The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System

The Chesapeake Research Consortium, Inc.

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THE CHESAPEAKE RESEARCH CONSORTIUM, INC.

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Preface

During June 1972 Tropical Storm Agnes released record amounts of rainfall on the watersheds of most of the major tributaries of Chesapeake Bay. The resulting floods, categorized as a once-in-100-to-200-year occurrence, caused perturbations of the environment in Chesapeake Bay, the nation's greatest estuary.

This volume is an attempt to bring together analyses of the effects of this exceptional natural event on the hydrology, geology, water quality, and biology of Chesapeake Bay and to consider the impact of these effects on the economy of the Tidewater Region and on public health.

It is to be hoped that these analyses of the event will usefully serve government agencies and private sectors of society in their planning and evaluation of measures to cope with and ameliorate damage from estuarine flooding. It is also to be hoped that the scientific and technical sectors of society will gain a better understanding of the fundamental nature of the myriad and interrelated phenomena that is the Chesapeake Bay ecosystem. Presumably much of what was learned about Chesapeake Bay will be applicable to estuarine systems elsewhere in the world. Most of the papers comprising this volume were presented at a symposium held May 6–7, 1974, at College Park, Maryland, under the sponsorship of the Chesapeake Research Consortium,Inc., with support from the Baltimore District, U.S. Army Corps of Engineers (Contract No. DACW 31-73-C-0189). An early and necessarily incomplete assessment, *The Effects of Hurricane Agnes on the Environment and Organisms of Chesapeake Bay* was prepared by personnel from the Chesapeake Bay Institute (CBI), the Chesapeake Biological Laboratory (CBL), and the Virginia Institute of Marine Science (VIMS) for the Philadelphia District, U.S. Army Corps of Engineers. Most of the scientists who contributed to the early report conducted further analyses and wrote papers forming a part of this report on the effects of Agnes. Additional contributions have been prepared by other scientists, most notably in the fields of biological effects and economics.

The report represents an attempt to bring together all data, no matter how fragmentary, relating to the topic. The authors are to be congratulated for the generally high quality of their work. Those who might question, in parts of the purse, the fineness of the silk must keep in mind the nature of the sow's ears from which it was spun. This is not to disparage the effort, but only to recognize that the data were collected under circumstances which at best were less than ideal. When the flood waters surged into the Bay there was no time for painstaking experimental design. There were not enough instruments to take as many measurements as the investigators would have desired. There were not enough containers to obtain the needed samples or enough reagents to analyze them. There were not enough technicians and clerks to collect and tabulate the data. While the days seemed far too short to accomplish the job at hand, they undoubtedly seemed far too long to the beleaguered field parties, vessel crews, laboratory technicians, and scientists who worked double shifts regularly and around the clock on many occasions. To these dedicated men and women, whose quality of performance and perseverance under trying circumstances were outstanding, society owes an especial debt of gratitude.

It should be noted that the Chesapeake Bay Institute, the Chesapeake Biological Laboratory, and the Virginia Institute of Marine Science, the three major laboratories doing research on Chesapeake Bay, undertook extensive data-gathering programs, requiring sizable commitments of personnel and equipment, without assurance that financial support would be provided. The emergency existed, and the scientists recognized both an obligation to assist in ameliorating its destructive effects and a rare scientific opportunity to better understand the ecosystem. They proceeded to organize a coordinated program in the hope that financial arrangements could be worked out later. Fortunately, their hopes proved well founded. Financial and logistic assistance was provided by a large number of agencies that recognized the seriousness and uniqueness of the Agnes phenomenon. A list of those who aided is appended. Their support is gratefully acknowledged.

This document consists of a series of detailed technical reports preceded by a summary. The summary emphasizes effects having social or economic impact. The authors of each of the technical reports are indicated. To these scientists, the editors extend thanks and commendations for their painstaking work.

Several members of the staff of the Baltimore District, U.S. Army Corps of Engineers, worked with the editors on this contract. We gratefully acknowledge the helpful assistance of Mr. Noel E. Beegle, Chief, Study Coordination and Evaluation Section, who served as Study Manager; Dr. James H. McKay, Chief, Technical Studies and Data Development Section; and Mr. Alfred E. Robinson, Jr., Chief of the Chesapeake Bay Study Group.

The editors are also grateful to Vickie Krahn for typing the Technical Reports and to Alice Lee Tillage and Barbara Crewe for typing the Summary.

The Summary was compiled from summaries of each section prepared by the section editors. I fear that it is too much to hope that, in my attempts to distill the voluminous, detailed, and well-prepared papers and section summaries, I have not distorted meanings, excluded useful information or overextended conclusions. For whatever shortcomings and inaccuracies that exist in the Summary, I offer my apologies.

Jackson Davis
Project Coordinator

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The Chesapeake Research Consortium, Inc. is indebted to the following groups for their logistic and/or financial aid to one or more of the consortium institutions in support of investigations into the effects of Tropical Storm Agnes.

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- Explosive Ordnance Disposal Unit Two, Fort Story, Virginia
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U. S. Coast Guard

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- Coast Guard Station, Little Creek, Virginia
- Portsmouth Supply Depot
- Light Towers (Diamond Shoal, Five Fathom Bank, and Chesapeake)

National Oceanic and Atmospheric Administration

- National Marine Fisheries Service (Woods Hole, Massachusetts and Sandy Hook, New Jersey)

The National Science Foundation

Food and Drug Administration

Environmental Protection Agency

U. S. Office of Emergency Preparedness

State of Maryland, Department of Natural Resources

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TABLE OF CONTENTS

APPENDICES: TECHNICAL REPORTS

A. Hydrological Effects

B. Geological Effects

C. Water Quality Effects

D. Biological Effects

E. Economic Impacts

F. Public Health Impacts

EFFECTS OF TROPICAL STORM AGNES ON NUTRIENT FLUX AND DISTRIBUTION IN LOWER CHESAPEAKE BAY[1]

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C. A. Lake[2]
J. G. Windsor, Jr.[2]

ABSTRACT

Nutrient concentrations measured in lower Chesapeake Bay in the summer of 1972 immediately following the flooding associated with Tropical Storm Agnes are compared with those in the summer of 1973, a season of more normal rainfall. The large amount of land runoff produced unseasonably high concentrations of dissolved inorganic nitrogen in the Bay near the mouth of the Potomac River. Phosphate concentrations were essentially unaffected by the flooding. Fluxes of total nitrogen and total phosphorus nutrients through the mouth of Chesapeake Bay were calculated for both summers. The calculated net export of nutrients from the Bay in both August 1972, and June 1973 was found to be small in comparison to nutrient inputs.

INTRODUCTION

The passage of Agnes in late June 1972, produced unusually heavy rainfall on the drainage basins of tributaries of Chesapeake Bay, providing a unique opportunity to investigate the effects of a major flood on nutrients in the Bay. The volume of water entering the Bay during the month of June 1972 was estimated to be nearly 23.9 billion cubic meters, or about six times the normal streamflow for June (Kammerer et al. 1972). This volume of water, most of which was discharged into the Bay during the last week of June 1972, is nearly half the mean low water volume of the Bay--50 billion cubic meters (Cronin 1971).

One can envision two possible consequences of the rapid addition of such a large amount of water on Chesapeake Bay nutrient concentrations. If the added water was very low in nutrients, then the Bay would have experienced dilution of the nutrients already present. If, on the other hand, the added water had high nutrient loadings, nutrient concentrations in the Bay would have increased. The latter case is the more probable, as the flood waters should have contained nutrients from sewage system overflows, scour from nutrient rich sediments, and nutrients leached from the land, particularly agricultural land.

The purpose of this study was twofold. First, to document the effects of Agnes on nutrients in lower Chesapeake Bay. Measurements of nutrient concentrations along two transects across the Bay were conducted during the two months following Agnes for the documentation. Second, an attempt was made to measure the flux of nutrients out of the Bay through the Bay mouth. Because the Chesapeake Bay mouth is, with the minor exception of the Chesapeake and Delaware Canal, the only connection between the Chesapeake estuarine system and the Atlantic Ocean, it is the strategic location for such measurement. Knowledge of the magnitude of nutrient flushing at the Bay mouth enables better understanding of the distribution of nutrients observed in the Bay, and on its ability to accept nutrient loadings from wastewater treatment plants and from land runoff.

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METHODS

Sampling

Most work was conducted in lower Chesapeake Bay, south of the Potomac River mouth. Stations were established along two transects; one between Smith Point and Tangier Island, and one between Cape Henry and Fisherman Island (Fig. 1). Stations on both transects were occupied periodically during the two months following Agnes, and the stations on the Bay mouth transect were re-occupied in June 1973. Two slack water runs were made between the two transects during the summer of 1973, and one sampling cruise was conducted on the continental shelf offshore from Chesapeake Bay.

Current meters were deployed at each station of both transects at approximately 3 meter depth intervals, and current velocities were recorded at 20 minute intervals. Water samples collected with plastic Frautschy bottles were stored in Nalgene containers at about 4°C before processing the same in the laboratory. One aliquot from each sample was filtered through a .8μ membrane filter and preserved by the addition of 40 mg/l $HgCl_2$ for later analysis of dissolved nutrients. A second aliquot was removed for determination of salinity by induction salinometer, and a third unfiltered aliquot was frozen and stored at -20°C in plastic bags for later analysis for total nitrogen and total phosphorus. Slack water run stations were sampled on the same low slack tide, and samples treated as above. Continental shelf stations were sampled from the R/V *Ridgely Warfield* in July 1972. Samples were treated as above.

Chemical Analyses

Nutrient analyses were conducted using standard methods of seawater analysis (Strickland & Parsons 1968). Total phosphorus was determined by spectrophotometry of the reduced phosphomolybdic heteropoly acid after digestion of the unfiltered water sample with perchloric acid. Total Kjeldahl nitrogen was determined by the Griess reaction following H_2SO_4-SeO_2 digestion of the unfiltered water sample and oxidation of the resulting ammonium ion by HClO. Dissolved nutrients in the filtered water samples were analyzed by an automated reagent mixing and spectrophotometry system (Technicon Auto-Analyzer): dissolved orthophosphate by spectrophotometry of the reduced phosphomolybdic heteropoly acid; dissolved nitrite by the Griess reaction; and dissolved inorganic nitrogen by the Griess reaction following reduction of nitrate to nitrite on a Cd column. Total nitrogen was calculated as:

$$(\text{Total N}) = (\text{Kjeldahl N}) + (NO_2^- + NO_3^-) - (NO_2^-)$$

Analytical methods were tested with standards and shown to be reliable within ± 10% of the reported value.

Flux Calculations

Two methods were used for the calculation of nutrient flux at the Bay mouth. In the first, the cross-sectional area along the Bay mouth transect was divided into 20 subsections, each associated with a current meter. The product of the nutrient concentration, the current velocity, and the cross-sectional area of the subsection provided the instantaneous nutrient flux through the subsection. Total nutrient flux through the Bay mouth transect per tidal cycle was obtained by summing the instantaneous nutrient fluxes for all subsections throughout one tidal cycle. Because adequate current data for this type of calculation were available only for the June 1973 section, a second method for estimation of nutrient flux was employed.

In the second method, the non-tidal transport of water through the Bay mouth is used to estimate the nutrient flux. This non-tidal transport is due to 1) the net discharge of water from the Bay, and 2) the gravitational circulation at the Bay mouth. The net discharge of water from the Bay was assumed to be equal the mean streamflow entering the Bay, which is published by the U. S. Geological Survey (Kammerer, et al. 1972 & U. S. Geological Survey 1972-1973). Mean streamflow for August 1972 was used for the August 1972 calculation, and mean streamflow for May and June 1973 was used for the June 1973 calculation. The nutrient flux was calculated by summing the product of mean streamflow and the average nutrient concentrations at the Bay mouth over a tidal cycle.

The transport of water due to gravitational circulation was calculated from a model based on Rattray and Hansen's theory of estuarine circulation (1965) which was verified and calibrated from salinity gradient data (Kuo, personal communication). According to this model, the water mass above a certain critical depth of no net motion is transported out of the Bay, and that below the critical depth is transported into the Bay. The available water--that net volume of water in either layer which passes through the transect during one tidal cycle--was multiplied by the tidal cycle averaged total nitrogen and total phosphorus concentrations in the upper and lower water layers to give nutrient fluxes. The difference in flux between the upper and lower layers is the net nutrient flux produced by the gravitational circulation. The sum of nutrient flux produced by net discharge of water and by gravitational circulation was taken to be the total flux for the Bay mouth.

RESULTS

Nutrient concentrations measured at both transects in both 1972 and 1973 showed little or no systematic variation with depth, tidal stage, or distance along the transect. Therefore, nutrient concentrations presented in Table 1 are cross-sectional and tidal cycle averages.

The total nitrogen concentrations measured at the Smith Point transect in 1972 were generally higher than those at the Bay mouth transect for the same period (Table 1), but were well within the range of values measured on slack water runs in 1973 (Tables 2 and 3). Dissolved inorganic nitrogen concentrations (primarily NO_3^-) measured along the Smith Point transect in 1972 were considerably higher than those measured at the Bay mouth. These high concentrations, ranging from 23-27 μg-at N/l, were not observed in 1973, even at slack water run stations near the Smith Point transect, where dissolved inorganic nitrogen did not exceed 5 μg-at N/l.

Total phosphorus concentrations were similar at both transects in 1972, and were comparable to those measured in 1973. Orthophosphate concentrations at the Smith Point transect in 1972 were somewhat lower than those measured at the Bay mouth during the same period. Orthophosphate concentrations measured on slack water runs in 1973 exhibited considerable patchiness; no consistent trend up the Bay could be discerned.

Fluxes of total nitrogen and total phosphorus at the Bay mouth estimated for June 1973 using current meter measurements (Table 5, A) were not only quite small in magnitude, but indicated transport of nutrients into the Bay. Fluxes calculated by the second method using mean streamflow and the gravitational circulation model were considerably larger, and nutrient transport for both August 1972

Table 1. Tidal cycle averaged nutrient concentrations for transects.

Station	Total Nitrogen (μg-at N/l)	Total Phosphorus (μg-at P/l)	Dissolved Inorganic Nitrogen (μg-at N/l)	Dissolved Orthophosphate (μg-at P/l)
Smith Point Transect				
10-11 Jul 72	45.0 ± 4.1	1.19 ± 0.28	23.0 ± 1.5	0.20 ± 0.03
17 Jul 1972	45.3 ± 3.9	0.89 ± 0.37	24.2 ± 3.3	0.24 ± 0.03
24 Jul 1972	50.2 ± 4.2	1.03 ± 0.30	26.6 ± 2.1	0.34 ± 0.08
Cape Henry Transect				
5 Jul 1972	49.4 ± 14.1	3.48 ± 1.51	1.9 ± 2.1	0.41 ± 0.24
12 Jul 1972	40.3 ± 5.5	1.23 ± 0.23	2.8 ± 1.4	0.44 ± 0.14
14 Jul 1972	34.2 ± 5.2	1.26 ± 0.15	3.5 ± 1.5	0.46 ± 0.13
20 Jul 1972	38.7 ± 9.2	1.00 ± 0.13	1.5 ± 0.92	0.42 ± 0.12
27 Jul 1972	35.8 ± 5.2	1.23 ± 0.15	1.4 ± 0.56	0.52 ± 0.10
17-18 Aug 1972	30.3 ± 5.1	1.61 ± 0.14	0.9 ± 0.09	0.64 ± 0.16
5 Jun 1973	29.1 ± 5.2	1.29 ± 0.65	0.32 ± 0.14	0.48 ± 0.14

Table 2. Nutrients from slack water run, 21 June 1973.

Station	Total Nitrogen (μg-at N/l)	Total Phosphorus (μg-at P/l)	Dissolved Inorganic Nitrogen (μg-at N/l)	Dissolved Orthophosphate (μg-at P/l)
1 Surface	28.6	0.58	1.1	0.39
2 Surface	61.8	1.36	1.0	0.37
3 Surface	39.8	0.67	0.5	0.35
4 Surface	43.4	0.82	0.2	0.15
5 Surface	48.9	0.81	0.1	0.24
6 Surface	42.7	0.92	-	0.16
7 Surface	48.2	0.82	0.5	0.40
8 Surface	39.8	0.88	0.5	0.36
9 Surface	40.1	1.33	0.3	0.16
10 Surface	-	0.94	1.4	0.16
11 Surface	59.8	1.02	0.3	0.38
12 Surface	54.5	2.79	0.5	0.44
13 Surface	19.2	1.36	2.5	0.44
14 Surface	50.8	1.33	4.0	0.48
15 Surface	55.2	1.77	3.5	0.22

Table 3. Nutrients from slack water run, 25 July 1973.

Station	Total Nitrogen (µg-at N/l)	Total Phosphorus (µg-at P/l)	Dissolved Inorganic Nitrogen (µg-at N/l)	Dissolved Orthophosphate (µg-at P/l)
1 Surface	20.0	1.52	-	0.17
Bottom	41.8	1.47	0.6	0.19
2 Surface	43.4	0.89	0.6	0.10
Bottom	-	1.83	1.0	0.39
3 Surface	23.3	1.53	-	0.15
Bottom	69.4	1.31	0.8	0.63
4 Surface	52.6	1.69	2.0	0.29
Bottom	-	1.91	1.4	0.49
5 Surface	26.2	2.03	2.4	0.29
Bottom	43.0	1.85	1.9	0.50
6 Surface	39.6	1.95	1.7	0.20
Bottom	45.9	2.25	1.7	0.90
7 Surface	55.4	1.95	1.6	0.29
Bottom	42.0	1.52	1.8	0.86
8 Surface	35.7	1.51	1.4	0.26
Bottom	55.5	1.51	0.9	0.33
9 Surface	-	2.32	2.0	0.29
Bottom	64.2	2.66	1.1	0.21
10 Surface	62.9	2.17	2.7	0.36
Bottom	49.2	1.56	1.4	0.24
11 Surface	52.5	1.86	1.5	0.29
Bottom	32.6	1.86	1.5	0.29
12 Surface	40.1	1.53	1.7	0.31
Bottom	43.5	1.95	-	-
13 Surface	49.8	2.69	0.8	0.22
Bottom	57.8	2.13	1.6	0.66
14 Surface	-	2.05	1.4	0.23
Bottom	70.8	1.85	0.8	0.14
15 Surface	34.3	1.13	0.8	0.08
Bottom	40.9	1.93	0.6	0.68

and June 1973 was out of the Bay (Tables 4 and 5), as would be expected.

DISCUSSION

Distribution of Nutrients

The major effect of Agnes on nutrient distribution in lower Chesapeake Bay was an elevated concentration of dissolved inorganic nitrogen, not common to that area in that season. Levels were highest near the mouth of the Potomac River, where dissolved inorganic nitrogen comprised nearly half the total nitrogen, and considerably lower near the Bay mouth. Levels of dissolved orthophosphate near the mouth of the Potomac River were somewhat depressed relative to those at the Bay mouth. These effects persisted for at least a month following the passage of Agnes near the Potomac, but returned to normal during that time at the Bay mouth. The large input of nutrients from the Agnes flood-flows, mostly in the form of dissolved inorganic nitrogen, produced a situation in lower Chesapeake Bay similar to that normally observed much earlier in the year. For example, in upper Chesapeake Bay, Carpenter, et al. (1969) found strong seasonal variation of both total and dissolved inorganic nitrogen concentrations. Total nitrogen concentrations in the spring ranged from 80-105 μg-at N/1, but dropped to around 50 μg-at N/1 in other seasons. Likewise, dissolved inorganic nitrogen concentrations averaging near 45 μg-at N/1 in mid-April had dropped to less than 1μg-at N/1 by September. Scattered data from the lower portion of Chesapeake Bay show that this basic seasonal variation occurs, but to a lesser degree. Dissolved inorganic nitrogen concentrations rarely exceed 20 μg-at N/1 in any season (Grant, unpublished data). The regular seasonal increase of nitrate concentrations presumably is due to the higher average rainfall, with associated higher streamflows, and the decreased level of primary production in late winter and early spring.

The small depression in orthophosphate concentration observed at the Smith Point transect relative to that at the Bay mouth might be due to the adsorption of orthophosphate on sediment particles associated with the high river discharge. These particles mostly settle out of the water column before reaching the lower Bay, thus removing orthophosphate from the water. Such a phenomenon has been documented for the upper portion of the Potomac River (Jaworski, Lear, & Villa 1971).

Flux of Nutrients

Fluxes of total nitrogen and total phosphorus calculated by the first method employing current meter velocity approach to flux measurement must be regarded as invalid. For such a large cross-sectional area as that of the Bay mouth, it is impractical to deploy a sufficient number of current meters to accurately monitor the total flow through the section. Furthermore, strong oscillatory tidal currents at the Bay mouth tend to obsure measurement of any net flow of water through the section. Consequently, a better estimate of nutrient flux must be obtained by the second method, employing published streamflow data and the gravitational circulation model. Nutrient fluxes calculated by the second method for August 1972 (Table 4) are comparable in magnitude to those for June 1973 (Table 5). By August 1972, streamflow into the Bay had not only decreased from the June 1972 record discharges, but were even smaller than the June 1973 flows. Sufficient data were not collected to enable complete calculation of nutrient fluxes for June 1972. However, it is expected that nutrient flux was considerably enhanced by the massive input of water to the Chesapeake Bay system. If one uses the nutrient concentrations measured at the Bay mouth in early July 1972, and the peak streamflow of June 24, 1972, the fluxes of total nitrogen and

and total phosphorus due to the net discharge of water are two orders of magnitude larger than those calculated for August 1972. Unfortunately, the contribution due to gravitational circulation cannot be estimated for that time.

Table 4. Nutrient flux for Chesapeake Bay mouth - August 17-18, 1972.

Station	Flux of total P* (gP/tidal cycle)	Flux of total N* (gN/tidal cycle)
A. Due to net discharge of water.		
Bay Mouth	+2.70 x 10^6	+2.30 x 10^7
B. Due to gravitation circulation		
A & B	+9.30 x 10^5	+8.16 x 10^5
C	+3.44 x 10^6	+5.36 x 10^7
D	+1.55 x 10^5	+3.22 x 10^6
E	+0.0 x 10^5	-2.39 x 10^7
Bay Mouth	+4.53 x 10^6	+3.37 x 10^7
C. Total Flux		
Bay Mouth	+7.23 x 10^6	+5.67 x 10^7

*Positive sign indicates net flux out of Bay, negative into Bay.

Table 5. Nutrient flux for Chesapeake Bay mouth - June 5-6, 1973.

Station	Flux of total P* (gP/tidal cycle)	Flux of total N* (gN/tidal cycle)
A. Total flux using current meter velocities		
A	+3.08	+1.75 x 10^1
B	-5.58	-7.98 x 10^1
C	+1.77	+6.49
D	-5.20	+7.25 x 10^1
E	+3.50	-2.22 x 10^1
Bay Mouth	-2.44	-1.50 x 10^2
B. Due to net discharge of water		
Bay Mouth	+5.22 x 10^6	+5.28 x 10^7
C. Due to gravitational circulation		
A	-8.49 x 10^5	-6.17 x 10^5
B	-1.26 x 10^5	+1.02 x 10^7
C	-1.22 x 10^5	-7.31 x 10^6
D	-3.22 x 10^5	-5.80 x 10^5
E	+4.31 x 10^4	-5.82 x 10^5
Bay Mouth	-1.38 x 10^6	+2.28 x 10^6
D. Total flux		
Bay Mouth	+3.84 x 10^6	+5.50 x 10^7

*Positive sign indicates net flux out of Bay, negative into Bay.

The most striking result of the nutrient fluxes calculated for the Bay mouth is the relatively small extent of nutrient flushing. In part, this must be due to the gentle gradient of nutrient concentrations on the Continental shelf offshore from the Bay (Figs. 3 and 4). Without a water mass deficient in nutrients for dilution, tidal flushing is less effective. The net total fluxes of nitrogen and phosphorus out of the Bay calculated for June 1973 are respectively two and ten times smaller than the normal rates of addition of those nutrient species to the Bay via the Potomac River from the wastewater treatment facilities in Washington, D. C. alone (Jaworski, Lear, & Villa 1971). When the additional loading from land runoff and wastewater discharges from other metropolitan areas (Baltimore, Hampton Roads, etc.) are considered, it is apparent that in times of normal streamflow, vastly greater amounts of nutrients are being added to the Bay than are being removed at the Bay mouth. Since the Bay waters are not drastically increasing in concentration of nitrogen and phosphorus, there must be other mechanisms operating to remove these nutrients. Excess phosphate is probably removed by adsorption on suspended sediment, and subsequent deposition on the bottom. Nitrogen may behave similarly, and be deposited on the bottom with organic detritus, or may be converted to volatile compounds (i.e. NH_3, N_2) and lost to the atmosphere.

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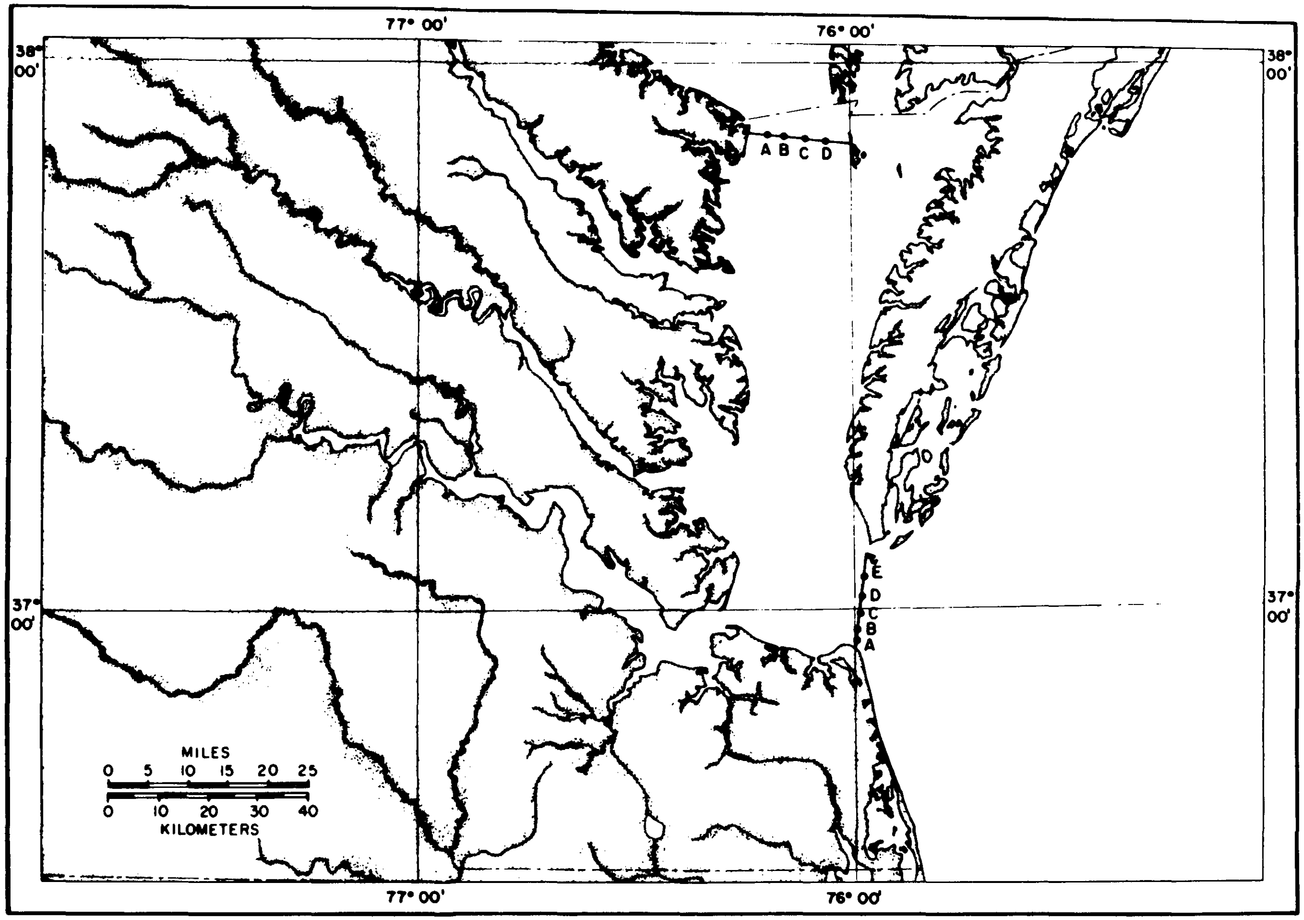

Figure 1. Smith Point and Bay mouth transect stations.

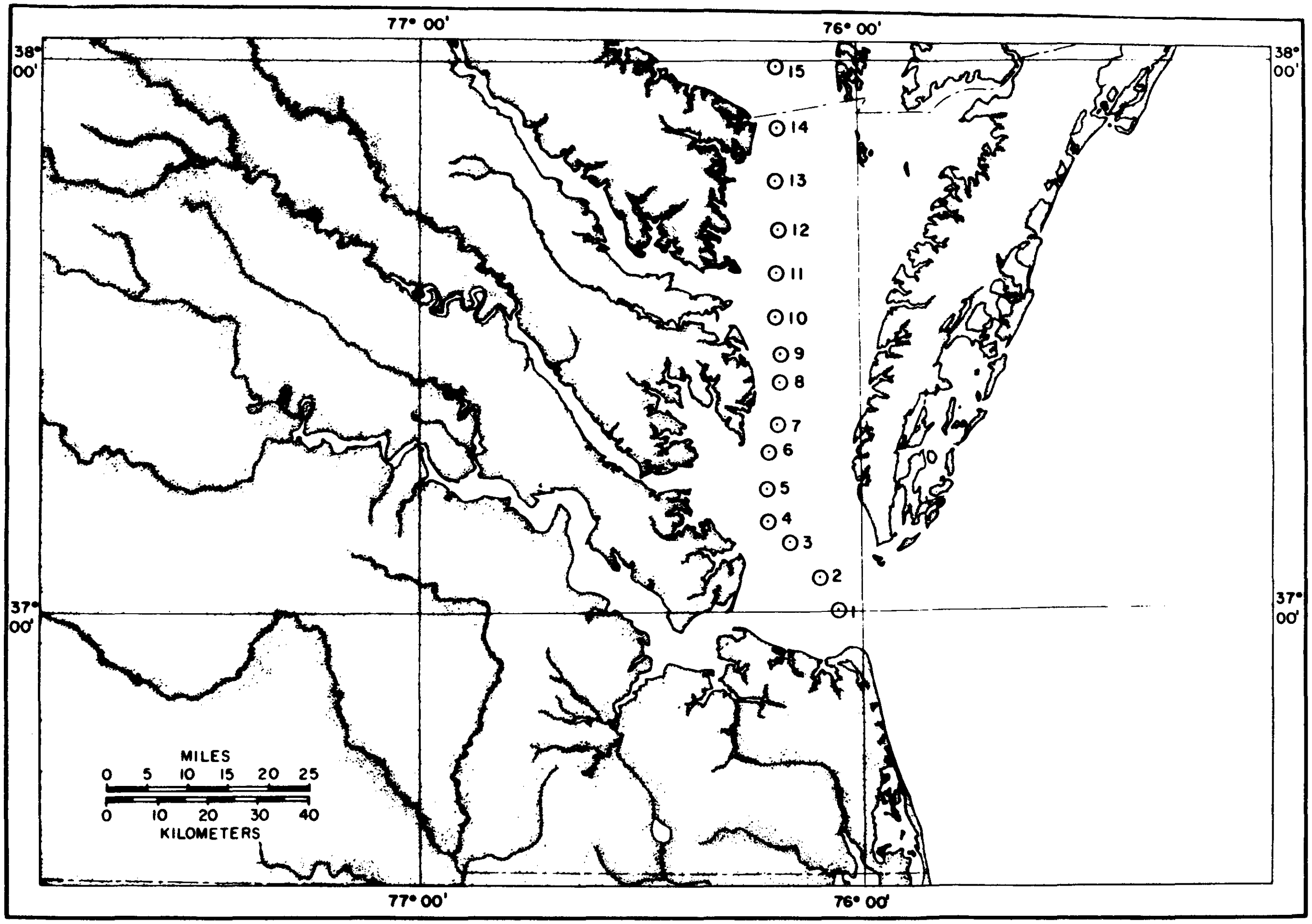

Figure 2. Slack water run stations.

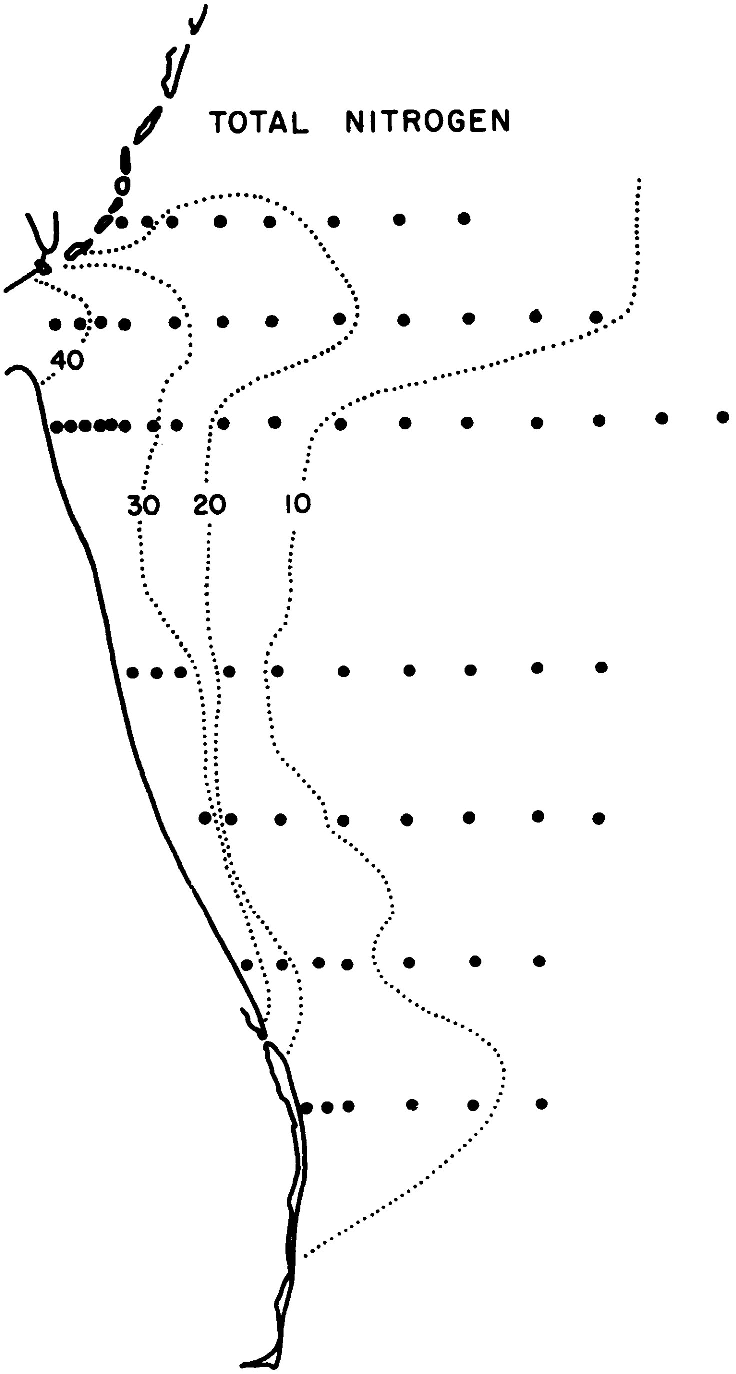

Figure 3. Distribution of total nitrogen concentration on continental shelf, July 1972, 2 m depth, in µg-at N/l.

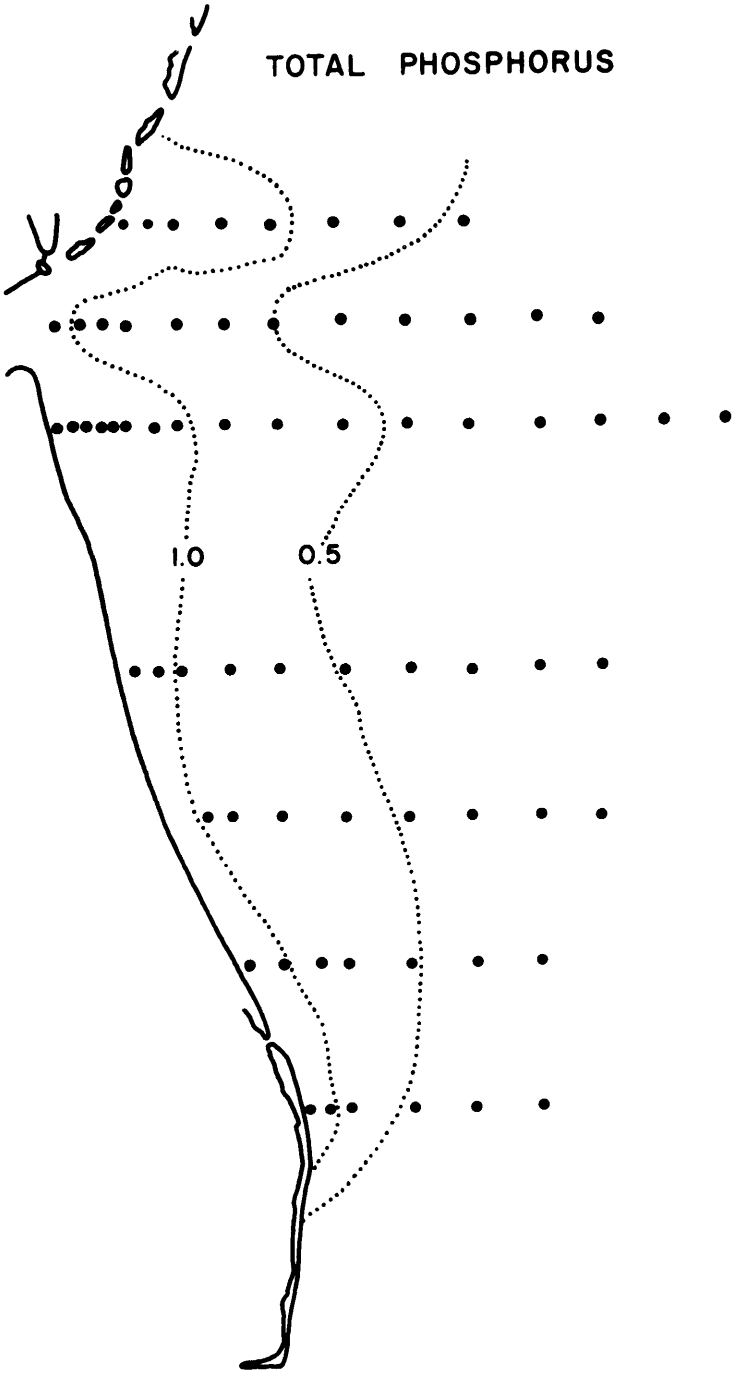

Figure 4. Distribution of total phosphorus concentration on continental shelf, July 1972, 2 m depth, in μg-at P/l.