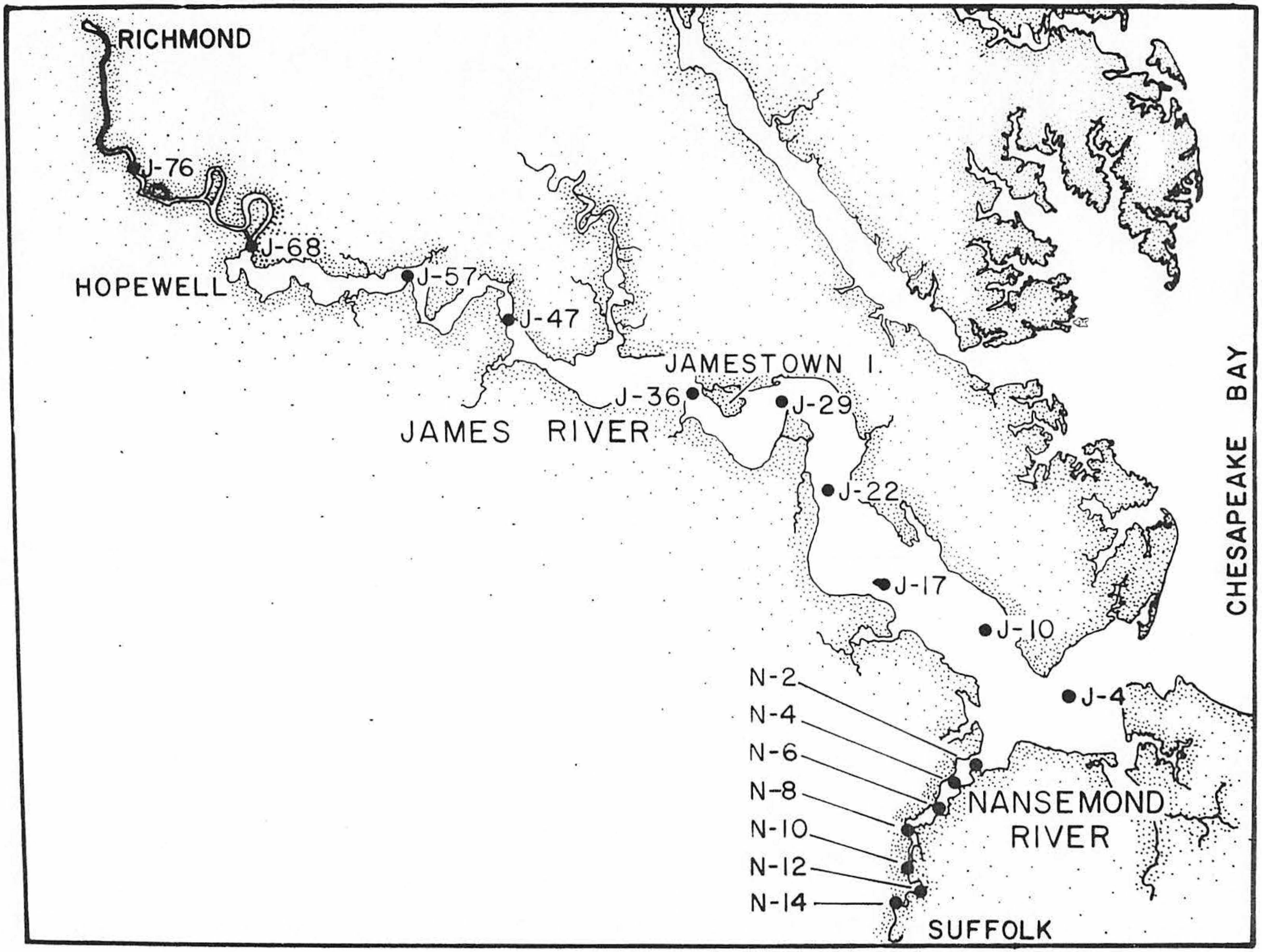

Fig. 1.--James and Nansemond Rivers. Sampling Stations Designated According to Miles from Mouth.

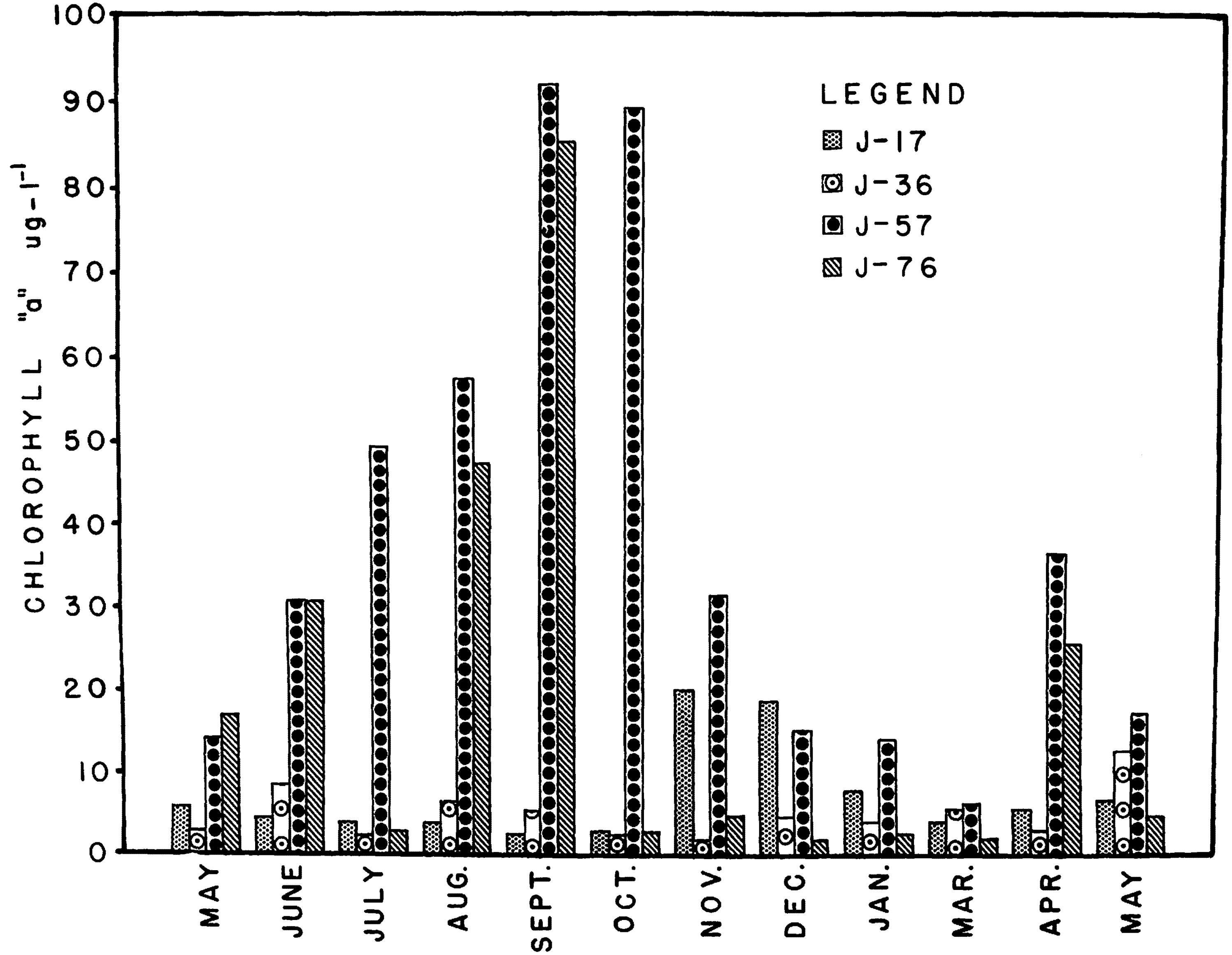

Fig. 2.--Phytoplankton Levels at Two Estuarine and Two Fresh-water Stations on the Tidal James River.

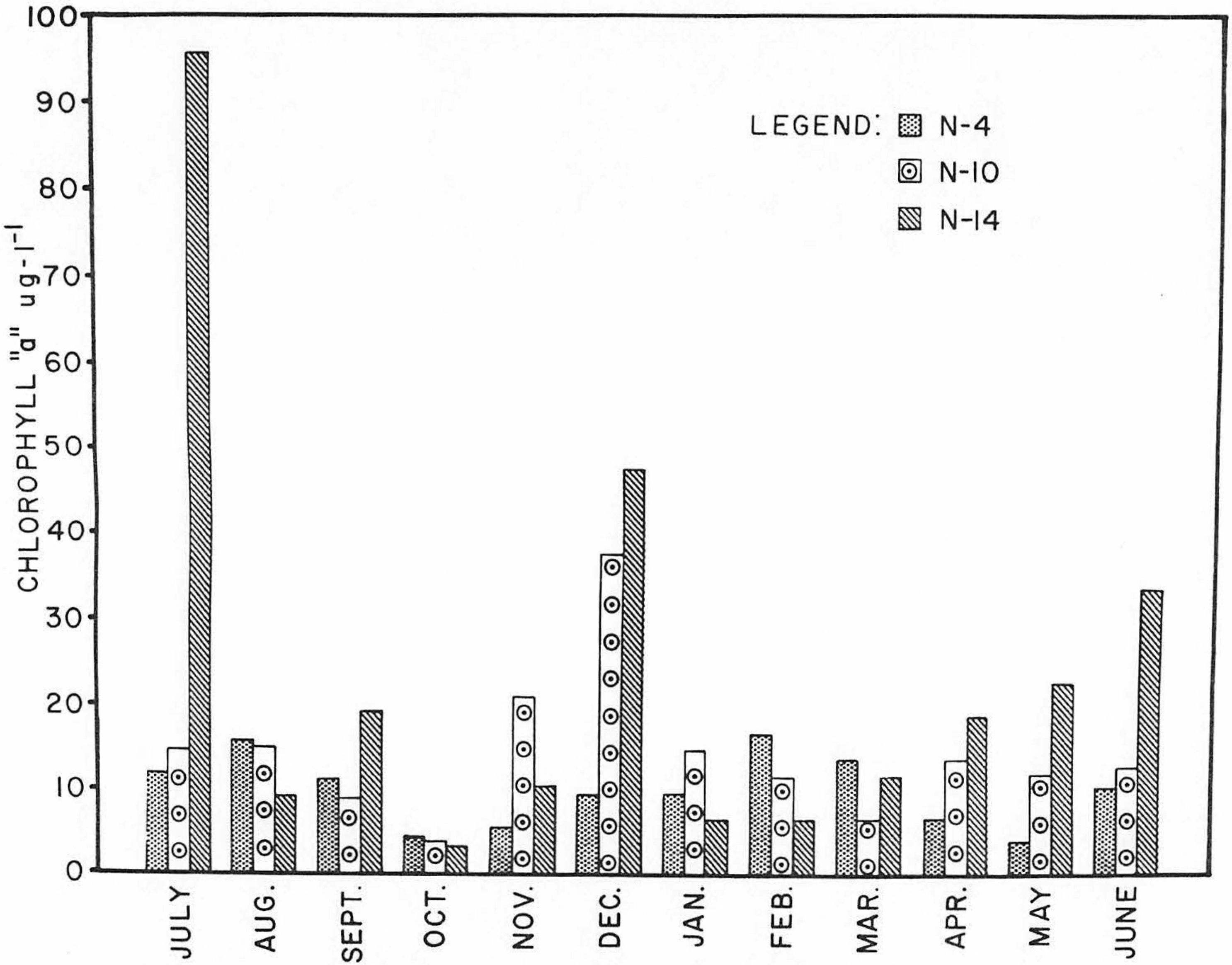

Fig. 3.--Phytoplankton Levels at Three Stations on the Nansemond River.

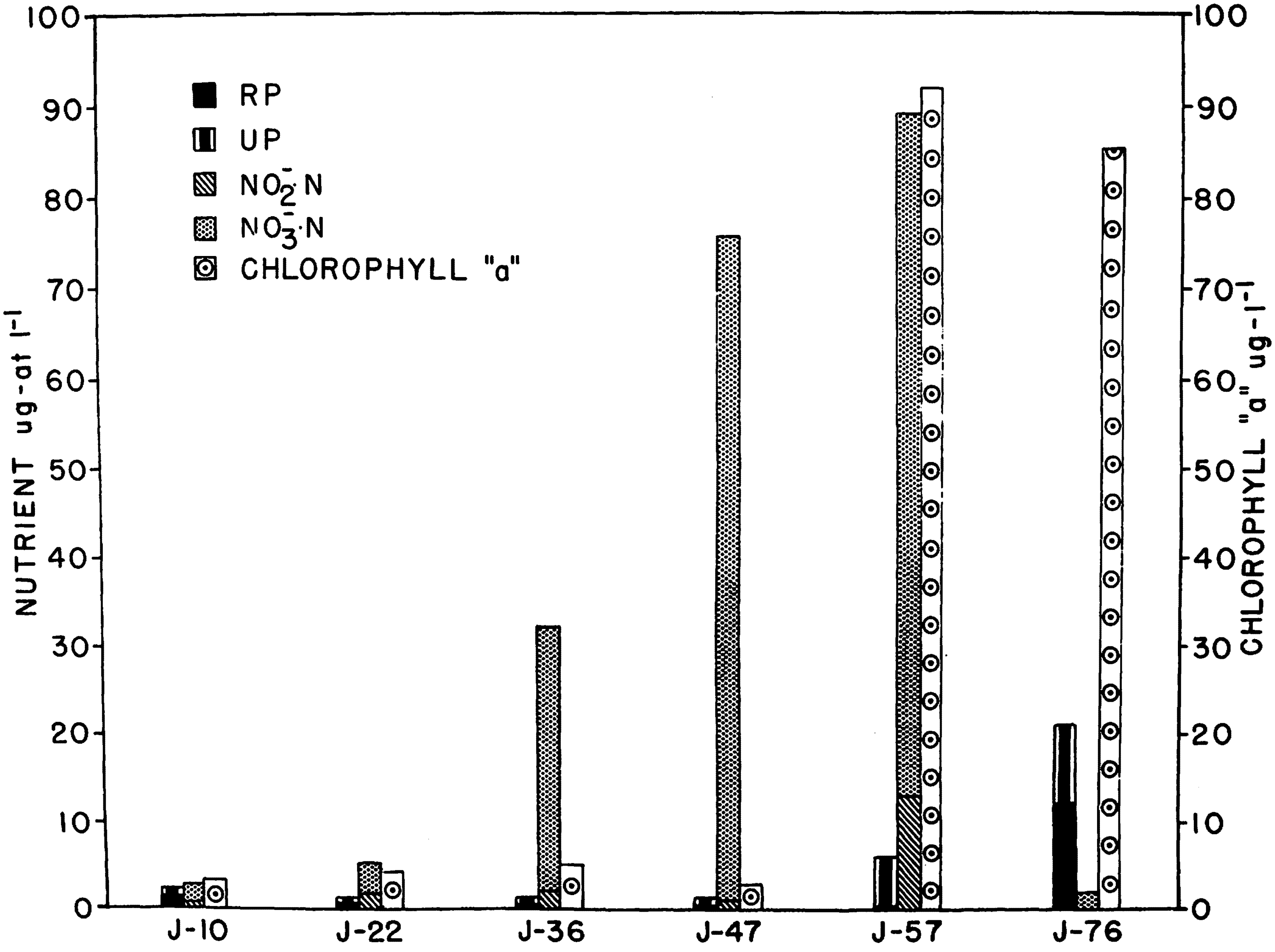

Fig. 4.--Chlorophyll "a", Nitrite and Nitrate Nitrogen, and Phosphorus at Six Stations on the James River During September.

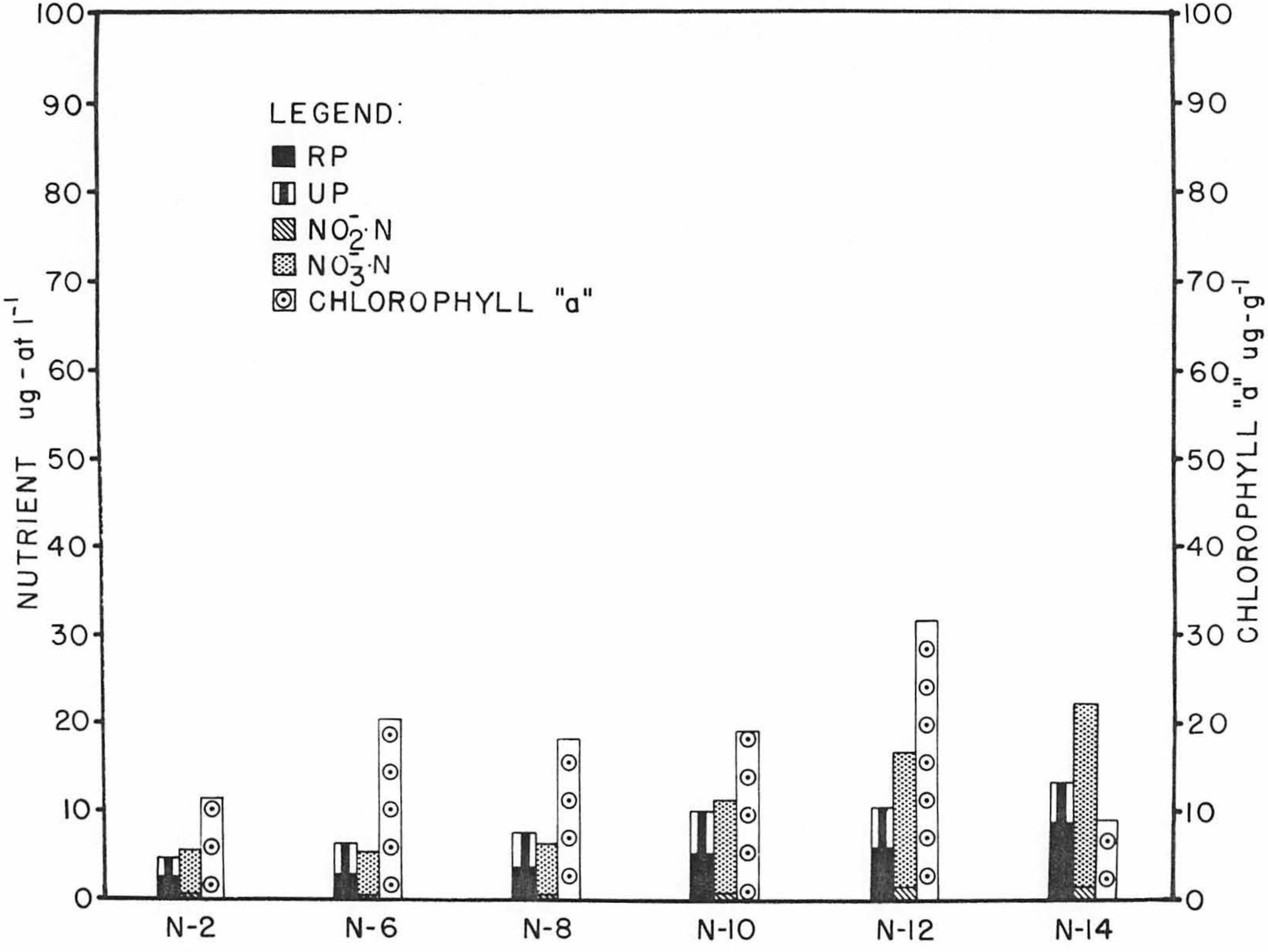

Fig. 5.--Chlorophyll "a", Nitrite and Nitrate Nitrogen, and Phosphorus at Six Stations on the Nansemond River During September.

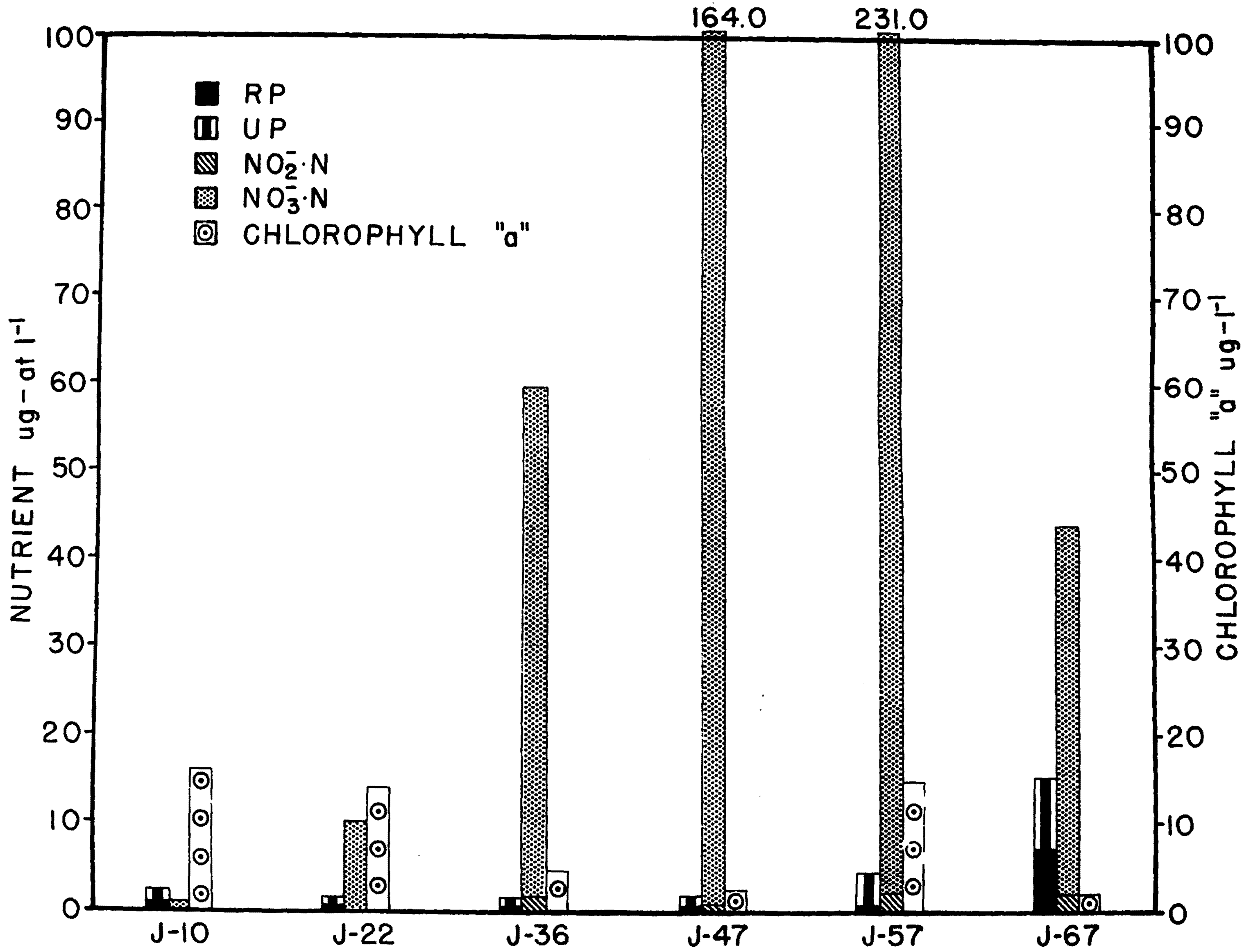

Fig. 6.--Chlorophyll "a", Nitrite and Nitrate Nitrogen, and Phosphorus at Six Stations on the James River During December.

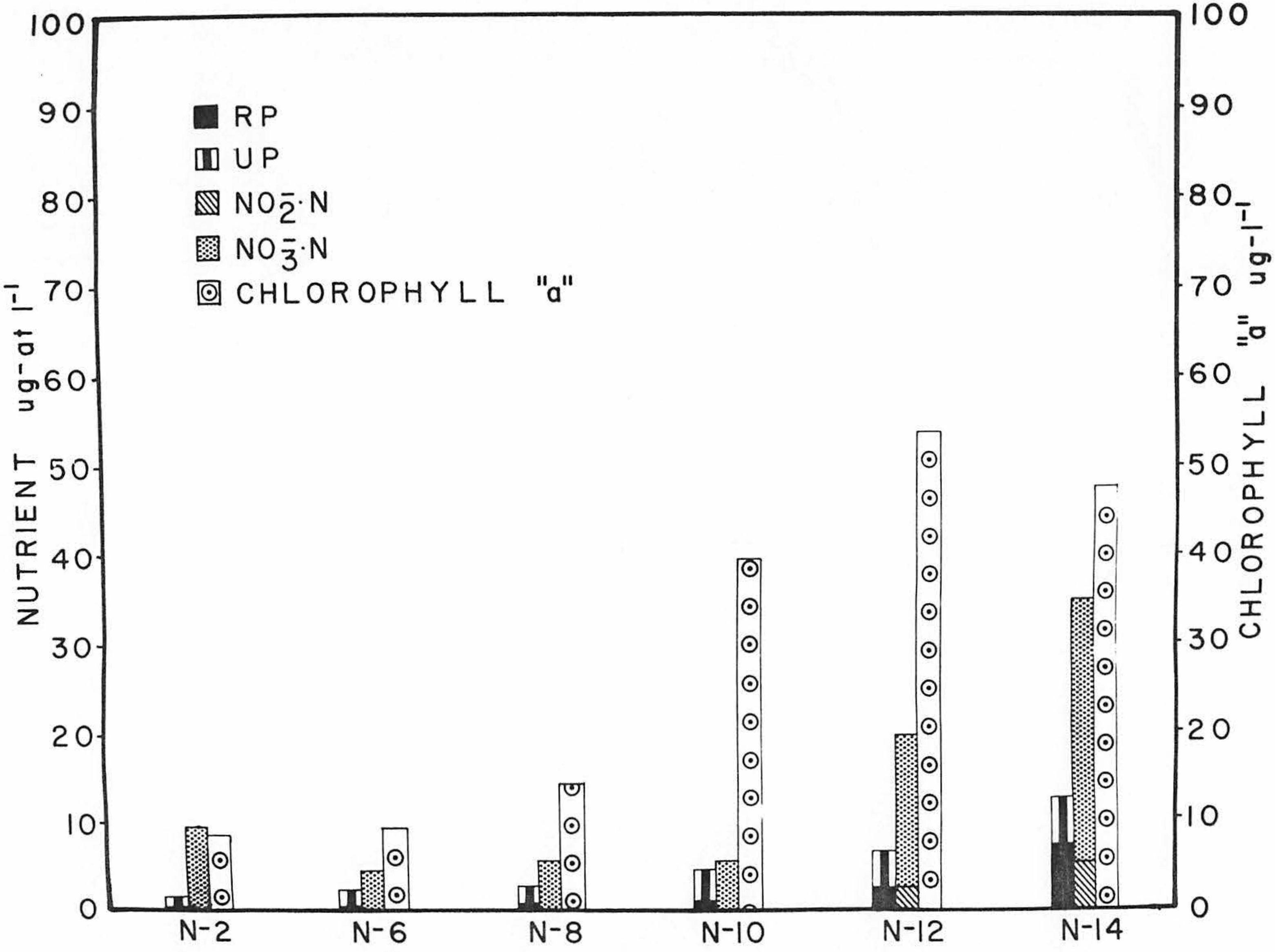

Fig. 7.--Chlorophyll "a", Nitrite and Nitrate Nitrogen, and Phosphorus at Six Stations on the Nansemond River During December.

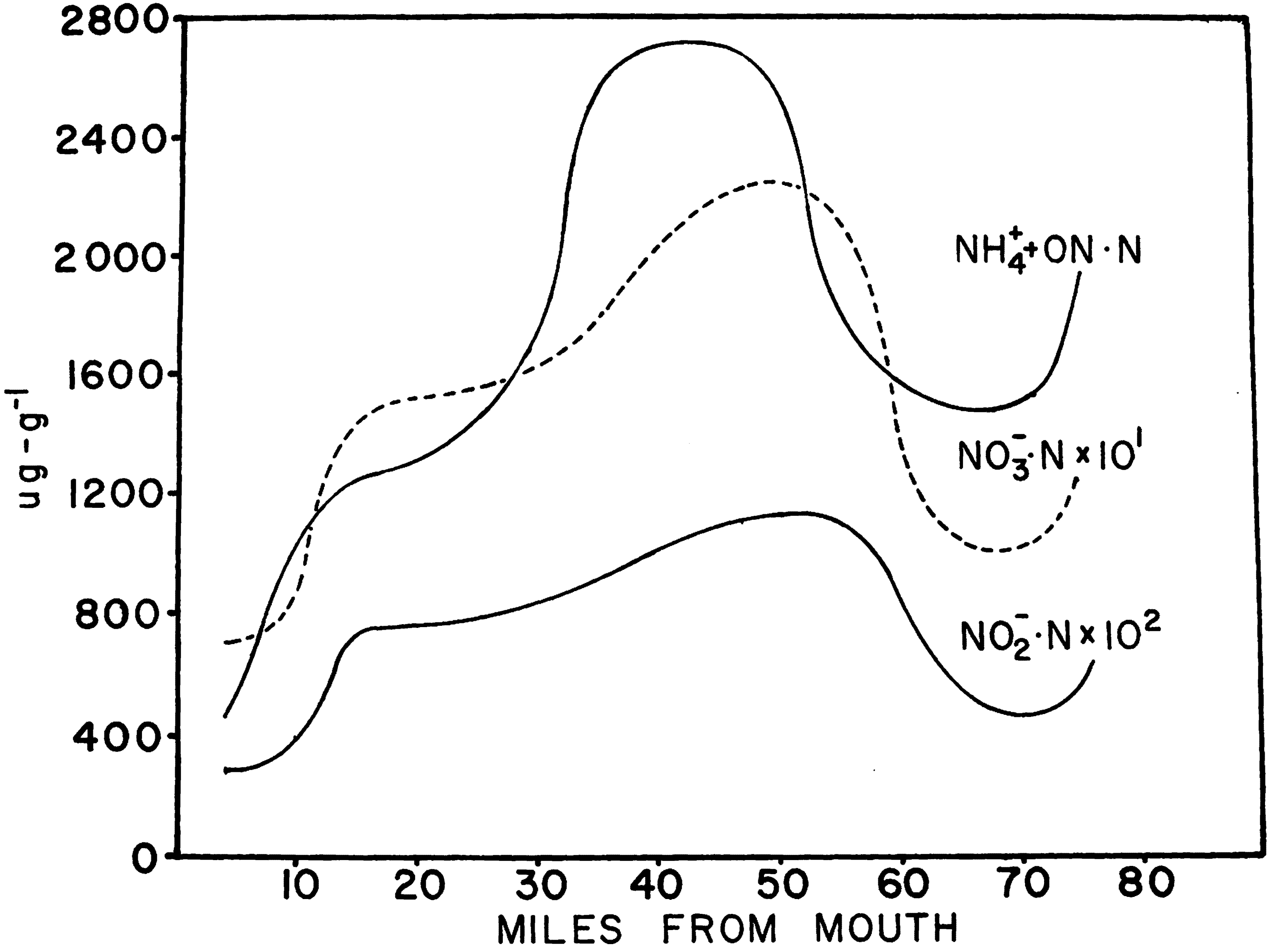

Fig. 8.--Nitrite, Nitrate, Ammonia, and Organic Nitrogen in Top 1 cm of James River Sediments.

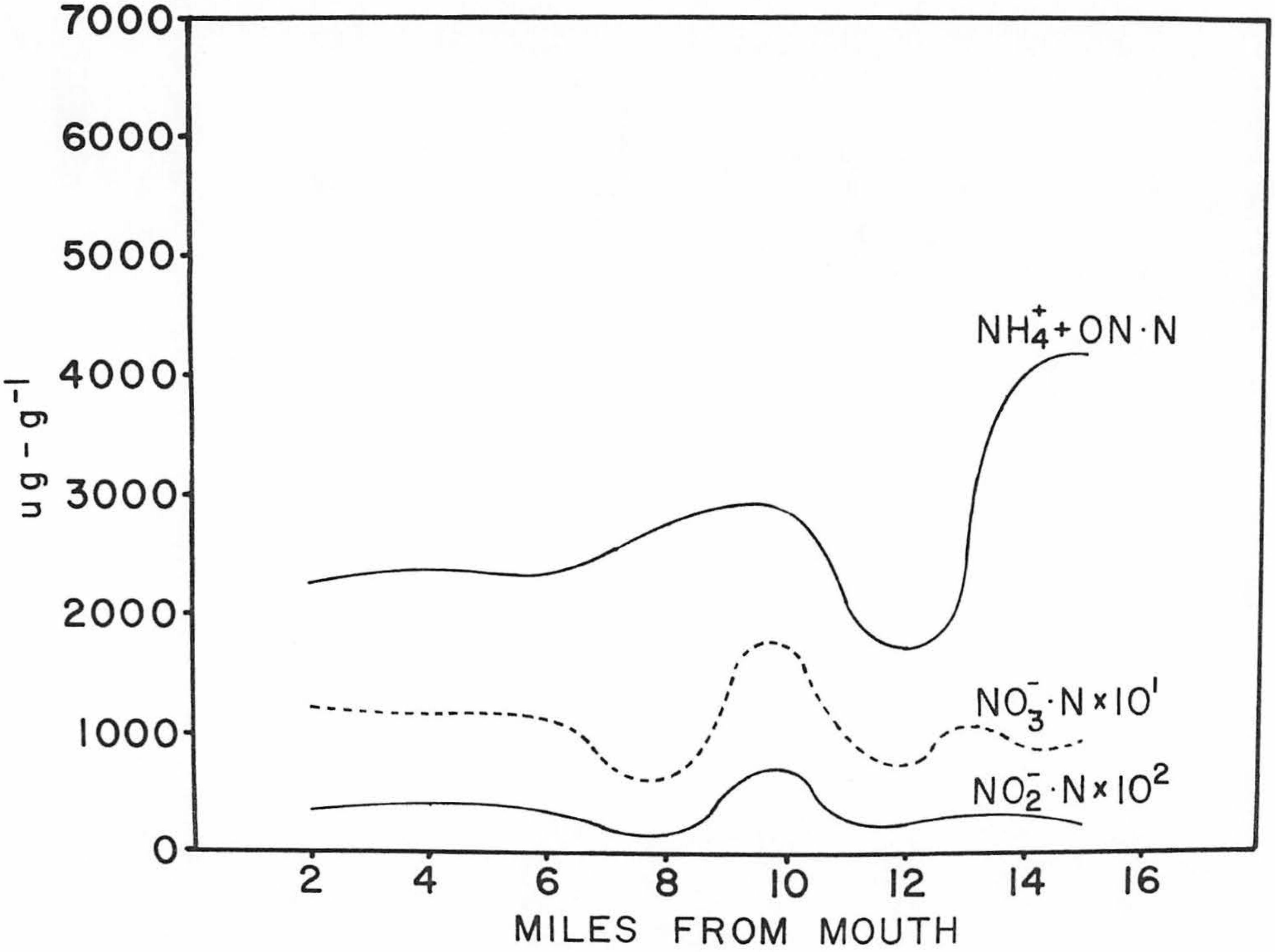

Fig. 9.--Nitrite, Nitrate, Ammonia, and Organic Nitrogen in Top 1 cm of Nansemond River Sediments.

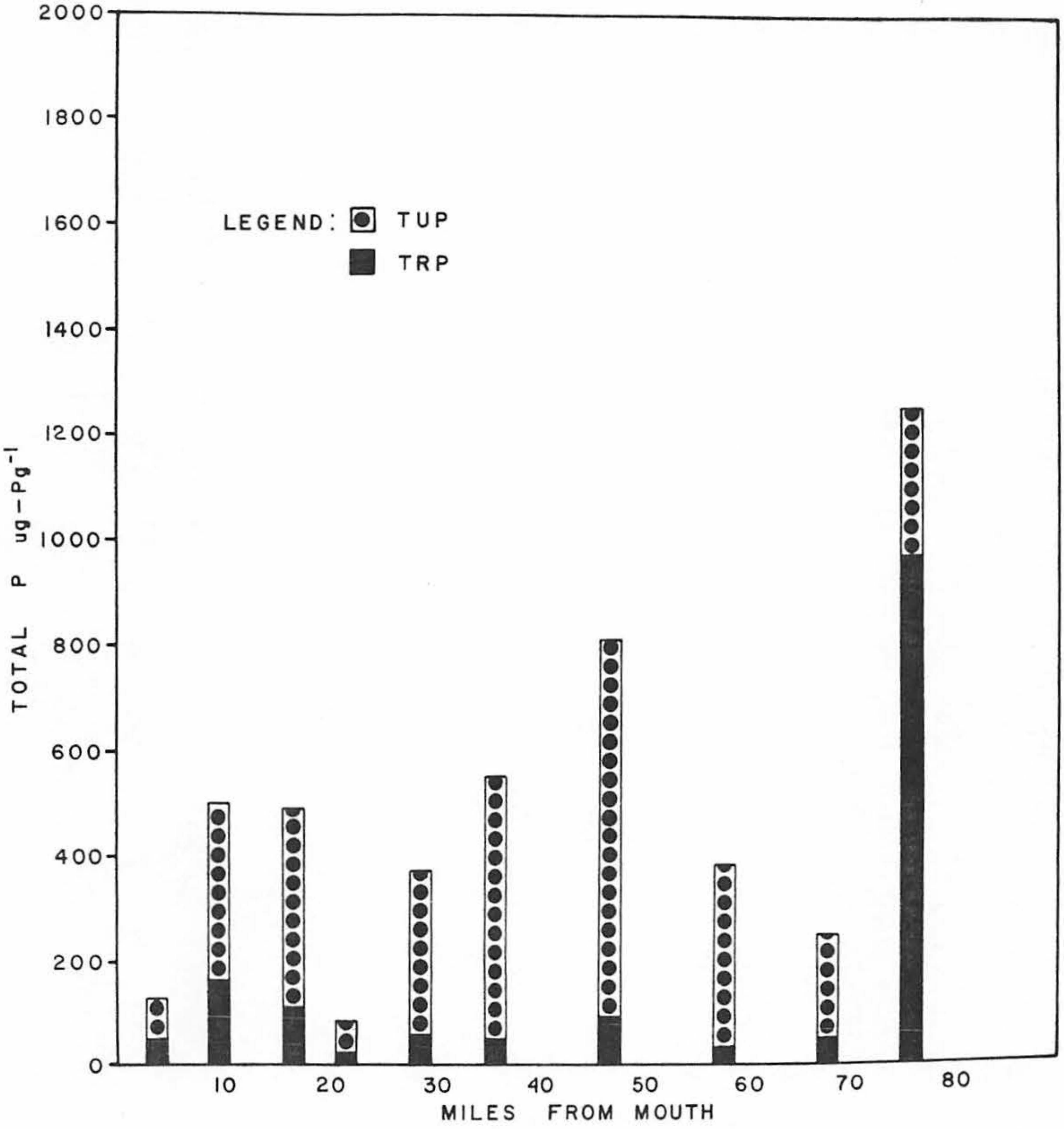

Fig. 10.--Total Unreactive and Reactive Phosphorus in Top 1 cm of James River Sediments.

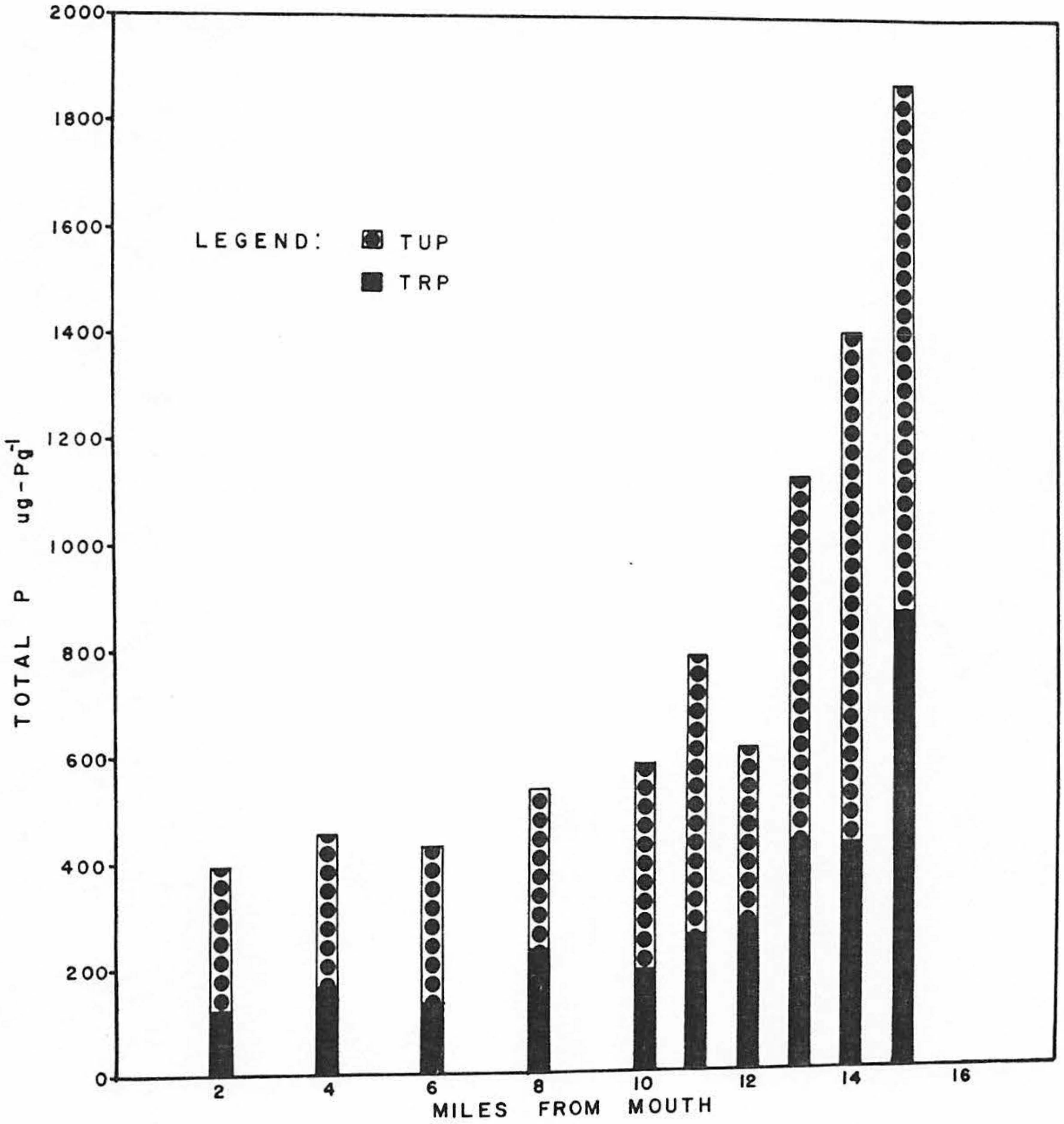

Fig. 11.--Total Unreactive and Reactive Phosphorus in Top 1 cm of Nansemond River Sediments.