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Determination of Nutrient Levels and Proposed Predictive Models for Phosphate in the Lafayette River, Norfolk, Virginia

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DETERMINATION OF NUTRIENT LEVELS AND PROPOSED PREDICTIVE MODELS FOR PHOSPHATE IN THE LAFAYETTE RIVER, NORFOLK, VIRGINIA

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ABSTRACT

The Lafayette River, an urban, well-mixed estuarine embayment, was sampled from October, 1970 to January, 1972 for phosphate, nitrate, nitrite, oxygen, water temperature and salinity. The mean values found for these samples were: oxygen saturation from 69% to 106%, nitrite from 0 to 4 microgram-atoms per liter, and salinity from 13°/oo. to 24°/oo. The mouth of the Elizabeth River to Hampton Roads was also sampled from May, 1971 to August, 1971. The Lafayette and Elizabeth Rivers were also sampled over a 24 hour period in the summer of 1971 and the Lafayette River again in the winter of 1972. The mean concentration of phosphate in the summer varied from 3 to 16 microgram-atoms per liter for the Lafayette River and from 2 to 12 microgram-atoms per liter for the Elizabeth River. The highest values of phosphate occurred in the summer months and the lowest in the winter. The mean concentration of phosphate for the Elizabeth River ranged from 3 to 5.7 microgram-atoms per liter with the highest value in June, 1971. The mean concentration of phosphate for the Lafayette River ranged from 1.9 to 8.6 microgram-atoms per liter with the highest value in August, 1971.

Multiple linear regression models revealed that the daily concentration of phosphate is related to the stage of the tide, and rate of flow of phosphate from the Lamberts Point sewage outfall as follows:

1. The concentration of phosphate increases on the ebb tide and decreases on the flood tide because of the diluting effect of the Hampton Roads water.

2. The concentration of phosphate is also directly related to the rate of flow of phosphate from the Lamberts Point sewage outfall on the flood tide but quantitively is not as important as the diluting effects of the Hampton Roads water. Seasonal multiple linear regression models show a direct relation of temperature to the concentration of phosphate and an indirect relation with the amount of rainfall. The effect of temperature was ascribed to increased bilological activity and the effect of rainfall to the dilution of the water in the Lafayette River.

ACKNOWLEDGMENT

"Nature hides her secrets through her intrinsic grandeur, but not through deception"

Albert Einstein

The statement above is a highly optimistic philosophy. However, without a similar optimism, a project such as a Master's thesis can appear hopeless.

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As you can see, although there is only one author on the title page there were many who aided in the completion of this thesis. One who is remembered with affection and pride for her hard work, in collection of samples, typing, rewriting, and encouragement is my wife, Sarah.

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CHAPTER I

THE PROBLEM AND DEFINITIONS OF TERMS

Many variables can effect the productivity and aesthetic qualities of an urban estuarine embayment, some of which are salinity, dissolved oxygen, availability of sunlight, pH, pollution by-products, circulation, morphometry of the embayment, water temperature, land run-off, and nutrient concentrations in the water (Steward and Rohlich, 1967). Although it is difficult to state which of these is the most important to the embayments' ecology, the nutrients, especially phosphate, play an important role (Redfield, 1958 and Likens, 1972). Pritchard states (1969), that when the total phosphate concentration exceeds 3.3 microgram-atoms phosphate phosphorous per liter, that undesirable conditions associated with eutrophication occur.

I. THE PROBLEM

Statement of the purpose. At this time, there are no published studies for nutrient concentrations in the Lafayette River. The Lafayette River has recreational and aesthetic value for the citizens of Norfolk, Virginia, and provides a breeding and feeding site for numerous species of wildlife. It is imperative to obtain a basic knowledge of the nutrient cycles in the Lafayette River to be used in determining the present base levels of these nutrients in the Lafayette River for comparison with the nutrient levels of future studies.

Statement of the problem. It is the purpose of this study to determine the yearly cycle of phosphate, oxygen, nitrate, and nitrite concentrations in the Lafayette and Elizabeth Rivers. A portion of this data will be used to attempt to answer the following questions:

1. Does the Lafayette River's concentration of phosphate exceed the value of 3.3 microgram-atoms per liter as stated by Pritchard (1969).
2. If the concentration of phosphate in the Lafayette River does exceed the 3.3 microgram-atoms phosphate per liter, what are the explanations for this phenomenom?
3. How do the levels of phosphate in the Lafayette River compare to other estuaries?

Statement of the Research Hypothesis. The Lafayette River is a small, shallow urban estuary that drains a large paved watershed. The Lamberts Point Sewage Plant, a large primary treatment plant, is located at the mouth of the river. It was postulated that the levels of phosphate in the Lafayette River would show a change in concentration over a twenty four hour period. The concentration would increase on the flood tide and decrease on the ebb tide.

This increase in phosphate would be due to the tidal currents moving the sewage laden waters from the Lamberts Point Sewage outfall into the Lafayette River. On the ebb tide the inverse or flushing would occur. The wind direction could either increase the flow of sewage into the river or decrease the flow depending on its direction. It was further postulated that over a longer seasonal time period, wind direction, urban storm water runoff and sluggish water circulation would increase the levels of phosphate in the Lafayette River over those levels found in Hampton Roads.

II. DEFINITIONS OF TERMS USED

Multiple linear regression model. The model is of the form (Draper and Smith, 1967; Snedecor and Cochran, 1968; Sokal and Rohlf, 1969):

$$Y = a + B_1X_1 + B_2X_2 + \ldots B_oX_o + E^1$$

a is the constant or Y intercept.

B_n are the regression coefficients of the independent variables, X_n, used to predict the estimation of the dependent variable Y.

B_oX_o is the joint effect of all the terms omitted from the n variable model.

E^1 is the residual or error term and is assumed to be distributed independently of the X's with zero mean and variance, σ^2

The model is of Type I (Sokal and Rohlf, 1969). This means that the predicted $\hat{Y}$ or phosphate concentration is dependent on "error free" independent variables, i.e. variables that can essentially be said to be measured with no, or more realistically, small error. Notice that $\hat{Y}$ is the predicted value and therefore, has a statistically normally distributed range of values for each set of independent variables. The linear least squares fit for the model is a Y on X regression.

Primary treated sewage. This term refers to the treatment involved in the mechanical settling out and screening of large sewage particles. After this has been accomplished, the final effluent is heavily dosed with chlorine to kill pathogenic organisms. This treatment has little or no effect on nutrient levels in the sewage.

Elizabeth River and Lafayette River. As the Lafayette River and the Elizabeth River have a common mouth, the sampling section D refers to the Elizabeth River and sections A, B, and C refer to the Lafayette River. Sampling sections were labelled A, B, C, or D. Sampling stations are the individual sampling locations within the sections and have a letter and number designation.

Tidal samples. The term will refer to multiple samples collected from one or more sampling stations over a partial or complete tidal cycle.

Daily samples. The term refers to multiple samples collected from one or more sampling stations over a twenty-four hour period.

Seasons. The seasons will be defined as follows:

Summer - the months of June, July, and August.
Fall - the months of September, October, and November.
Winter - the months of December, January, and February.
Spring - the months of March, April, and May.

Cosine theta. The wind direction will be expressed numerically as the cosine theta. Theta is the angle the resultant wind makes to the main Lafayette River channel. The main Lafayette River channel bears 028^{o} true at the mouth of the river.

Wind component. The wind velocity is a vector designated as cosine theta times the wind speed in knots.

F value. A statistical parameter used to determine the significance of a regression equation. It is the ratio of the mean square for the regression divided by the variance of the regression.

F value. When used in nutrient calibration curves, it is equal to the nutrient concentration divided by the corrected absorbance. (Strickland & Parsons, 1965)

Tide stages. The stage of tide was expressed numerically in order to include the tidal parameter in the regression equations. Beginning ebb tide is expressed as 1 (one) and includes all values up to but not including 2 (two). Beginning flood tide is expressed as 2 (two) and includes all values up to but not including 3 (three). Therefore 1.5 designates a sampling point halfway into the ebb tide and 2.75 indicates a sampling point three quarters into the flood tide.

CHAPTER II

REVIEW OF THE STUDY AREA AND RELATED RESEARCH

I. REVIEW OF THE STUDY AREA

Bacteriological. The Lafayette River (see Figures 1 and 2) was once called Tanners Creek but has been called the Lafayette River since 1934. In 1916, an investigation of the oyster beds in the Hampton Roads area (cited in Crohurst and Sullinon, 1935) concluded that oysters from the Elizabeth River and its tributaries, which includes the Lafayette River, could not be safely used for human consumption. The Crohurst report of December, 1935 (Crohurst and Sullinon, 1935) showed the coliform values in the Lafayette River to vary from 1700 to 4400 per 100 cubic centimeters and concluded "...the stream obviously is grossly polluted under all tidal conditions." This could hardly be otherwise since raw sewage from an estimated population of 10,000 was deposited from 35 public sewers directly into the Elizabeth and Lafayette Rivers (Smith, 1950). In addition to the above public sewers, there were approximately 300 family sewage units with direct connections to the Lafayette River and its branches. The water quality survey by the Virginia State Department of Health in August, 1950 showed the Lafayette River to have a median coliform density of over 500 per 100 milliliters. Since the construction of the Hampton Roads Sanitation District's Army Base Plant and Lamberts Point (see Figure 2) Plant in 1947 and 1948, respectively (Gene Goffigon, personal communication Hampton Roads Sanitation District, 1972), there is no known direct raw sewage input into either the Lafayette or the Elizabeth River. However, the present total coliform count data from the Norfolk Department of Health (Wise, 1970) remains or is higher than the values in 1934 and 1949, especially in the summer months.

Algal studies. Marshall (1967, 1968, 1969) has compiled plankton surveys on the Lafayette and Elizabeth Rivers. Diatoms were shown to predominate in the Lafayette River in April and June, 1964 with a ratio to phytoflagellates of 7:1 and 317:1, respectively. Skeletonema costatum was the major constituent on both these dates. This also held true for the Eastern and Western branches of the Elizabeth River.

II. REVIEW OF RELATED RESEARCH

Nutrients in the Elizabeth River. No other published nutrient studies or bacterial studies for the Lafayette could be found. However, the State Water Control Board of Virginia (Jennings, 1965) performed a survey on the Eastern Branch of the Elizabeth River. Daily oxygen profiles were prepared from August 10-11, 1964, as well as monthly surface samples from March to August, 1964, were taken. The samples covered various stages of the tidal cycle and included chlorophyll extractables, biomass, as total organic volatile substance, total phosphate, orthophosphates, biological oxygen demand, ammonia, and coliform counts. Table I lists the orthophosphate trends and total phosphate concentration as extracted from this survey report. Jennings (1965), assuming 15 milligrams per liter of phosphorous in the primary treated sewage effluents deposited in the Eastern Branch of the Elizabeth River, calculated that 123 pounds of phosphorous per day would be discharged into the river with an effluent discharge rate of approximately one million gallons per day. The total quantity of phosphorous in pounds, calculated from the concentration of phosphorous found in the water and the depth of the river, "...far exceeds that which could be discharged to this stream each day from sewage treatment plants. Therefore, it appears that buildup of nutrient material has occurred, or there is a substantial contribution from some other source."

The State Water Control Board of Virginia periodically monitors the Eastern and Southern Branches of the Elizabeth River for nutrients, oxygen, biological oxygen demand, alkalinity, and other parameters. A partial summary of this data is shown in Table II.

Phosphate levels in similar estuaries. Dissolved inorganic phosphate is higher in coastal waters and does not have a 15:1 atomic ratio of nitrogen/phosphorous as is found

TABLE 1

Orthophosphate Concentration Trends and Total Phosphate, in Microgram-atoms Per Liter for the Eastern Branch of the Elizabeth River

The samples were taken at bridges crossing the river. The data in this table was compiled by Jennings (1965).

Location	Total Phosphate	Orthophosphate Trends
U. S. Route 13 Bridge	increase March to August Range 4 to 14	increase March to August
State Route 165 Bridge	May to June increase July to August decrease Maximum in July Range 8 to 35	increase March to August

TABLE II

A Summary of the Orthophosphate and Nitrate Concentration Values in Microgram-atoms Per Liter, and Trends for the Eastern and Southern Branches of the Elizabeth River Norfolk, Virginia, 1971, as Reported by the State Water Control Board

Location	Orthophosphate phosphorous a.	Nitrate - Nitrogen a.
Eastern Branch		
0.7 miles from the juncture of the Eastern & Southern Branches of the Elizabeth River	maximum in July minimum in May range 2.5 to 11	maximum in May minimum in July range 0.7 to 2.9
4.62 miles from the juncture of the Eastern & Southern Branches of the Elizabeth River	maximum in May minimum in July Range 1 to 4.6	maximum in June minimum in May Range 0 to 10
Southern Branch		
2.03 miles from the juncture of the Eastern & Southern Branches of the Elizabeth River	maximum in May and July minimum in June Range 3 to 3.5	maximum in June minimum in May/June Range 3.6 to 30

a. The values for nutrients as shown in the above table are suspect as the water samples were not adequately preserved.

in the open ocean. This is probably due to the low nitrogen/phosphorous rationfound on land (Sverdrup, et al., 1942; Pomeroy, et al., 1972). Although dissolved inorganic phosphate appears to be always in excess in coastal waters and nitrogen to be limiting to phytoplankton (Ryther and Dunstan, 1971; Likens, 1972), it is possible for dissolved inorganic phosphate to be used as an index of pollution (Ketchum, 1967; Ryther and Dunstan, 1971). The levels of phosphate found for other estuaries are shown in Table III.

Daily cycles of phosphate. It has been noted (Newcombe and Lang, 1939; Newcombe and Brust, 1940; Kuenzler, McKellar and Muse, 1970; McKellar, 1971), that a daily cycle of dissolved inorganic phosphate exists in estuaries. The dissolved inorganic phosphate increases during the night and decreases during the day. McKellar ascribes this to an increase in the flux of phosphate from the sediment (McKellar, personal communication, 1972). This study was done in a sewage waste pond where the level of dissolved inorganic phosphate was approximately 50-60 microgram-atoms phosphate phosphorous per liter. Newcombe and Lang (1939) believe the daily fluctuations "...to be due to an accelerated regeneration and reduced utilization of phosphate as a corellary of poor light penetration."

Atypical cycles of phosphate in estuaries. Pomeroy summarizes and defines "atypical" cycles of phosphates in estuaries (Pomeroy, et al., 1972). In an "atypical" cycle

TABLE III

Comparison of the Dissolved Orthophosphate in the Lafayette/ Elizabeth River to its Concentration in Other Estuaries

Estuary	Phosphate level microgram-atoms phosphate phosphorous per liter or atomic N/P ratio	Location	Reference
Elizabeth River Eastern Branch	5 - 36	Upriver of the study area	Jennings, 1965
Hampton Roads	0 - 0.8	Hampton Roads	Stroup & Wood 1966
York River	0.02 - 2.66	Lower Chesapeake Bay	Patten, et al., 1963
Patuxent River	0.6 - 1.6	Upper Chesapeake Bay	Newcombe & Lang, 1939
Patuxent River	0 - 2.1	Upper Chesapeake Bay	Herman, et al., 1968
James, York & Rappahanok Rivers	1 - 4 mean 2	Rivers draining into Chesapeake Bay	Brehmer, 1972
Delaware Bay salt marsh	20 - 30	Delaware	Reimold, 1965
Pamlico River	1 - 9	N. Carolina	Hobbie, 1970
Sapelo Sound	2 - 4	Georgia estuaries	Pomeroy, et al., 1972
Biscayne Bay	0.14 - 1.10 decrease to 0.14 - 0.49 when sewage effluent stopped	Florida	McNulty, 1970
Moriches Bay, Great So. Bay	1.3 - 4.4 N/P atomic ratio	Long Island, New York	Ryther, 1954
Forge River	40	Long Island, New York	Barlow, et al., 1963
Raritan Bay	11.4 - 1.3:1 N/P atomic ratio	Atlantic coast New Jersey	Jeffries, 1962
Narragansett Bay	mean 1.10 - 1.46	Rhode Island	Smayda, 1957

Tabel III continued

Estuary	Phosphate level microgram-atoms phosphate phosphorous per liter or atomic N/P ratio	Location	Reference
New York Bight	2.9	New York Bight	Ketchum, 1967
New York Harbor	8.5	New York	Howells, et al., 1970
St. Margaret's Bay	0.13 - 1.36	Nova Scotia, Canada	Platt & Irwin, 1968
Kaneohe Bay	1.07 increased to 3.94 when sewage plant opened	Oahu, Hawaii	Caperon, et al., 1971

of phosphate, the level of phosphate is greatest in the summer and least in the winter. This is, in general, the opposite of the cycle in the open ocean where phosphate is a limiting nutrient and is greatest in the winter and least in the summer. This atypical cycle has been noted by others (Newcombe, et al., 1939, 1940; Hutchinson and Bowen, 1947, 1950; Pratt, 1950; Rochford, 1951; Reimold, 1965; Gooch, 1968; McKellar, 1971) and their explanations can be summarized as follows:

1. Accelerated regeneration and reduced utilization, as a corollary of poor light penetration (Newcombe and Brust, 1940).

2. Uptake and release of large amounts of loosely bound inorganic phosphate adsorbed on clay particles (Reimold, 1965; Pomeroy, et al., 1965).

3. Increase of pH and/or Eh which releases phosphate from estuarine sediments (Carrit and Goodgal, 1954; Jitts, 1959; Young, 1968).

4. Remineralization of phosphate by sulfate reducing bacteria or other microorganisms (Teal and Kanwisher, 1961; Oppenheimer and Ward, 1963; Gooch, 1968), including equilibrium reactions of dissolved inorganic phosphate, dissolved organic phosphate and particulate phosphorous (Hutchinson and Bowen, 1950; Rigler, 1956).

5. Nutrient enrichment of the estuaries and slow exchange between estuaries and the open seas (Jeffries, 1962; Barlow, et al., 1963).

6. Shifting of the rates of metabolic processes that move phosphate from sediments to the water (Pomeroy, et al., 1972).

7. Greater wind generated interaction between bottom deposits and the water column in shallow areas (Aurand, 1968).

8. Excretion and rapid liberation of phosphate from zooplankton, especially in the summer (Hayes, 1963; McKellar, 1971).

9. A seasonal regeneration and adsorption equilibrium cycle where in spring, adsorption is greater than regeneration and the opposite in the summer. In winter, adsorption equals regeneration due to reduced biological activity (Redfield, et al., 1963; Odum, 1971).

Pomeroy (1972) postulated a model of dissolved inorganic phosphate for Georgia salt marshes, rivers, and sounds which had several parameters that are very similar to the present study area. These parameters are:

1. Morphometry. The Duplin River has a water area of 1.3×10^6 miles^2 at mean low water as compared to the Lafayette River's water area of 7.12×10^6 miles^2 and 1×10^7 miles^3 volume as compared to 4.3×10^6 miles^3 for the Lafayette River.

2. Annual cycle of dissolved inorganic phosphate varied from a high in the summer to a low in the winter.

3. The levels of dissolved inorganic phosphate in the Duplin River were several orders of magnitude higher

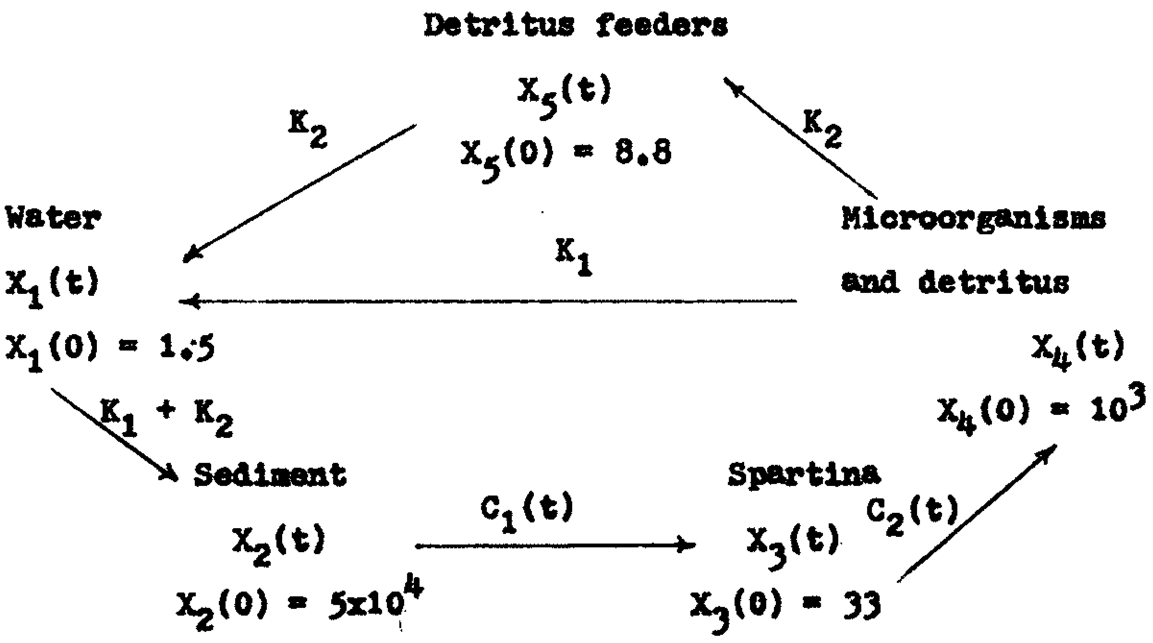
than the coastal zone. The range was 1 to 4 microgram-atoms phosphate phosphorous per liter.

The major differences for the areas are:

1. The Georgia area is not polluted.

2. The Georgia area is not heavily urbanized.

The Duplin River and the Lafayette River areas are similar in amount of rainfall and water temperature. The model postulated by Pomeroy is as follows (Pomeroy, et al., 1972, page 283, figure 7):



Initial concentrations, $X_n(0)$ are in microgram-atoms phosphate phosphorous per liter.

C_1 and C_2 describe seasonal variations in the transfer of dissolved inorganic phosphate from sediments to <u>Spartina</u> and vice versa.

Pomeroy found that levels of phosphate in the Duplin River decreased with an increase in rainfall and increased with an increase in water temperature.

This increase of phosphate with an increase of temperature was ascribed to a slight shift in the equilibrium of the dissolved inorganic phosphate from the sediment to the water because of an alteration of metabolic activity. The seasonal cycle of concentrations of phosphate in the Georgia salt marshes (Pomeroy, et al., 1972) is primarily controlled by the marsh grass (*Spartina*) metabolic processes and secondarily by sediment/water interactions.

Especially interesting was the high values of up to 10 microgram-atoms phosphate phosphorous per liter found in the water even in the winter due to a lag in the *Spartina*/sediment system.

CHAPTER III

METHODS AND MATERIALS

I. DESCRIPTION OF THE STUDY AREA

Description of the general area. The Lafayette River is located within the urban Norfolk, Virginia environs at 36° 55' W and 76° 20' N. The general area is shown in Figure 1 and the sampling area in Figure 2. The physical parameters are shown in Table IV.

The Lafayette River is lined with private residences, high rise apartments, three yacht clubs, a public park and zoo, and a U. S. Public Health Hospital. There is no industry of any consequence on the river. However, the Elizabeth River and Hamptons Roads area is heavily polluted by primary treated domestic wastes and commercial and U. S. Navy shipping. There is a dredge spoil depository at Craney Island at the juncture of the Lafayette River-Elizabeth River mouth. Furthermore, at the western edge of the juncture of the two rivers, there is a Hampton Roads Sanitation District sewage plant, called the Lamberts Point Plant, with a 19-31 million gallons per day capacity. On the Elizabeth River, the city of Portsmouth has at Pinners Point a sewage plant with a 16 million gallons per day capacity. Hampton Roads Sanitation District also has

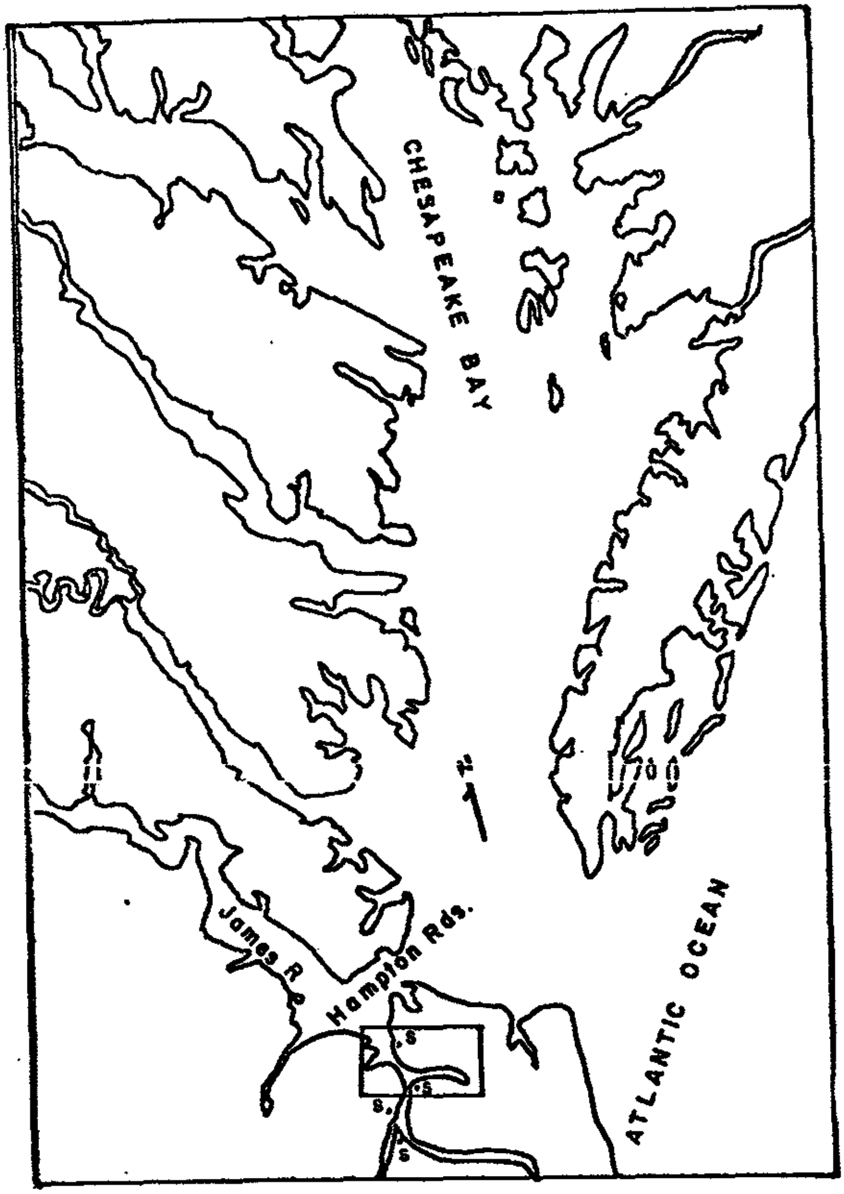


FIGURE 1

Chart of the General Study Area

The sampling area, outlined by the rectangle is shown in greater detail in Figure 2. S indicates sewage plants.

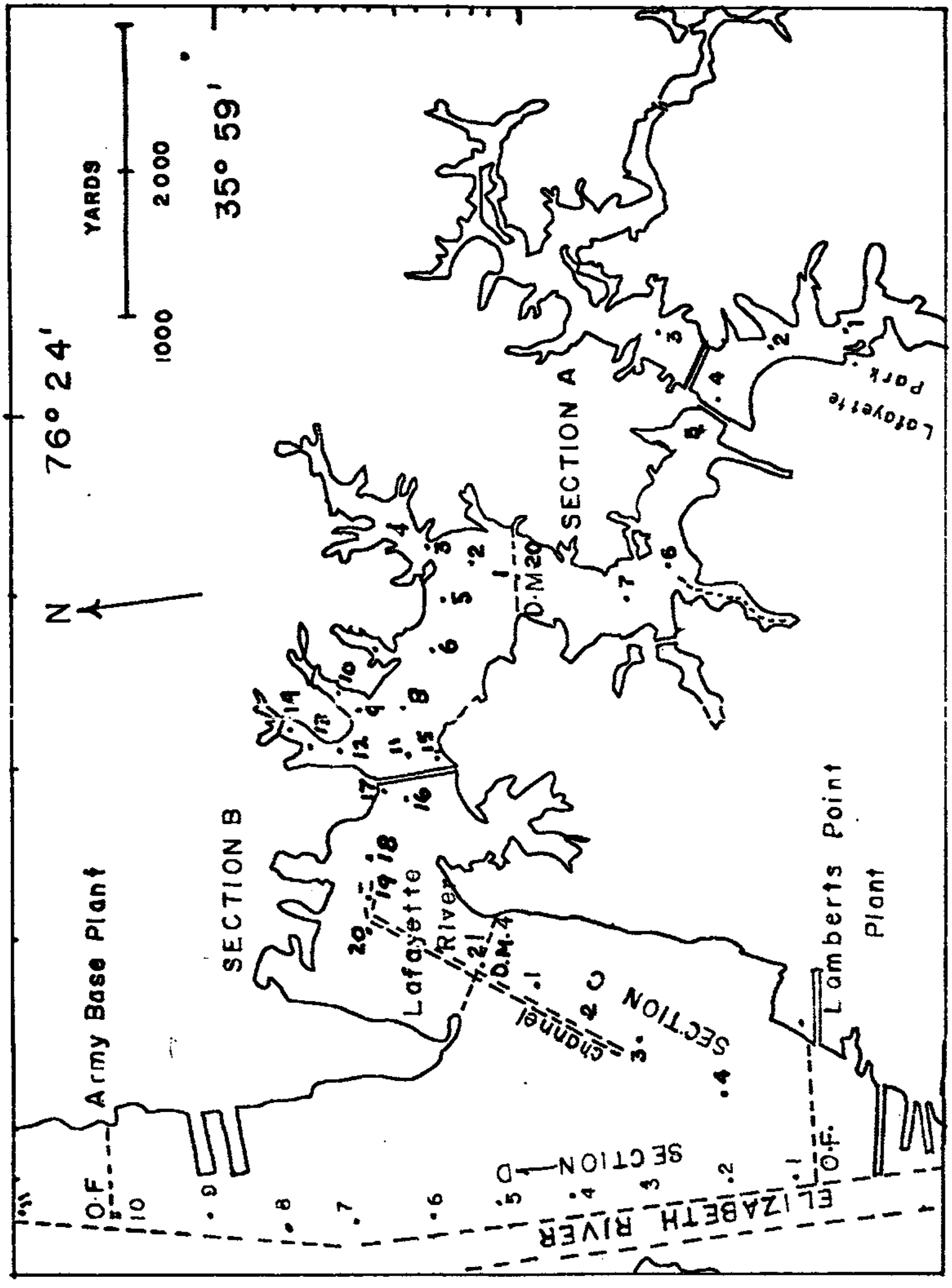


FIGURE 2

A Chart of the Lafayette/Elizabeth River Study Area With Sampling Sections and Locations

Sewer outfalls are marked O.F. Day markers are marked D.M.

TABLE IV

Physical Parameters of the Lafayette River

Physical parameters		Percentage of total water area
Maximum depth (M.L.W.)	22 feet	
Minimum depth (M.L.W.)	1 foot	
Mean depths - overall	4.4 feet	
Mouth of river to Hampton Boulevard Bridge	4.9 feet	31
Hampton Boulevard Bridge to Granby Street Bridge	4.4 feet	46.6
Granby Street Bridge to Lafayette Park	3.5 feet	21.9
Lafayette Park to head of river	2.0 feet	0.3
Drainage area (Seitz, 1971)	16.71 $miles^2$	
Water area (Seitz, 1971)	2.57 $miles^2$	
Length (White, 1972)	4 miles	
Mean volume (White, 1972)	1.5×10^8 $feet^3$	
Width (White, 1972)	390-2100 feet	

a plant on the Elizabeth River near the Pinners Point plant with an outflow of 2-4 million gallons per day of secondary treated sewage and the Army Base plant outside of the mouth of the Elizabeth River with an outflow of 10-12 million gallons per day. The Lamberts Point and Army Base plants are primary treatment plants and are shown in Figure 2. The flow data for these plants is in Appendix B and C.

Description of the sampling area. The sampling area was divided into four sections (Figure 2) labelled A, B, C, and D.

Section A-1 through A-7 is the area from Lafayette Park up to, but not including, Day Marker 20. Section B-1 through B-21 is the area from Day Marker 20 to Day Marker 4 at the mouth of the Lafayette River. Section C-1 through C-4 is the area within the confines of the common mouth of the Elizabeth and Lafayette Rivers. Section D-1 through D-11 is the Elizabeth River mouth out to Hampton Roads.

II. COLLECTION OF SAMPLES

Sampling times. All samples were collected either from an eleven foot skiff, the twenty-eight foot R/V African Queen, the nineteen foot R/V Pangea, the thirty-four foot Miss Priss III, from bridges spanning the Lafayette River, or from docks. In general, surface and bottom samples were taken at each station. The values for each sampling station are shown in Appendix A. The August, 1971 daily samples were collected from the R/V African Queen at stations B-18, C-4, and D-10. The January, 1972 daily samples were taken from the Miss Priss III anchored at station B-16. The May, 1971 tidal data was sampled from station B-16 using the Norfolk Yacht Club dock. The November, 1971 tidal samples were obtained from stations B-14, B-15, and B-16 using docks at these points. Times, dates, sections, wind velocity and tidal stages are shown in Table V for the sampling period 1970-1972.

Temperature. All temperature values are in degrees Centigrade (°C) and were obtained using either a bucket thermometer or the thermocouple circuit on the Beckman RS5 Induction Salinometer.

Salinity. A Beckman RS5 Induction Salinometer with a fifty foot cable was utilized to obtain the salinity in the field. The induction salinometer was calibrated prior to each sampling interval.

Oxygen. When the macro-Winkler technique was used, all oxygen samples were collected with a polyvinyl-chloride Van Dorn bottle. The first 100 milliliters of the sample was allowed to drain out before the oxygen sample was taken. The sample was then drained into the bottom of a 300 milliliter Biological Oxygen Demand bottle using rubber tubing. All precautions were taken to prevent the trapping of air bubbles in the sample container. The samples were stored, after addition of the reagents, at ambient temperature in the dark.

TABLE V

Sampling Information for All Dates for the Study Area Over the Sampling Period 1970-1972

Event	Date	Wind direction and speed	Sampling time interval	Section or Station sampled	Tide Stage
1	10/10/70	70-100° 4-10 knots	0830-1130	A,B	Flood
2	10/13/70	210-260° 3- 8 knots	0930-1200	A,B	Flood
3	10/17/70	240-280° 4- 5 knots	1100	B	Ebb
4	12/15/70	310° 13-10 knots	0830-1030	A,B	Ebb
5.	1/19/71	350-360° 14 knots	1010-1235	A,B	Ebb
6	1/28/71	250° 16 knots	1230-1320	A	Flood
7	3/ 6/71	240-230° 14-12 knots	1145-1300	A,B	Flood
8	5/11/71	90- 70° 4-10 knots	1210-1500	A,B, C,D	Flood
9	5/18/71	360/330/120° 7/3/6/ knots	1023-1700	B-16	1023 Slack flood 1523 Slack ebb
10	6/10/71	40- 80° 14- 8 knots	1530-1730	B,C,D	Flood
11	6/26/71	210-250° 13 knots	1200-1330	B,C,D	Flood
12	7/13/71	30- 50° 11- 9 knots	1320-1550	B,C,D	Flood
13	7/29/71	180-190° 10-12 knots	0810-1010	B,C,D	Ebb
14	8/4-5/71	140-188° 4-12 knots 170-330° 7-12 knots	0850-0743 Daily	B-16 C-4 D-10	Daily
15	10/20/71	115° mean 18.2 knots	1145-1345	A,B	Flood

Table V continued

Event	Date	Wind direction and speed	Sampling time interval	Section or Station sampled	Tide Stage
16	11/13/71	210/220/270/ 360/040° 11/10/14/8/ 9 knots	0640-1825	B-15 B-16 B-17	0553 Slack ebb 1259 Slack flood 1805 Slack ebb
17	1/12-13/72	140° 6.2 knots mean for 1/12 210° 7.6 knots mean for 1/13	1100-1100 Daily	B-16	Daily

Nutrients. The samples were collected with either a Van Dorn bottle or by dipping a polyethylene bottle just below the surface. All samples were stored in the dark on ice. All nutrient samples were analyzed within 3 to 4 hours for most studies or within 30 minutes for the daily survey.

III. TIDE AND WEATHER DATA

Tidal data. The tidal data was obtained from standard tide tables for Lamberts Point, Virginia (U. S. Department of Commerce, Tidal Current Tables, 1970-1972).

Weather data. Wind information was procurred from the National Weather Service at Norfolk Regional Airport.

IV. SEWAGE PUMPING RATE

This rate is expressed in million gallons per day and was taken from the flow records of the Hampton Roads Sanitation District. The sewage pumping rate over a twenty-four hour period for August 4 and 5, 1971 and January 11 and 12, 1972 for the Lamberts Point Sewage Plant is found in Appendix C. The mean monthly sewage pumping rate for the Lamberts Point Plant and the Army Base Plant is shown in Appendix B.

V. ANALYTICAL

Nutrients. All samples were shaken and brought to room temperature prior to analysis. At this point, the various reagents for nutrient assay were added. A one centimeter pathlength was used in the Bausch and Lomb Spectronic 20 spectrophotometer. The wavelength for the determination of phosphate was 705 nm and for the determination of nitrate and nitrite, 525 nm. Corrections were made for turbidity, reagent, and tube to tube effects for all absorbance readings. The Hach Chemical Company method[R] was used for all nutrients. The Hach method for phosphate involves the formation of a phosphomolybdenum blue complex which is reduced by stannous chloride to a blue compound. The nitrate method reduces the nitrate, with an activated cadmium compound, to nitrite. The nitrite then forms a diazo dye compound as in the Griess reaction.

Preparation of calibration curves. All of the methods used for determination of nutrients were based on a chemical reaction which produces a colored product. The absorbance of this colored product is directly proportional to the nutrient concentrations in the sample. Therefore, varying concentrations of the nutrient must be assayed by the particular method in question, so that a calibration curve

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[R]Hach Chemical Company, Ames, Iowa.

of absorbancy versus concentration can be prepared. A least squares fit of the curve is adopted to produce a regression equation. This equation can then be employed to predict the unknown nutrient concentration in a sample.

However, some of the methods utilized are subject to salt errors. If this is so, the calibration curves should be done in waters whose salinities approach that of the study areas. If a salt error is detected, then a calibration should be carried out in water taken from the study area. This will insure that the salt error is truly a salt error and not due to other factors peculiar to the water quality of the study area. Since the Hach[a] methods for nutrient analyses were not in common use at the time this study was conducted, they must be compared to a standard method. The standard methods for this study are those contained in Strickland and Parsons (1965). The efficacy of the Hach method calibration curves over an extended period must be examined to determine if the curves are stable.

The preparation of the calibration curves were examined for:

1. Preparation of the Hach[a] method calibration curves in different artificial salinities and distilled water

2. Determination and statistical comparison of the curves to detect the presence of any salt error

3. Comparison of the Hach® calibration curves in artificially prepared saline waters with those in Lafayette River water

4. Comparison of the Hach® method for phosphate and nitrite and the standard methods

5. Comparison of recent Hach® method calibration curves with previous calibration curves.

Oxygen.

Macro Winkler method. The method used is outlined in Hydrographic Office Publication 607 (U. S. Navy Oceanographic Office, 1968) except that 0.025N phenylarsineoxide (P.A.O., Hach Chemical Company, Ames, Iowa) was used in place of 0.01N sodium thiosulfate. The manganous salt and alkaline iodide were added immediately to the water sample, shaken once, the brown precipate allowed to settle halfway, then reshaken. The samples were stored in the dark. The sulfuric acid was added in the laboratory just prior to titration with phenylarsineoxide. Duplicate aliquots of the sample were always analyzed. The mean of the two titrations was employed to compute the oxygen in milliliters per liter at standard temperature and pressure. The oxygen saturation, in per cent, was computed from a nomograph (Gilbert, et al., 1968).

Oxygen meter A Yellow Spring International (Y.S.I.-51-A) oxygen meter was utilized to obtain in situ oxygen values. The machine was calibrated prior to each use and checked with the macroWinkler method. The machine can be adjusted to compensate for different temperatures, salinities, and ambient pressures, so that the concentration of oxygen can be read from the machine.

VII. STATISTICAL METHODS

<u>Test for null hypothesis</u>. Unless otherwise stated, all tests were run at the p greater than 0.05 level. The significance test for the null hypothesis that the two population means are equal was based upon the "t" statistic (Snedecor and Cochran, 1968).

<u>Analysis of variance for the regression</u>. Draper and Smith (1967) have shown that the sum of the squares about the mean equals the sum of the squares about the regression plus the sum of the squares due to the regression. This allows the deviation from the regression line to be partitioned into two parts. Therefore, it can be applied in the assessment of the usefulness of the regression line. When the sum of the squares (S. S.) due to the regression is much greater than the sum of the squares about the regression or R^2 equals $\frac{\text{Sum of the squares due to regression}}{\text{Sum of the squares about the mean}}$ is not too far from unity, then the regression appears to be a useful predictor. This does not hold true when the number of variables is nearly as large as the number of observations. It would then be possible to get a spuriously high R^2 or multiple correlation coefficient. The method

in Table VI served to construct the analysis of variance (anovar) table. The actual computation was done by an I.B.M. 1130 or 360 digital computer (Dixon, 1970).

<u>Stepwise multiple regression</u>. To obtain a regression equation of the form $Y = B_o + B_1X_1 + B_2X_2 .... B_nX_n + e$ (Equation III-1) (Draper and Smith, 1967), where the variables in the regression may have interrelationships, the order of insertion in the regression could determine the significance and fit of the regression. The Biomedical Research Program for stepwise multiple regression was adopted (Dixon, 1970). This program allows the variables to be inserted in the regression equation if their partial F criterion is greater than a preselected percentage of the appropriate F distribution. If all variables are greater than the percentage of the F value, then the most highly correlated is inserted. The program computes and prints the multiple correlation coefficient, means, standard deviation, anovar table, F values, partial correlation coefficients and constants, and a summary of the increase in R^2.

TABLE VI

Computation of the Analysis of the Regression Table

(Draper and Smith, 1967, p. 15)

Source	Sum of the squares ss	Degree of Freedom df	Mean square ms	F value
Regression	$b_1 X_1Y_1 - \frac{(X_1)(Y_1)}{n}$	1	$MS_r = \frac{ss}{df}$	$\frac{MS_r}{S^2}$
About the regression (residual)	by subtraction	n-2	$s^2 = \frac{(S.S.)}{n-2}$	
About the mean (total corrected for mean)	$Y_1^2 - \frac{(Y_1)^2}{n}$	n-1		

Confidence interval for the regression intercept b_o was:

$b_o \pm t(n-2, 1-\frac{1}{2}a)$ times the standard error of the intercept.

Confidence interval for the regression slope b_1 was:

$b_1 \pm t(n-2, 1-\frac{1}{2}a)$ times the standard error of the slope.

CHAPTER IV

RESULTS OF THE STUDY

The results of this study have been divided into three sections. The first section, laboratory results, will deal with the statistical examination of the nutrient calibration curves. This examination will determine if the curves are significant and whether a "salt error" exists for the Hach[a] methods. Special attention will be paid to the method for phosphate, and the oxygen meter will be compared to the Winkler method. The second section entitled field results will list the concentrations of oxygen, nitrate, nitrite, salinity, water temperature and phosphate for the tidal cycle, daily, seasonal and annual samples. The last section will examine proposed multiple linear regression predictive models for concentrations of phosphate. These models will be utilized in an attempt to determine the relationship of phosphate to the following parameters: tide, phosphate in sewage, rain, wind direction, and water temperature.

I. LABORATORY RESULTS

The results of the statistical tests of the calibration curves for the Hach[a] method are:

1. Dissolved inorganic phosphate. There is a definite salt effect that appears to cause a difference in the slope and intercept of the regression equations between distilled and saline water. The regression equations for the various salinities are shown in Table VII.

2. Nitrate. The slope of the regression equations for the Hach[R] method in distilled water was not significantly different from those in saline waters. However, the intercepts are significantly different indicating a possible salt effect for this method. All the regression equations were significant at the p greater than 0.05 level (Table VII).

3. Nitrite. The results for this method are the same as those for the method for nitrate (Table VII).

<u>Comparison of the Hach Methods with the Standard Methods for distilled water.</u>

1. Dissolved inorganic phosphate. The Hach[R] method for dissolved phosphate in distilled water and at different salinities compares favorably with the standard method (Table VIII).

2. Nitrate. Although the regression equation was significant, the Hach[R] method displayed very erratic results. It was never possible to consistently repeat the Hach[R] determination of nitrate and get the same regression equation. Therefore, a calibration curve was prepared before every daily study and the resulting regression equation used for that determination. The concentrations

TABLE VII

Hach Method Calibration Curve Data for Nutrients

The nutrients were dissolved in waters of different salinities. The concentration ranges for the nutrients are: 1.3 to 12.5 microgram-atoms phosphate phosphorous per liter, 5 to 30 microgram-atoms nitrate nitrogen per liter, 0.05 to 3.04 microgram-atoms nitrite nitrogen per liter. All the regressions are significant at the p greater than 0.05 level.

Regression data	Distilled water	Salinity 15°/oo	25°/oo	30°/oo
Phosphate				
Intercept	26.6 ± 1.3	30.0 ± 0.8	32.7 ± 0.9	
Slope	-0.3 ± 0.04	-0.3 ± 0.02	-0.4 ± 0.03	
Nitrate				
Intercept	———	134.2 ± 3.1	126.0 ± 1.3	134.2 ± 3.2
Slope	———	-1.3 ± 0.2	-1.2 ± 0.1	-1.3 ± 0.2
Nitrite				
Intercept	16.3 ± 7.7	15.38± 0.36	14.55± 0.75	
Slope	-0.7 ± 0.03	-0.16± 0.06	-0.15± 0.05	

TABLE VIII

Comparison of the Standard Method Regression Data and the Hach® Method Regression Data for Dissolved Inorganic Phosphate

Distilled water	Hach® Method	Standard Method
Slope	0.059	0.11
Intercept	0.023	0.20
Concentration range microgram-atoms phosphate phosphorous per liter	2.4 - 9.6	3.0[a]
F value	37.43 ± 2.73	42.8 ± 0.4

a. The F value was determined using only this concentration of phosphate (Strickland and Parsons, 1965).

of nitrate are not presented in the main body of the paper because of inaccuracies in the Hach® method. They are listed in Appendix A.

3. Nitrite. The Hach® method for nitrite compares very favorably with the standard method (Strickland and Parsons, 1965), however, it is not as sensitive nor as precise as the standard method.

One sample, from station B-16, of Lafayette River water was analyzed in quadruplicate by the Hach® and standard phosphate method, giving the following results: 1.4 ± 0.01 microgram-atoms per liter for the Hach® method and 1.6 ± 0.01 microgram-atoms per liter for the standard method. The Hach® method for phosphate was also shown to be stable for at least a year by using the "t" test and comparing the mean F value (defined on page 5, this thesis) of curves P1 plus P2 plus P3 with curve P4 (Table IX).

<u>Comparison of Yellow Springs International oxygen meter, model 51A, with the Macrowinkler oxygen determination</u>. The oxygen meter was compared with oxygen values as determined by the macroWinkler method in waters with different concentrations of oxygen (Table X).

II. FIELD RESULTS

<u>Oxygen</u>.

<u>Range</u>. The range of saturation of oxygen for the Lafayette River was from 56 to 143 per cent (Appendix A).

TABLE IX

Comparison of the Hach Method Calibration Curves for Dissolved Inorganic Phosphate Over an Extended Period, 1970-1972

Curve	Date prepared	Type	F value	Mean F value (pg.5, this thesis)
P1	12/15/70	in 25°/oo NaCl solution	52.5	45.0 ± 4.40
P1			50.3	standard deviation 5.25
P1			46.0	
P2	1/15/71	in 20°/oo NaCl solution	38.3	
P2			42.4	
P3	7/25/71	Lafayette River water	37.8	
P3			46.4	
P3			46.4	
P4	1/11/72	Lafayette River water	51.7	54.0 ± 4.90
P4			54.6	standard deviation 1.99
P4			55.6	

TABLE X

Comparison of Yellow Springs International Oxygen Meter, 4S1-51A, With the MacroWinkler Oxygen Determination (U. S. Navy Oceanographic Office, 1968)

Date	Condition	macroWinkler parts per million oxygen 1	Y.S.I. meter parts per million oxygen 2	Difference (1-2)
July, 1971	tap water equilibrated with air	8.36	8.3	+.06
July, 1971	tap water directly from the tap	7.02	6.9	+.12
July, 1971	helium bubbled through tap water using a diffuser in a covered beaker	2.4	2.7	-.3
July, 1971	tap water directly from the tap	6.5	6.4	+.1
July, 1971	Lafayette River water	7.3	7.2	+.1
March, 1971	tap water directly from the tap	7.31	7.3	+.01
March, 1971	tap water directly from the tap	6.89	6.8	+.09

The values do not include the results of the daily studies in August, 1971 (Event 14) and January, 1972 (Event 17).

Vertical distribution. There was no significant difference ("t" test) between the surface and bottom except in the summer for section C.

Section analysis. There was no significant difference between sections B, C, and D over all seasons. However, section A was significantly different from sections B and C in the fall of 1970 and 1971.

Seasonal analysis. Although there was no significant difference in sections A, B, and C between winter and spring there was a significant difference in both sections A and B between fall and winter and in section B between spring and summer.

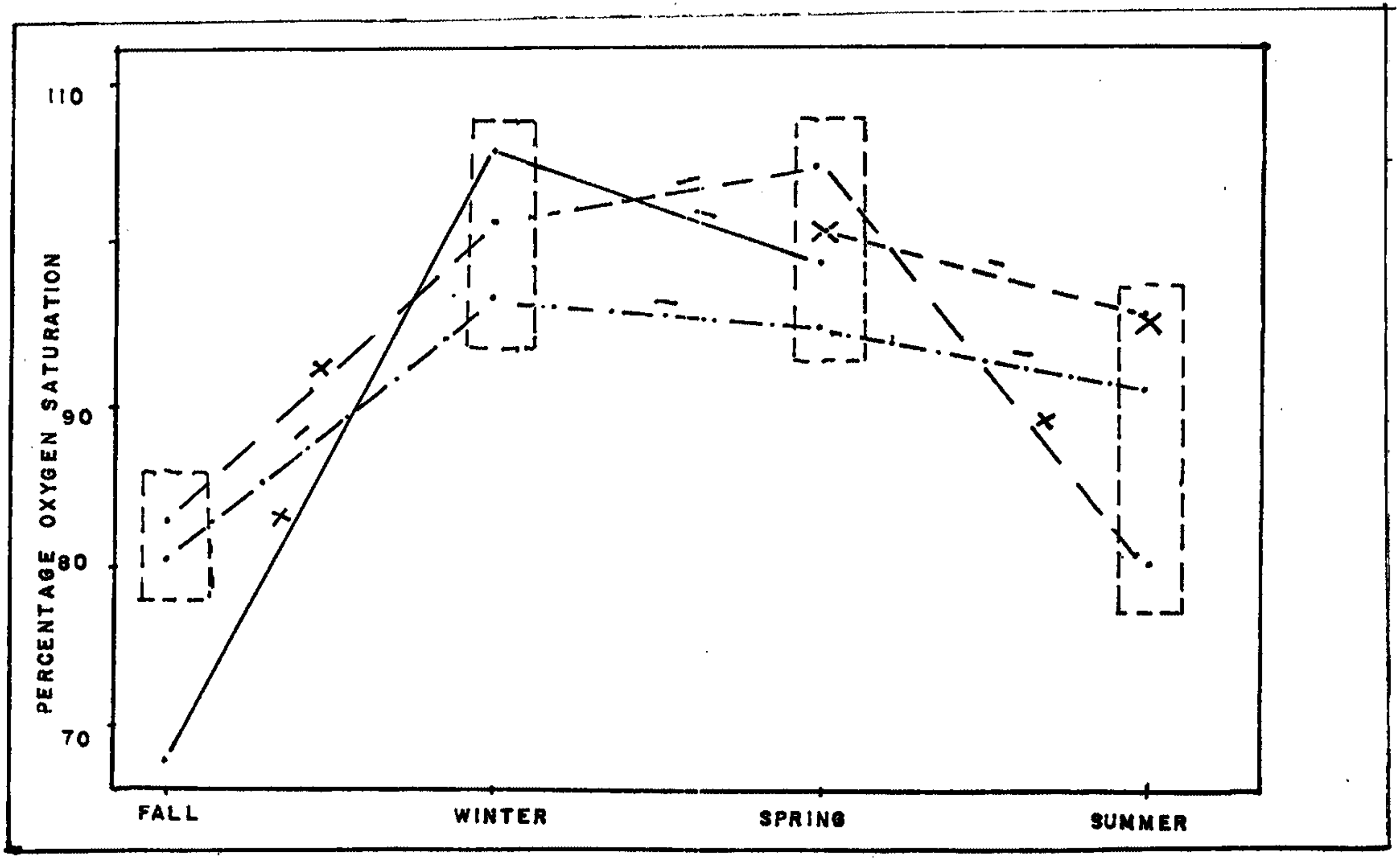
Oxygen per cent saturation seldom reached critical values of 57% (Klein, 1959; State of Virginia, 1971) in the Lafayette River. Section B appeared to have two distinct oxygen levels, these being 80% saturation for the summer and fall and 100% saturation for the winter and spring. Section C had essentially the same oxygen values for all the seasons sampled.

Temperature. The range of temperature was from 0°C to 27.7°C. There was no significant difference ("t" test) between the surface temperature values of all sections over the sampling period nor between the various sections in the same season. The mean temperature for all sections

FIGURE 3

Seasonal Values of Oxygen Saturation Expressed as Percentages, for Sections A(.——.), B(.——.), C(-.-.) and D(X---X) Through 1970-1971.

Sectional oxygen values are combined averages of surface and bottom samples. A + on the line between seasons indicates a significant difference in the values. A - on the line indicates that there is no significant difference in the values. A dotted rectangle indicates that there is no significant difference in the oxygen values for sections for that season.


PERCENTAGE OXYGEN SATURATION
110
90
80
70
FALL
WINTER
SPRING
SUMMER

by season is given in Table XI. There appears to be a temperature difference between fall and winter.

Salinity. The range of salinity was from 11.0 to 24.9 parts per thousand. There was no significant difference ("t" test) between surface and bottom salinity values nor between the various sections at the same season, therefore the mean salinity values for all sections were used (Table XI). The salinity appears to be higher in the fall and lower in the spring.

Nitrate. The method for determination of nitrate was found to be too variable and imprecise to be of any actual use in this study. The range was from 0 to 18 microgram-atoms nitrate nitrogen per liter. The largest values were in the summer and fall and lowest in the spring. The values obtained are shown in Appendix A but no further use will be made of the data for nitrates in this paper.

Nitrite. The value for nitrites ranged from 0 to 4 microgram-atoms nitrite nitrogen per liter. The higher values were generally found in the fall although the maximum nitrite was in the winter at section C. The lowest values were always in the spring (Appendix A).

Tidal cycle. On May 18, 1971 (Event 9), water samples were collected at the Norfolk Yacht Club pier (station B-16) over a six and one half hour period. Data for nitrates,

TABLE XI

Seasonal Salinities, in Parts Per Thousand, and Water Temperature, in Degrees Centigrade, for the Composite Section A + B + C + D for the Period 1970-1972.

The values are composite means for all four sections by seasons. If two values are shown the first is the surface and the second is the bottom value.

Season	Temperature	Salinity
Summer	25.31	15/17
Fall	21.9	24/24
Winter	4.38	19
Spring	12.92	15/13

nitrites, phosphates, and oxygen was collected (Table XII and Appendix A). On November 13, 1971, a 12 hour study (Event 16) was conducted over a wide area to detect any differences in concentrations of dissolved inorganic phosphate. Three stations were chosen so as to span the Lafayette River at the Hampton Boulevard Bridge. Data on nitrates, nitrites, phosphates, oxygen and temperature was collected (Appendix A). Data of phosphates, oxygen, and temperature for this event are shown in Table XIII. When these values were examined statistically, no significant difference was found either between the surface and bottom values for phosphate at each station or between stations.

Daily results. A daily study was made on August 4-5, 1971 (Event 14) and on January 12-13, 1972 (Event 17). Event 14 was done at three different sites; these being stations B-18, C-4, and D-10. Stations C-4 and D-10 are located near the Lamberts Point and Army Base sewage plant outfalls respectively (Appendix E and A). The January daily samples were collected at site B-16, where data of nitrates, nitrites, dissolved inorganic phosphate, oxygen, salinity, and temperature was analyzed (Appendix E and A).

Oxygen. The mean saturation of oxygen for both August, 1971, and January, 1972, ranged from 74-133 per cent. The saturation values of oxygen for both events were essentially the same.

TABLE XII

Dissolved Inorganic Phosphate, in Microgram-atoms Phosphate Phosphorous Per Liter, Oxygen, as Per Cent Saturation, and Tide Stage for the Lafayette River Station B-16 on May 18, 1971 (Event 9) Over a Six and One Half Hour Period

Time (E.D.S.T.)	Phosphate	Oxygen	Tide Stage
1023	4	72	Slack flood
1155	5	80	Ebb
1400	5	107	Ebb
1700	5	112	Flood
Mean	4.8	94	
Standard deviation	0.5	19	
P greater than 0.05 confidence limits	4.8 ± 0.8		

TABLE XIII

Dissolved Inorganic Phosphate, in Microgram-atoms Phosphate Phosphorous Per Liter, Temperature in Degrees Centigrade, Oxygen, as Per Cent Saturation, and Tide Stage, for the Lafayette River, Stations B-15, B-16, and B-17 on November 13, 1971 Over a Twelve Hour Period

P is expressed at the greater than 0.05 confidence limits.

Station	Time, in hours (E.S.T.)	Phosphate surface/ bottom values	Oxygen	Temperature	Tide Stage
B-16	0650	4.3/4.6	91	12.9	Flood
	0910	4.4/4.6			Flood
	1130	4.2/4.1	92		Flood
	1235	4			Flood
	1435	3.9		13.5	Ebb
	1628	4.4		13.9	Ebb
	1835	4.3		13.9	Flood
Mean		4.3 ±0.2	91.5		
Standard deviation		0.2	0.7		
B-17	0710	4.1/4.8	86	13.5	Flood
	0903	4.5/5.3			Flood
	1120	4.1/4.2	102		Flood
	1230	4.1			Flood
	1430	3.8		14	Ebb
	1625	4.1		14	Ebb
B-16	1830	4.4		13.9	Flood
Mean		4.3 ±0.3	94		
Standard deviation		0.4	11		
B-15	0640	4.1	87	13	Flood
	0825	4.2			Flood
	1010	4.9	102	13.5	Flood
	1225	5.3			Flood
	1425	4.1		15.5	Ebb
	1615	4.6		14	Ebb
	1825	4.5			Flood
Mean		4.5 ±0.4	94.5	14	
Standard deviation		0.5	11		

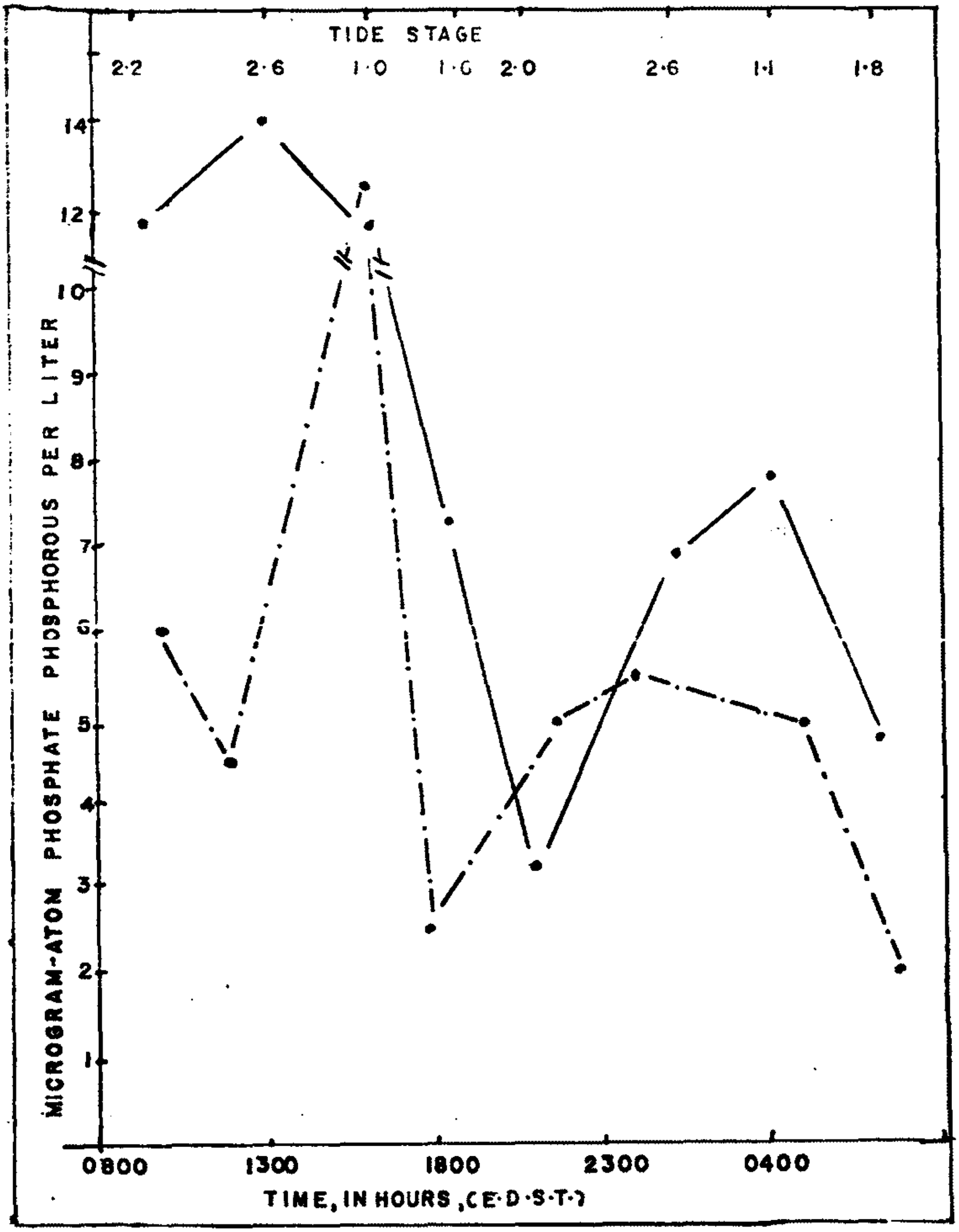
Phosphate. No significant difference was found between surface and bottom values of dissolved inorganic phosphate for either August, 1971 or January, 1972. For the remainder of the discussion the mean of the surface and bottom values will apply. No significant difference existed between the mean values of section B and C, August, 1971. Therefore, the combined means for the same time period were used (Appendix E). The values of stations B-16 and C-4 were combined because the difference in sampling times and the distance between stations were insignificant (Appendix E). There was a significant difference in the values between stations B-18 and D-10 (Appendix E&A). Values for dissolved inorganic phosphate for these time periods in August, 1971 and January, 1972 are given (Figures 4 and 5, and Appendix E).

Seasonal cycle of phosphate. The levels of dissolved inorganic phosphate, water temperature, rainfall, and wind direction for the sampling period are shown in Appendix F. The data was expressed as the means of the combined sections A plus B plus C. These three sections comprise the Lafayette River. The wind directions was expressed as cosine theta (page 5, this thesis). The Elizabeth River, section D, with the same information, excepting cosine theta, are shown in Appendix F. These same parameters were then further combined into seasons for the composite section A + B + C comprising the Lafayette River and are shown in Appendix G.

FIGURE 4

Dissolved Inorganic Phosphate, in Microgram-atoms Phosphate Phosphorous Per Liter for August 4-5, 1971 Over a 24 Hour Period (E.D.S.T.) at Two Sampling-sites B-18 + C-4 (.-.) and D-10 (.-.-.)

Tidal stages are shown and are coded 1 for beginning flood tide and 2 for beginning ebb tide. All of the dissolved inorganic phosphate values are composite means for the surface and bottom values. The values for Stations (B-18 + C-4) are composite means of the two stations for each sampling time.


TIDE STAGE
2·2
2·6
1·0
1·6
2·0
2·6
1·1
1·8
MICROGRAM-ATOM PHOSPHATE PHOSPHOROUS PER LITER
14
12
10
9
8
7
6
5
4
3
2
1
0800
1300
1800
2300
0400
TIME, IN HOURS, (E·D·S·T·)

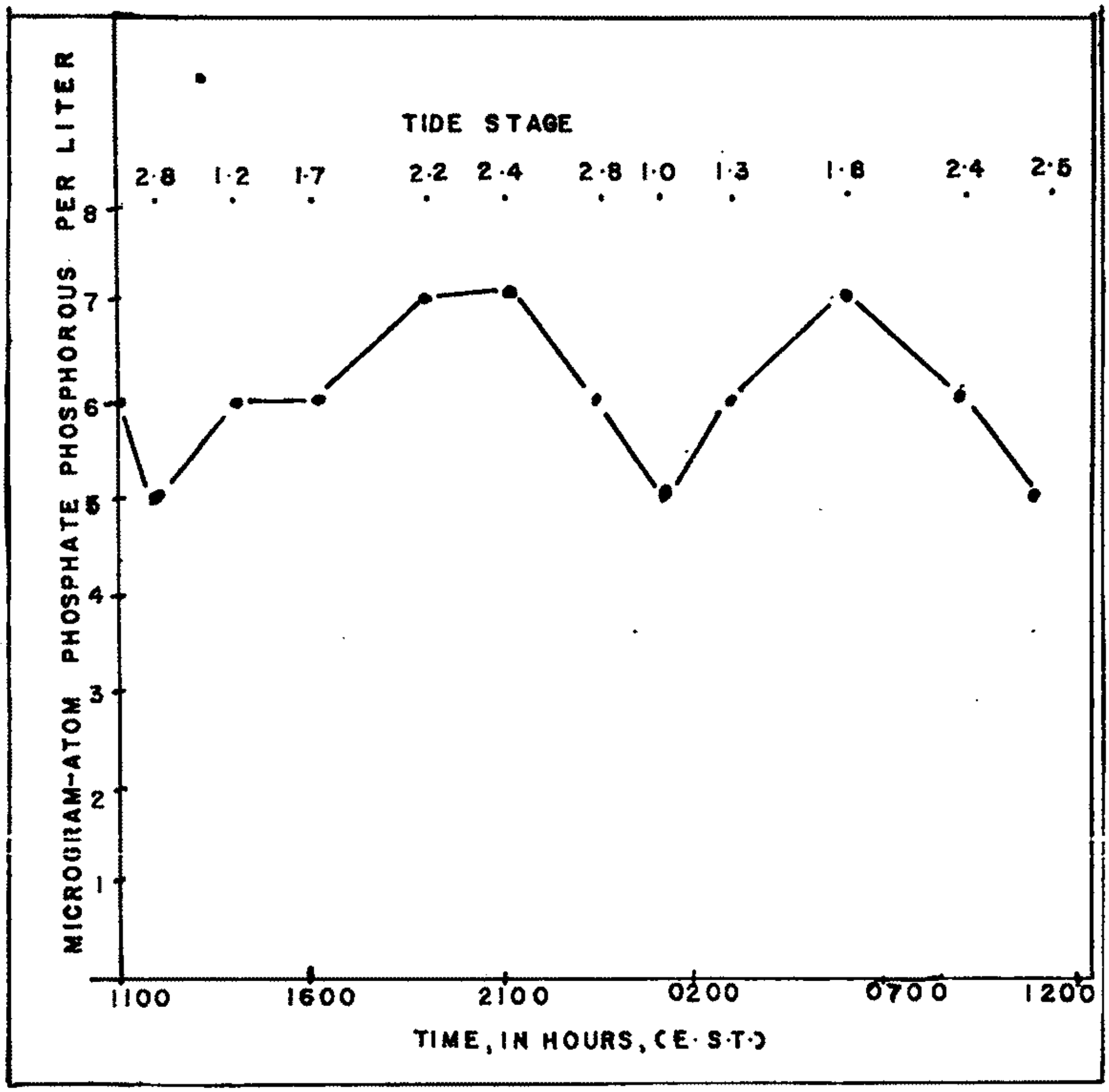


FIGURE 5

Dissolved Inorganic Phosphate, in Microgram-atoms Phosphate Phosphorous Per Liter Over a 24 Hour Period (E.S.T.) for January 12-13, 1972, at Station B-16

Tidal stages are shown and are coded 1 for beginning flood tide and 2 for beginning ebb tide. The dissolved inorganic phosphate values are composite averages of the surface and bottom values.

III. PROPOSED PREDICTIVE MODELS FOR PHOSPHATE

Daily models. A linear regression model was proposed for the dissolved inorganic phosphate in the combined stations B-18 and C-4 for August, 1971. The same model was proposed for January, 1972, station B-16. The predicted dissolved inorganic phosphate is expressed as the logarithm to the base 10. This form was found to give the best fit when the following independent variables were used in the regression: tidal stage, wind component (page 5, this thesis), and the rate of dissolved inorganic phosphate, in kg/hr, from the sewage outfall. This rate of flow of phosphate from the Lamberts Point Plant was determined using the data in Appendix D. The mean daily sewage pumping rates for August, 1971 (Appendix C) and January, 1972 (Appendix C), and the mean daily sewage pumping rates for March, 1972 (Appendix D) were not found to be significantly different. It was assumed that the levels of dissolved inorganic phosphate in the final effluent of the Lamberts Point Plant for August, 1971 and January, 1972 were not significantly different from the levels of phosphate found in March, 1972. Therefore, the rate of flow of phosphate on March, 1972 was used to compute the levels of dissolved inorganic phosphate in the final sewage effluent for the August, 1971 and January, 1972 sampling periods. The concentration of dissolved inorganic phosphate, tidal stage, rate of phosphate from the sewage outfall, wind component and sampling time is shown for August, 1971 and January, 1972 (Appendix E). The resulting linear regression models computed from these variables are shown in Table XIV, formulas IV-2 through IV-5. The observed and predicted concentrations of phosphate are given for August, 1971 (Figure 6) and January, 1972 (Figure 7).

Seasonal models. Using the observed dissolved inorganic phosphate from the sampling period 1970 to 1972 for combined sections A plus B plus C (Appendix F and G), an attempt was made to form a linear regression model for the dissolved inorganic phosphate in these three sections for that period. This seasonal model utilized the following independent variables: water temperature, rainfall, and wind direction, expressed as the cosine of the angle the resultant wind makes relative to the Lafayette River Channel at the mouth. The summary of these resultant models are disclosed in Table XV, formulas IV-6 and IV-7, and the observed and predicted levels of dissolved inorganic phosphate are shown in Figures 8 and 9.

TABLE XIV

Results of the Daily Dissolved Inorganic Phosphate Prediction Models for August 4-5, 1971 and January 12-13, 1972 for the Lafayette River

The models are for Ebb or Flood tides. The estimated dependent variable, $\hat{P}$, is the ordinate expressed as $\log_{10}$ of dissolved inorganic phosphate in microgram-atoms/liter.

August 4-5, 1971	Section B plus C	Flood tide
$\log_{10} \hat{P} = 1.3 - 0.43(T) + 0.009(S)$ Significance level of the regression $p > 0.10$ $R^2\% = 75.3$		equation (IV-2)
August 4-5, 1971	Section B plus C	Ebb tide
$\log_{10} \hat{P} = 0.17 + 1.0(T) - 0.07(S)$ Significance level of the regression $p > 0.10$ $R^2\% = 81$		equation (IV-3)
January 12-13, 1972	Section B	Flood tide
$\log_{10} \hat{P} = 0.91 - 0.04(T) - 0.18(W)$ Significance level of the regression $p > 0.10$ $R^2\% = 94$		equation (IV-4)
January 12-13, 1972	Section B	Ebb tide
$\log_{10} \hat{P} = 1.3 - 0.2(T)$ Significance level of the regression $p > 0.10$ $R^2\% = 68$		equation (IV-5)

Code: Independent variables (X_n)

- T indicates the stage of the tide either ebbing or flooding.
- S indicates the rate of phosphate phosphorous from sewage effluent in kilograms per hour interpolated from March, 1972 data.
- W indicates the wind component computed by taking the cosine of the angle of the wind relative to the Lafayette River channel at 28° True and multiplying this times the wind speed in knots.

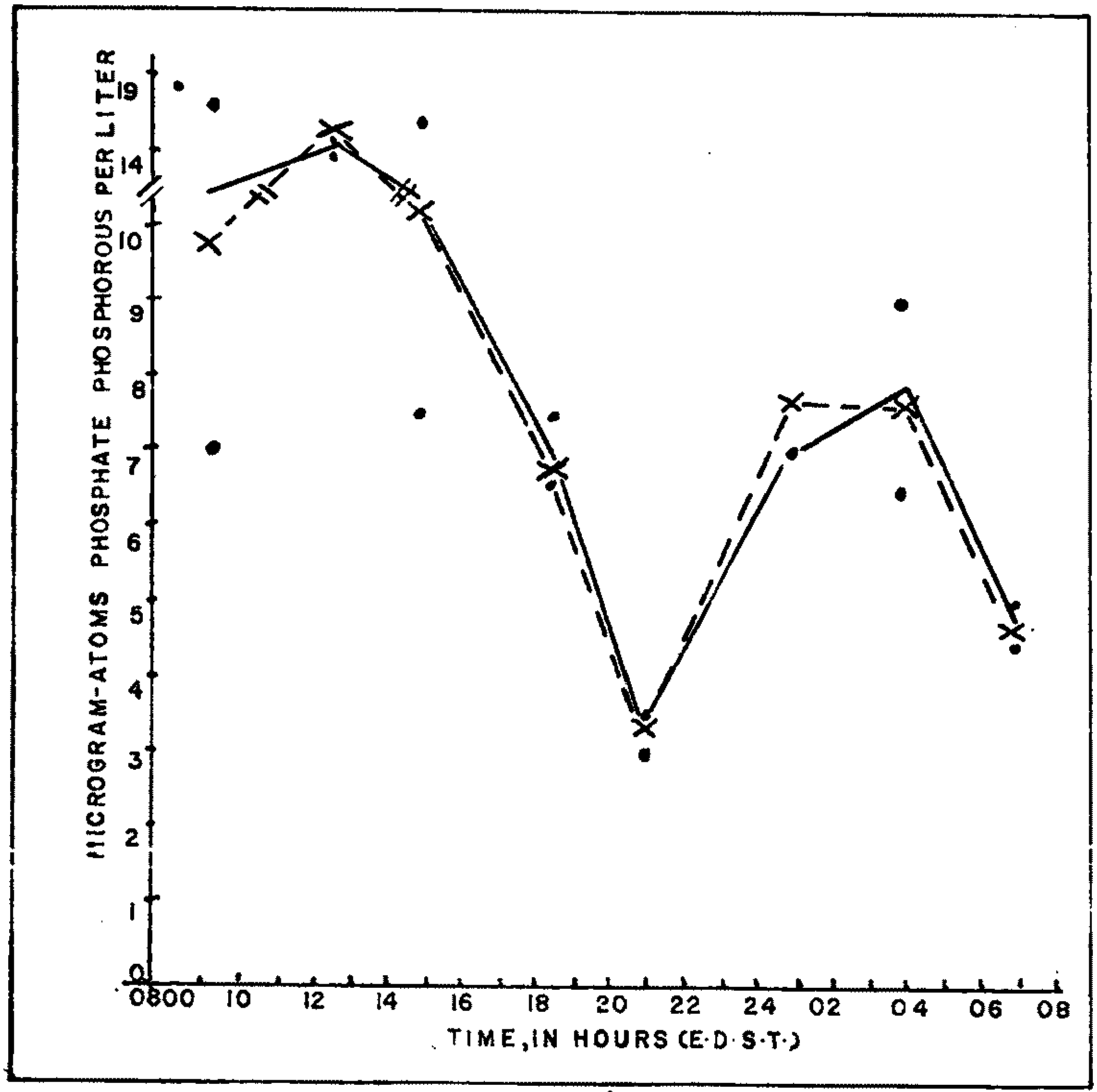


FIGURE 6

Observed (.—.) and Predicted (X..X) Values of Dissolved Inorganic Phosphate in Microgram-atoms Phosphate Phosphorous, for August 4-5, 1971, Over a 24 Hour Period

The regression model equations from Table XIV and the data from Appendix E were used. Note the break in the ordinate. The two observed values shown for each sampling time are the values from station B-18 and C-4.

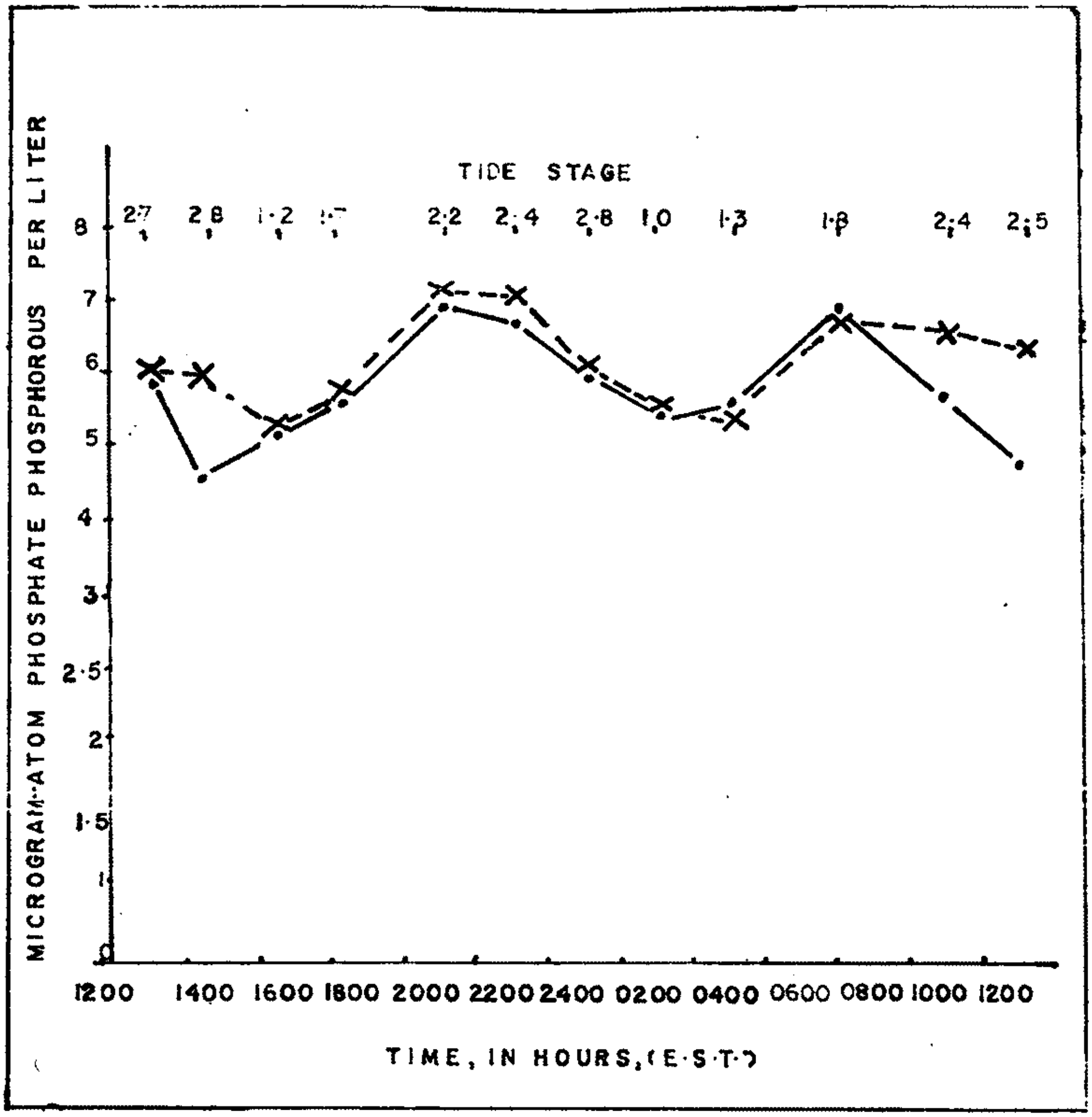


FIGURE 7

Observed (.—.) and Predicted (X--X) Values of Dissolved Inorganic Phosphate, in Microgram-atoms Phosphate Phosphorous Per Liter, for January 12-13, 1972 Over a 24 Hour Period (E.S.T.) at Station B-16

The regression equations from Table XIV and the data in Appendix E were used.

TABLE XV

Annual and Seasonal Predictive Model for Dissolved Inorganic Phosphate for the Combined Lafayette River Sections A Plus B Plus C

Predictive model for dissolved inorganic phosphate over the sampling period 1970 to 1972

$\widehat{D.I.P.} = 1.04 + 0.2(^{o}C) - 0.05(R) - 0.87\ (\cos\theta)$ equation (IV-6)

Significance level of the regression equation, P greater than 0.10

$R^2 = \frac{30.3}{47.7} = 67\%$

Predictive model for seasonal dissolved inorganic phosphate over the sampling period 1970 to 1972

$\widehat{D.I.P.} = 1.1 + 0.19(^{o}C) + 2.2\ (\cos\theta)$ equation (IV-7)

Significance level of the regression equation, P greater than 0.10

$R^2 = \frac{17.8}{20.6} = 86\%$

Code

$\widehat{D.I.P.}$ is the estimated phosphate phosphorous in microgram-atoms per liter.

^{o}C is the water temperature in degrees centigrade.

R is the rainfall in inches.

Cos θ is the cosine of the angle (θ) that the resultant wind makes to the main Lafayette River channel (028° True).

FIGURE 8

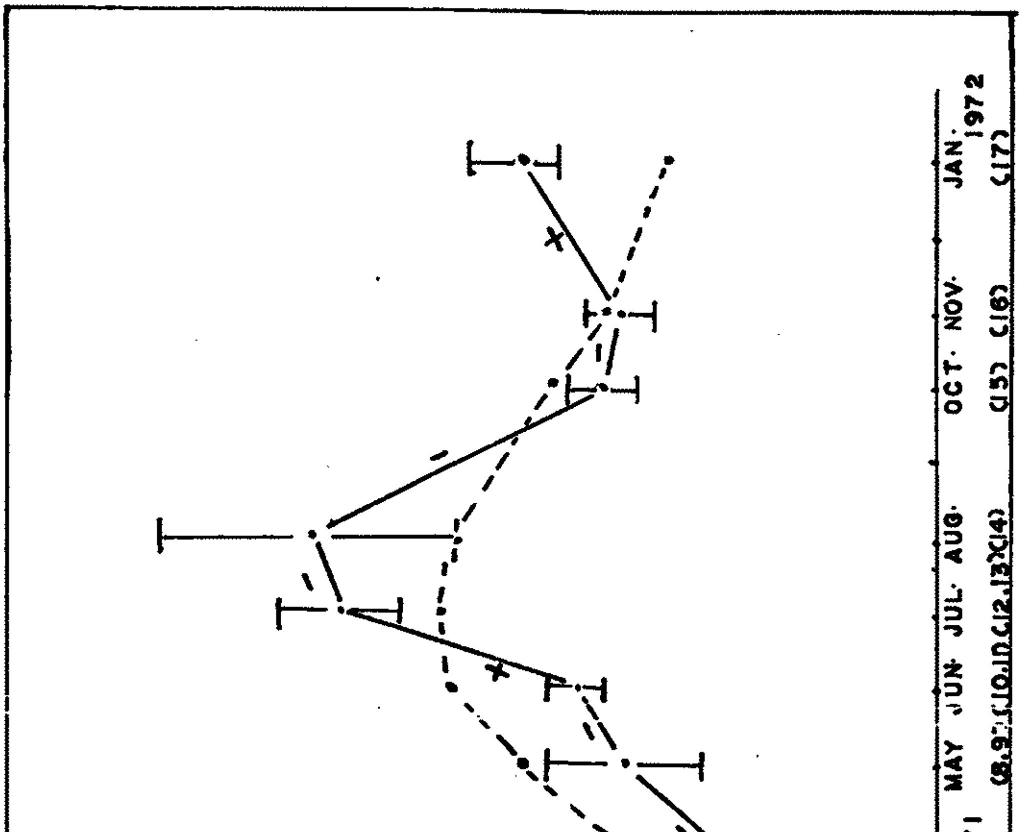
Observed and Predicted Levels of Dissolved Inorganic Phosphate, in Microgram-atoms Phosphate Phosphorous Per Liter for the Lafayette River (Sections A+B+C) for the Sampling Period 1970-1972.

Predicted values were obtained using regression model equations from Table XV. The observed values are combined averages for Section A, B, and C for the months during which the samples were collected.

I———I Observed values and p greater than 0.05 confidence limits.

•———• Predicted values.

A + between months indicates that a significant difference existed between these two values. A - between months indicates that there was no significant difference.


MICROGRAM-ATOMS PHOSPHATE PHOSPHOROUS PER LITER
1 2 3 4 5 6 7 8 9 10 11
MONTH OCT. DEC. JAN. MAR. MAY JUN. JUL. AUG. OCT. NOV. JAN.
year 1970 1971 1972
EVENT (1,2,3) (4) (5,6) (7) (8,9) (10,11) (12,13) (14) (15) (16) (17)

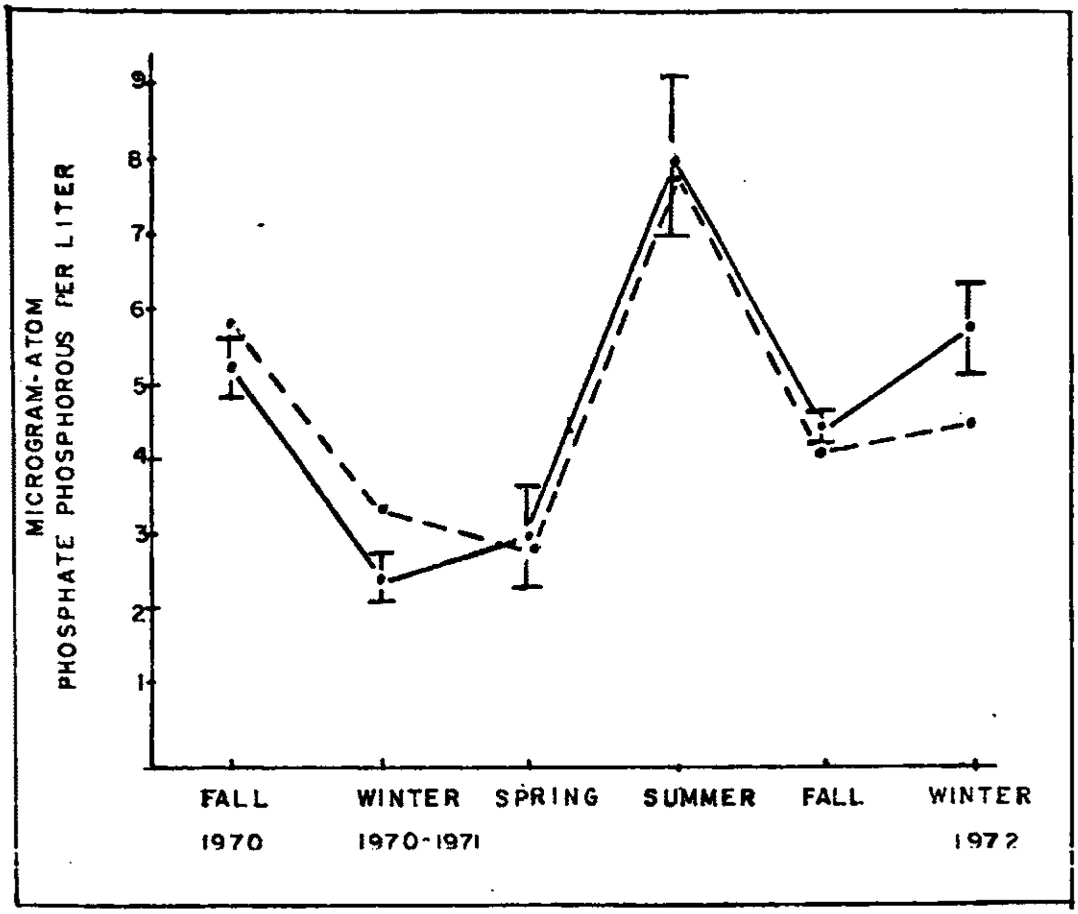


FIGURE 9

Observed (I——I) and Predicted (.---.) Mean Seasonal Values of Dissolved Inorganic Phosphate in Microgram-atoms Phosphate Phosphorous Per Liter for the Lafayette River (Section A+B+C) for the Sampling Period 1970-1972.

Predicted values were obtained using the regression model equations from Table XV. The observed values are combined means for Sections A, B, and C for the seasons during which samples were collected. The P greater than 0.05 confidence limits for the observed values are shown for the observed values.

CHAPTER V

DISCUSSION OF RESULTS

I. LIMITATIONS OF THE COLLECTED DATA

Discussion of the data gathered over the sampling period must be considered within the restrictions of the sampling method, i.e., the samples are consecutive and not synoptic, and therefore, there is a possibility that nutrient levels could be affected by the tidal stage or the time of day. Also, the sampling dates and times chosen for the sampling period could bias the data. Another factor to be considered is that the analytical methods could not detect nutrient values below one microgram-atom dissolved inorganic phosphate phosphorous per liter.

II. DISCUSSION OF THE CIRCULATION OF THE LAFAYETTE RIVER

In general there was no difference in the surface and bottom values of temperature, oxygen, salinity and nutrients over the sampling period. This indicates that the Lafayette River is thoroughly mixed in the vertical direction. This is probably due to its shallow depth and the turbulent diffusion produced by tidal currents. Pritchard (1960) states that vertical diffusion is most intense in layers having vertical homogeneity. The role of tidal movements and mixing in vertically homogenious estuaries is also very large as compared to the water motion and stability produced by inflowing fresh water (Pritchard, 1960).

III. DATA FOR OXYGEN, NITRATE, AND NITRITE

Except in the fall of 1970 and 1971, there was no significant difference between the saturation values of oxygen in the sampling sections A, B, C, or D. In the fall of 1970 and 1971 oxygen saturation values in section A of 69 per cent were significantly lower than those of section B at 82 per cent. Section B levels of oxygen were also significantly lower, at 80 per cent saturation in the fall and summer of 1970 and 1971, as compared to 100 per cent saturation in the winter and spring of 1970 and 1971 (Appendix H). The difference between sections A and B in the fall of 1970 and 1971 could be due to higher heterotrophic activity, and to the increased organic load of the higher phytoplankton densities in this section (T. Purcell, personal communication). This could also indicate that the circulation of the Lafayette River is sluggish, especially in the warm dry months when the water movement in the river is dependent on tidal exchange only.

The method for nitrate used was too imprecise to yield any valid results. The values of nitrites ranged from one to four microgram-atoms nitrite nitrogen per liter and appeared to be inversely related to the levels of oxygen i.e., higher in the fall and summer of 1970 and 1971 when the level of oxygen was lowest (Figure 3).

IV. DISSOLVED INORGANIC PHOSPHATE LEVELS OVER THE SAMPLING PERIOD

Vertical and horizontal distribution. There was no observable difference in the surface to bottom concentration of dissolved inorganic phosphate concentration at any section over the complete sampling period. The lack of any observed lateral difference in the dissolved inorganic phosphate in November, 1971 at stations B-15, B-16 and B-17 over a 12 hour period (Table XIII, page 48) was the reason for the assumption that although the level of dissolved inorganic phosphate may vary from the head of the river to the mouth and at one station over time, there is probably no lateral difference in dissolved inorganic phosphate in the Lafayette River. This lends further weight to the contention that the river is dominated by tidal influence rather than fresh water influx.

Possible mechanisms for the levels of phosphate in the Lafayette River. The level of dissolved inorganic phosphate over the sampling period exceeded the upper limit value of 3.3 microgram-atoms per liter, as suggested by Pritchard (1969), in all the months sampled (Appendix F) except December, 1970, January, 1971 and March, 1971. The levels of phosphate seem to depend on water temperature. This can be shown by comparing the January, 1972 (Section B) mean water temperature of 11°C and the mean concentration of phosphate of 5.8 microgram-atoms per liter with the January, 1971 (Section B) mean water temperature of 2°C and mean level of phosphate of 2.4 microgram-atoms per liter. The water temperature is 9°C higher in 1972 and dissolved inorganic phosphate in 1972 is double that of the 1971 concentration of phosphate. This appears to agree with the general statement that for an increase of 10°C in the temperature the chemical reaction rate is doubled (Briscoe, 1949). The fact that levels of phosphate in estuaries increase with temperature is further supported by Pomeroy (1960). Pomeroy (1960) showed that the concentration of dissolved inorganic phosphate increased from 3 to 5.5 microgram-atoms dissolved inorganic phosphate phosphorous per liter when the water temperature rose from 15°C to 27°C. As well as a direct relationship between phosphate and temperature, there was an increase in phosphate turnover time from 2.0 to 4.0 milligrams phosphate phosphorous per cubic meter per hour. The influence of temperature on the level of dissolved inorganic phosphate of the Lafayette River is best shown by the results of the annual and seasonal models for dissolved inorganic phosphate (Table XV, page 58, equation IV-6 and IV-7). The model using the composite mean of the dissolved inorganic phosphate for the months sampled is referred to as the annual model. This annual model has a positive regression coefficient for temperature and negative regression coefficients for rain and wind direction. This annual model has a constant value of approximately one. The seasonal model of dissolved inorganic phosphate in the Lafayette River has a constant of one and positive regression coefficients for temperature and wind direction. The seasonal model accounts for approximately 86 per cent and the annual model 65 per cent of the variance in the dissolved inorganic phosphate level. The prediction of a constant level of one microgram-atom dissolved inorganic phosphate phosphorous per liter in both models, which can be obtained by setting the independent variables to zero in the regression equations, agrees with the value which Pomeroy et al., (1965) states is the equilibrium value for an estuarine system. This system (Pomeroy, 1965) consists of a two step ion exchange between clay minerals and water, and interstitial microorganisms and water. This system maintains a concentration of dissolved inorganic phosphate of one microgram-atom phosphate phosphorous per liter. Pomeroy's hypothesis could explain the fact that there were very few times when dissolved inorganic phosphate was not found in the Lafayette River over this sampling period (Appendix A). The regression of dissolved inorganic phosphate with temperature suggests a possible biological mechanism for the high levels of phosphate found in the Lafayette River. Few of the purely physical or chemical models for phosphate in estuaries (Rochford, 1951; Carritt and Goodgal, 1954; Jitts, 1959; Pomeroy, et al., 1965; Reimold, 1965; Young, 1968), appear to be capable of the high levels of phosphate found in the Lafayette River. Pomeroy postulates a model for a Georgia salt marsh estuary that is very similar to the Lafayette River in many physical aspects but dissimilar in three main categories, which are:

1. Concentration of phosphate in the Lafayette River ranged from 1.9 to 8.6 microgram-atoms per liter whereas the Duplin River ranged from 1.0 to 4.0 microgram-atoms phosphate phosphorous per liter.

2. The Duplin River was dominated by Spartina type marsh grasses, whereas the Lafayette River has comparatively few marshes.

3. The Duplin River area is not urbanized or polluted while the Lafayette River is surrounded by the City of Norfolk whose sewage outfalls deposit primary treated sewage effluent at the mouth of the river.

Pomeroy's model uses the Spartina marsh grass as the controlling mechanism for the level of phosphate. If this same general model is appropriate for this area, then the small amount of marsh grass in the Lafayette River could cause the Spartina-sediment equilibrium to shift and release higher quantities of phosphate to the waters of the Lafayette River. This shifting of the Spartina-sediment system, with an increase in phosphate from 1 to 10 microgram-atoms phosphate phosphorous per liter, has been noted by Pomeroy in the Georgia salt marsh. Pomeroy's model reveals that the level of phosphate in the Duplin

River is directly related to water temperature and inversely related to rainfall. The annual and seasonal models show that similar results were found in the Lafayette River (Table XV, page 58, this thesis). It would appear that the Lafayette River's level of dissolved inorganic phosphate is controlled primarily by metabolic processes of the organisms in the sediment or water rather than the marsh grass as in Pomeroy's model. If this is so, then it is possible that the level of dissolved inorganic phosphate could result from the metabolic activities of zooplankton or other organisms in the water (Rigler, 1956, 1964; Smayda, 1957; Hayes, 1963; Raymont, 1963; Martin, 1965; Satami and Pomeroy, 1965; McKellar, 1971), or in the sediment (Zobell and Feltham, 1948; Teal and Kanwisher, 1961; Oppenheimer and Ward, 1963; Wood, 1965; Aurand, 1968; Gooch, 1968; Pomeroy, et al., 1972). The high values of loosely bound phosphate found in estuarine sediments (Moore, 1929; Rochford, 1951; Young, 1968), lends strength to the belief that the primary control of the levels of dissolved inorganic phosphate in the Lafayette River is determined by the sediment-water system.

The inverse relationship of rainfall to the level of dissolved inorganic phosphate in the Lafayette River suggests that the rainfall either dilutes the concentration of phosphate in the water thereby reducing the level of phosphate or causes a body of more saline water with a lower value of phosphate to enter the Lafayette River. This water deficient in phosphate could be water from the Hampton Roads area which has been shown to contain lower concentrations of phosphate (Stroup and Wood, 1966). The concentration of phosphate in storm runoff for similar areas can range from 3.5 to 29 microgram-atoms phosphate per liter (Fruh, 1968). The values of phosphate for rainwater can vary from 0.13 to 3.2 microgram-atoms phosphate phosphorous per liter (Fruh, 1968). As the magnitude of the concentration of phosphate in rainwater and storm runoff could cause the concentration of phosphate in the Lafayette River to increase rather than decrease, it appears that the influx of waters lower in phosphate from Hampton Roads may better explain the diluting effect of rainwater on the content of phosphate in the Lafayette River.

The direct relation of a northerly or a southerly wind to levels of phosphate in the seasonal predictive model for phosphate seems to tie in with the seasonal shift in winds in the Norfolk area from a northeasterly direction in the winter to a southwesterly direction in the summer (Table XV, page 58). A northeasterly wind could cause a wind induced flow from the Lafayette River at the surface along with a bottom flow into the Lafayette River of Hampton Roads water, which is lower in dissolved inorganic phosphate. A southeasterly wind could cause just the opposite result.

<u>Discussion of the daily fluctuation of phosphate</u>. The daily cycle of dissolved inorganic phosphate for August, 1971 appears to be controlled by tide and the rate of flow of phosphate in the sewage effluent, from the Lamberts Point Sewage Plant outfall. The regression coefficients in the daily model (Table XIV, page 55, this thesis) reveal that on a flood tide a unit increase in tide stage has three times the effect as a unit increase in the rate of flow of phosphate from the sewage outfall. However, on the ebb tide the coefficients have equal weight. The level of phosphate in the Lafayette River decreases as the tidal stage changes from slack to flood and increases as the tide progresses from slack to ebb. At the same time there is a positive regression coefficient for the rate of flow of phosphate from the sewage plant outfall during the flood tide and a negative regression coefficient for this variable on the ebb tide. In August the size of the tidal regression coefficients seems to indicate that the tidal effect is more important than the flux of phosphate from the sewage plant outfall. The positive signs for the tidal regression coefficient in the August, 1971 daily model could indicate the following:

1. The source of dissolved inorganic phosphate for the Lafayette River is upstream (Section A) from the daily sampling stations (Section B and C).

2. The ebbing waters of the Elizabeth River, along with its high load of dissolved inorganic phosphate from

the sewage outfall, forms an eddy of water which enters the Lafayette River.

3. The model is wrong and the regression equation results purely by chance.

4. The B_oX_o values (page 3, this thesis) are more important in the regression than the variables entered into the model.

5. The flood waters coming from the Hampton Roads area, where the values of dissolved inorganic phosphate are lower, could dilute the waters of the Lafayette River.

Of these five alternatives, it is not possible to dispute numbers three and four with the small amount of data presently available. The first alternative, that the source of phosphate is upstream (Section A) does not appear to be valid as it was very seldom that concentrations of phosphate were higher upstream (Appendix A, Section A). The second alternative appears more likely but the daily model for concentration of phosphate on the ebb tide also contains a negative regression coefficient for the rate of flow of phosphate from the Lamberts Point sewage outfall. This indicates that if there is an eddy at ebb tide, it is not bringing water with a high content of phosphate from the Elizabeth River into the Lafayette River. The August, 1971 daily prediction model for phosphate seems to show that the phosphate from the sewage plant on the Elizabeth River does affect the levels of phosphate in the Lafayette River on the flood tide. The concentration of phosphate in the Lafayette River increases as the flow of phosphate in the effluent from the Lamberts Point sewage plant increases. However this is true only on the flood tide when the Elizabeth River water moves into the Lafayette River. The daily model for January, 1972 is entirely different from the August, 1971 daily prediction model for phosphate, especially in these aspects:

1. The water temperature in August, 1971 was approximately 25°C whereas in January, 1972 it was approximately 10°C.

2. The overall range of concentrations of phosphate in August, 1971 was from 5-16 microgram-atoms phosphate per liter as compared to 5-7 microgram-atoms phosphate per liter for January, 1972.

3. The mean concentration of phosphate for August, 1971 was 8.6 as compared to 5.8 microgram-atoms phosphate per liter for the January, 1972 daily study.

The differences in concentration of phosphate for the two studies could be due to the following:

1. The August, 1971 or the January, 1972 values of phosphate resulted totally from chance and were not typical of that sampling period.

2. The levels of phosphate in the Lafayette River are the result of a biological-sediment-water regeneration of phosphate, where colder temperatures would depress the release of phosphate from the sediment to the water.

The daily fluctuations of phosphate are the result of a dilution of the higher level of dissolved inorganic phosphate in the waters of the Lafayette River by the lower content of phosphate in the flooding waters of Hampton Roads. There is then less production of phosphate in the waters of the Lafayette River in the winter. Therefore, when the level of phosphate in the Lafayette River is diluted by the waters deficient in phosphate from Hampton Roads, there is no noticeable effect because the level of phosphate is already low in the Lafayette River. There is greater production of phosphate in the Lafayette River in the summer. When the summer level of phosphate in the Lafayette River is diluted by the waters deficient in phosphate from Hampton Roads, there is a noticeable difference, for the Lafayette River has a higher concentration of phosphate at this time.

<u>Discussion of the "atypical" cycle of phosphate in the Lafayette River as compared to other estuaries</u>. It has been noted by many researchers (Newcombe, et al., 1939, 1940; Rochford, 1951; Smayda, 1957; Pomeroy, et al., 1972) that estuaries have an "atypical" cycle of phosphate, i.e., high values of phosphate in the summer and low values of phosphate in the winter. This cycle is in general just the opposite of that in the open ocean (Sverdrup, et al., 1942; Moore, 1958). The Lafayette River has the same type of "atypical" cycle of phosphate. The Lafayette River has levels of phosphate similar to those in the polluted New York

Harbor (Howells, et al., 1970). However, the values are far less than those of a Delaware salt marsh (Reimold, 1965). The Lafayette River has much higher values of phosphate then either Hampton Roads, lower Chesapeake Bay, or the York River in the lower Chesapeake Bay. The levels of phosphate for other estuaries (Table III, pages 13 and 14, this thesis) appear to dispute the statement by Pritchard (1969) that 3.3 microgram-atoms phosphate phosphorous per liter is the upper limit for estuarine waters before the deleterious effects of eutrophication occur. The values for salt marshes and rivers bordering salt marshes (Reimold, 1965; Pomeroy, et al., 1972) are from two to ten times the value stated by Pritchard (1969). Although phosphate can be used as an index and tracer of pollution (Ketchum, 1967), it can not be used *a priori* to define pollution. There are environments which normally contain concentrations of phosphate much greater than 3.3 microgram-atoms phosphate phosphorous per liter.

CHAPTER VI

CONCLUSION

The Lafayette River is a shallow, turbid, urban estuary in Norfolk, Virginia. Water movement is controlled mainly by the tide rather than fresh water influx. Oxygen, temperature and salinity values are vertically and laterally homogenious in the Lafayette River. Temperature and oxygen are also horizontally homogenious except during the warm, dry months when the oxygen values at the head of the river were lower than those at the mouth. There is usually a small horizontal salinity gradient from the mouth to the head of the river.

The Lafayette River has an "atypical" phosphate cycle. The values of phosphate are higher in the summer and lower in the winter. The values of phosphate ranged from one to twenty four microgram-atoms per liter.

The mean values of phosphate in the Lafayette River for the winter (1970-1971 and 1972) ranged from 2.4 to 5.8 microgram-atoms per liter and for the summer of 1971, 8.0 microgram-atoms per liter.

The concentration of phosphate in the Lafayette River is much higher than that of the Hampton Roads and Chesapeake Bay area. The Lafayette River contains from two to four times as much phosphate as other estuaries and rivers in the Chesapeake Bay area, the Elizabeth River being the one exception with values of phosphate comparable to the Lafayette River. The levels of phosphate over the sampling period were in general higher than the value of 3.3 microgram-atoms per liter, set by Pritchard (1969) as the upper level for concentration of phosphate beyond which large algal blooms occur.

Multiple linear regression models were prepared and attempted to relate the daily changes in phosphate ($\hat{P}$) to: tide stage (T), wind component (W), rate of phosphate (kg/hr) from the Lamberts Point sewer outfall (S).

<u>Daily</u> August, 1971 Flood tide

$$\log_{10} \hat{P} = 1.3 - 0.43(T) + 0.009(S) \quad \text{(equation IV-2)}$$

Ebb tide

$$\log_{10} \hat{P} = 0.17 - 1.0(T) - 0.07(S) \quad \text{(equation IV-3)}$$

January, 1972 Flood tide

$$\log_{10} \hat{P} = 0.91 - 0.04(T) - 0.18(W) \quad \text{(equation IV-4)}$$

Ebb tide

$$\log_{10} \hat{P} = 1.3 - 0.2(T) \quad \text{(equation IV-5)}$$

As can be seen by equations IV-2 and IV-3 (August, 1971) the effect of the tide stage (T) is three times as important in the determination of the levels of phosphate as the rate of flow of phosphate from the sewage effluent (S) on the ebbing tide and is equally as important as the rate of flow of phosphate from the sewage effluent on the flooding tide.

The daily variations in phosphate are more noticeable in the summer because of the higher concentrations of phosphate in the Lafayette River during this season. The increase of phosphate on the ebb tide and the decrease on the flood tide over a daily cycle was attributed to a dilution of the waters of the Lafayette River by the water from Hampton Roads. The water from Hampton Roads contains from 0.8 to 1.0 microgram-atoms of phosphate per liter.

The predictive multiple regression model for phosphate ($\widehat{D.I.P.}$) over the sampling period 1970-1972 is found to be a function of water temperature (^{o}C), rainfall (R), and wind direction ($\cos \theta$), The predictive model for seasonal concentration of phosphate was a function of water temperature and wind direction.

Annual Model

$$\widehat{D.I.P.} = 1.0 + 0.2(^{o}C) - 0.05(R) - 0.87(\cos \theta) \quad \text{(equation IV-6)}$$

Seasonal Model

$$\widehat{D.I.P.} = 1.1 + 0.19(^{o}C) + 2.2(\cos \theta)$$

The direct relation of water temperature to content of phosphate was attributed to the increased biochemical activities of the microorganisms in the sediment-water system. The inverse relation of rain to concentration of phosphate was due to a dilution of the Lafayette River water by inflowing, more saline Hampton Roads water and its lower concentration of phosphate.

REFERENCES

REFERENCES CITED

Aurand, D. 1968. The seasonal and spatial distribution of nitrate and nitrite in the surface waters of two Delaware salt marshes. Masters thesis, University of Delaware, Newark, Delaware. 115p.

Barlow, J. P., C. P. Lorenzen, and R. T. Myren. 1963. Eutrophication of a tidal estuary. Limnol. Oceanogr. 8:251-262.

Brehmer, M. L. 1972. Biological and chemical study of Virginia's estuaries. Bulletin 45, Virginia Polytechnic Institute, Water Resources Research Center, Blacksburg, Virginia. 45 p.

Briscoe, H. T. 1949. General chemistry for colleges, 4th edition. Houghton Mifflin Co., Boston, Massachusetts. 773 p.

Carritt, D. E. and S. Goodgal. 1954. Sorptions reactions and some ecological implications. Deep-Sea Res. 1:224-243.

Caperon, J. S., A. Cottell, and G. Krasnick. 1971. Phytoplankton kinetics in a subtropical estuary: Eutrophication. Limnol. Oceanogr. 16:599-607.

Crohurst, A. R. and E. C. Sullinon. 1935. A study of the pollution of the waters of Hampton Roads and vicinity and a report on sewage and waste disposal for the adjacent communities. Chesapeake Bay Study, U.S.P.H.S., Norfolk, Virginia. 180 p.

Dixon, W. J. 1970. [ed.] Biomedical computer programs, University of California Publication in Automatic Computation number 2. University of California Press, Berkeley. 265 p.

Draper, N. R. and H. Smith. 1967. Applied regression analysis. John Wiley and Sons, Inc., New York. 407 p.

Fruh, E. G. 1968. Biological responses to nutrients. Eutrophication problems in fresh water, p. 49-64. In E. Gloyna and W. W. Eckenfelder [editors] Advances in water quality improvement. University of Texas, Austin, Texas. 513 p.

Gilbert, W., W. Pawley, and K. Park. 1968. Carpenter's oxygen solubility tables and nomograph for seawater as a function of temperature and salinity. Oregon State University Data Report No. 29, Corvalles, Oregon. 60 p.

Goffigon, G. 1972. Hampton Roads Sanitation District, Director of Treatment, Norfolk, Virginia. Personal communication.

Gooch, E. L. 1968. H_2S production and its effect on inorganic phosphate release from the sediments of the Canary Creek marsh. Masters thesis, University of Delaware, Newark, Delaware. 150 p.

Hayes, F. R. 1963. The role of bacteria in the mineralization of phosphate in lakes, p. 654-663. In C. Oppenheimer [ed.] Symposium on marine microbiology. C. Thomas Publisher, Springfield, Illinois. 769 p.

Herman, S. S., J. A. Mihursly, and A. J. McErlean. 1968. Zooplankton and environmental characteristics of the Patuxent River estuary, 1963-1965. Chesa. Sci. 9:67-82.

Hobbie, J. E. 1970. Phosphorous concentrations in the Pamlico River estuary of North Carolina. State of Agriculture and engineering, Water Resources Research Institute Report No. 33, North Carolina University, Raleigh, North Carolina. 49 p.

Howells, G. P., T. J. Kneipe, and M. Eisenbud. 1970. Water quality in industrial areas: profile of a river. Envir. Sci. Technol. 4:26-35.

Hutchinson, G. E. and V. T. Bowen. 1947. A direct demonstration of the phosphorous cycle in a small lake. Proc. Nat. Acad. Sci. 33:148-153.

Hutchinson, G. E. and V. T. Bowen. 1950. Limnological studies in Connecticut IX. A quantitative radiochemical study of the phosphorous cycle in Linsley Pond. Ecology 31:194-203.

Jeffries, H. P. 1962. Environmental characteristics of Raritan Bay: A polluted estuary. Limnol. Oceanogr. 7:21-31.

Jennings, R. R. 1965. An evaluation of water quality in the Eastern Branch of the Elizabeth River. A report from the Virginia State Water Control Board, Richmond, Virginia. 12 p.

Jitts, H. R. 1959. The adsorption of phosphate by estuarine bottom deposits. Aust. J. Mar. Freshwater Res. 10:7-21.

Ketchum, B. 1967. Phytoplankton nutrients, p. 329-335. In G. H. Lauff [ed.] Estuaries. A.A.A.S. Publication No. 83, Washington, D. C. 757 p.

Klein, L. 1959a. River pollution I. Chemical analysis. Butterworth, London. 454 p.

Klein, L. 1959b. River pollution II. Causes and Effects. Butterworth, London. 360 p.

Kuenzler, E. J., H. McKellar, and B. Muse. 1970. Phosphorous flux between water and plankton, p. 180-187. In H. T. Odum and H. F. Chestnut [principle investigators] Studies of marine estuarine ecosystems developing with treated sewage wastes, Annual Report for 1969-1970 to N.S.F. Sea Grants Project Div., North Carolina Board of Science and Techn., Chapel Hill, North Carolina, Unpublished ms. 364 p.

Likens, G. E. 1972. Eutrophication and aquatic ecosystems, p. 3-13. In G. E. Liken [ed.] Nutrients and Eutrophication: The limiting nutrient controversy. Proceedings of the Symposium on Nutrients and Eutrophication. Amer. Soc. Limnol. Oceanogr. Allen Press, Inc., Lawrence, Kansas.

Marshal, H. G. 1967. Plankton in James River estuary 2. Phytoplankton in the Elizabeth River. Virginia J. of Science. 18(new series):102-109.

Marshal, H. G. 1968. Plankton in the James River estuary II Phytoplankton in the Lafayette and Elizabeth Rivers (Western and Eastern Branches). Castanea. 33:255-258.

Marshal, H. G. 1969. Observations on the distribution of phytoplankton in the Elizabeth River, Virginia. Virginia J. of Science. 20:37-39.

Martin, J. 1965. Phytoplankton - zooplankton relationships in Narragansett Bay. Limnol. Oceanogr. 10(Redfield memorial edition):185-191.

McKellar, H. N., Jr. 1971. The phosphorous systems March-December 1970. In E. J. Kuenzler and A. F. Chestnut [principle investigators] Structure and functioning of estuarine ecosystems exposed to treated sewage. Annual Report for 1970-1971 to N.O.A.A., Office of Sea Grants Programs, Institute of Marine Sciences, University of North Carolina, Chapel Hill, North Carolina, Unpublished ms. 345 p.

McKellar, H. N., Jr. 1972. University of Florida, Tallahassee, Florida. Personal communication.

McNulty, J. K. 1970. Effects of abatement of domestic sewage pollution on the benthos, volumes of zooplankton and the fouling organisms of Biscayne Bay, Florida. Studies in tropical oceanography. Institute of Marine and Atmospheric Science, University of Miami Press, Coral Gables, Florida. 107 p.

Moore, H. B. 1929. The muds of the Clyde Sea area I. Phosphorous and mitrogen contents. J. Mar. Biol. Assn. U.K. 16:595-608.

Moore, H. B. 1958. Marine Ecology. John Wiley and Sons, Inc., New York. 493 p.

Newcombe, C. L. and A. F. Brust. 1940. Variations in the phosphorous content of the estuarine waters of the Chesapeake Bay near Solomans Island, Maryland. J. Mar. Res. 3:76-88.

Newcombe, C. L. and A. G. Lang. 1939. Distribution of phosphates in Chesapeake Bay. Proc. Amer. Phil. Soc. 81:393-419.

Newcombe, C. L., W. A. Horne, and B. B. Shephard. 1939. Studies on the physics and chemistry of estuarine waters in Chesapeake Bay. J. Mar. Res. 2:87-116.

Odum, E. P. 1971. Fundamentals of ecology, 3rd edition. W. B. Saunders Co., Phila., Pa. 574 p.

Oppenheimer, C. H. and R. A. Ward. 1963. Release and capillary movement of phosphate in exposed tidal sediments, p. 664-673. In C. H. Oppenheimer [ed.] Symposium on marine microbiology. C. Thomas Publisher, Springfield, Illinois. 769 p.

Patten, B. C., R. A. Mulford, and J. E. Warinner. 1963. An annual phytoplankton cycle in the lower Chesapeake Bay. Chesa. Sci. 4:1-20.

Platt, T. and B. Irwin. 1968. Primary productivity measurements in St. Margarets Bay, 1967. Fisheries Research Board of Canada, Tech. Rep. No. 77, Marine Ecology Laboratory Bedford Institute, Dartmouth, Nova Scotia. 123 p.

Pomeroy, L. R. 1960. Residence time of dissolved phosphate in natural waters. Science. 131:1731-1732.

Pomeroy, L. R., E. E. Smith, and C. M. Grant. 1965. The exchange of phosphate between estuarine water and sediments. Limnol. Oceanogr. 10:167-172.

Pomeroy, L. R., L. R. Shenton, R. D. H. Jones, and R. J. Reimold. 1972. Nutrient flux in estuaries, p. 167-172. In G. E. Likens [ed.] Nutrients and Eutrophication: The limiting - nutrient controversy. Special Symposia Volume I. Amer. Soc. Limnol. Oceanogr., Allen Press, Inc., Lawrence, Kansas. 328 p.

Pratt, D. M. 1950. Experimental study of the phosphorous cycle in fertilized sea water. J. Mar. Res. 9:29-54.

Pritchard, D. W. 1960. The movement and mixing of contaminants in tidal estuaries, p. 512-525. In E. A. Pearson [ed.] International Conference on waste disposal in the marine environment, Proceedings. New York, Pergamon. 525 p.

Pritchard. D. W. 1969. Dispersion and flushing of pollutants in estuaries. J. of the Hydraulics Div. A.S.C.E. 95 No. H.Y.I. Proc. paper 6344:115-124.

Public Health Bulletin No. 74. 1916. Cited in R. S. Smith, Water Quality Survey of Hampton Roads Shellfish areas, Oct. 11, 1949 to Feb. 21, 1950.

Purcell, T. 1972. Personal communication. Dept. of Biology, Old Dominion University, Norfolk, Virginia. Data from unpublished ms.

Raymont, J. E. G. 1963. Plankton and productivity in the oceans. Pergamon Press, New York and London. 659 p.

Redfield, A. C., B. H. Ketchum, and F. A. Richards. 1963. The influence of organisms on the composition of sea water, p. 26-49. In M. N. Hill [ed.] The sea - Ideas and observations on progress in the study of the seas, Vol. 2. Interscience, New York and London. 554 p.

Redfield, A. C. 1958. The biological control of chemical factors in the environment. Amer. Sci. 46:205-221.

Reimold, R. J. 1965. An evaluation of inorganic phosphate of Canary Creek marsh. Masters thesis, University of Delaware, Newark, Delaware. 61 p.

Reimold, R. J. and F. C. Daiber. 1967. Eutrophication of estuarine areas by rainwater. Chesa. Sci. 8:132-133.

Rigler, F. H. 1956. A tracer study of the phosphorous cycle in lake water. Ecology. 37:550-562.

Rigler, F. H. 1964. The phosphorous fractions and the turnover times of inorganic phosphate in different types of lakes. Limnol. Oceanogr. 9:511-518.

Rochford, D. J. 1951. Studies in Australian estuarine hydrology, I. Introduction and comparative features. Australian J. Mar. Freshwater Res. 2:1-116.

Ryther, J. H. and W. M. Dunstan. 1971. Nitrogen, phosphorous and eutrophication in the coastal marine environment. Science. 171:1008-1013.

Satami, M. and L. R. Pomeroy. 1965. Respiration and phosphate excretion in some marine populations. Ecology. 46:877-888.

Seitz, R. C. 1971. Drainage area statistics for the Chesapeake Bay freshwater drainage basin. Chesapeake Bay, Institute Special Report No. 19, Ref. 71-1, Johns Hopkins University, Baltimore, Maryland. 21 p.

Shelef, G. and R. Halperin. 1970. Wastewater nutrients and algae growth potential, p. 211-229. In H. I. Shuval [ed.] Development in water quality research. Humphrey Science Publ., Ann Arbor, Michigan. 312 p.

Smayda, T. J. 1957. Phytoplankton studies on lower Narragansett Bay. Limnol. Oceanogr. 2:342-359.

Smith, R. S. 1950. Water quality survey of Hampton Roads shellfish areas, Oct. 11, 1949 to Feb. 21, 1950. Div. of Engineering, Va. State Dept. of Health in cooperation with V.S.P.H.S. Environmental Health Center, Richmond, Virginia. 38 p.

Snedecor, G. W. and W. G. Cochran. 1968. Statistical Methods, Sixth edition. Iowa State University Press, Ames, Iowa. 593 p.

Sokal, R. R. and F. J. Rohlf. 1969. Biometry. W. H. Freeman, San Francisco. 716 p.

Stewart, K. M. and G. A. Rohlich. 1967. Eutrophication - a review report to the State Water Quality Control Board, Calif. Publ. No. 34. 2nd edition. Sacramento, Calif. 300 p.

Strickland, J. D. H. and T. R. Parsons. 1965. A manual of Sea Water Analysis, Fisheries Research Board of Canada, Ottawa, Canada. 203 p.

Stroup, E. D. and J. A. Wood. 1966. Atlas of the distribution of turbidity, phosphate, and chlorophyll in Chesapeake Bay, 1949-1951. Graphical summary report No. 4, Ref. 66-1. Chesapeake Bay Institute, Johns Hopkins University, Baltimore, Maryland. 193 p.

Sverdrup, H. J., M. W. Johnson, and R. H. Fleming. 1942. The Oceans. Prentice Hall, Englewood Cliffs, New Jersey. 1087 p.

Teal, J. M. and J. Kanwisher. 1961. Gas exchange in a Georgia salt marsh. Limnol. Oceanogr. 6:388-399.

U.S. Department of Commerce, Coast and Geodetic Survey 1970 to 1972, Tidal Current Tables for the Atlantic Coast.

U.S. Naval Oceanographic Office. 1968. Dissolved oxygen content determination of sea water samples, p. J1-J21. In Publication number 607, Instruction Manual for obtaining oceanographic data, 3rd edition. 105 p.

Virginia State Water Control Board, 1971. Water Quality Standards, Richmond, Virginia. 59 p.

White, Edwin G. 1972. A physical hydrographic study of the Lafayette River. Masters thesis, Old Dominion University, Norfolk, Virginia. 65 p.

Wise, H. 1970. Personal communication. Director, Norfolk Department of Health, Norfolk, Virginia.

Wood, E. J. F. 1965. Marine Microbial Ecology. Reinhold Publ. Corp., New York. 243 p.

Young, D. K. 1968. Chemistry of southern Chesapeake Bay sediments. Ches. Sci. 9:254-260.

Zobell, C. E. and C. B. Feltham. 1948. The bacterial flora of a marine mud flat as an ecological factor. Ecology. 23:69-98.

APPENDIX

APPENDIX A - RAW DATA

The phosphate values are expressed as microgram-atoms phosphate phosphorous per liter. The nitrate as microgram-atoms nitrate nitrogen per liter and nitrite as microgram-atoms nitrite nitrogen per liter. The oxygen is in milliliters of oxygen per liter, temperature as degrees Centigrade and salinity in parts per thousand. If there are two values at one station the first value is the surface sample and second is the bottom sample. The tide stage is coded E for ebb and F for flood.

Station	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
October 10, 1970, Event 1						
A- 1	3	0	0	3.42	21.70	23.34
A- 3	3	4	1	4.07	21.61	23.66
A- 4	3	5	1	3.53	21.65	23.71
A- 7	4	9	1	4.29	21.57	24.02
B- 1	4/4	11/11	1/1	4.38/4.21	21.83	24.1
B-11	5/5	15/17	1/1	4.86/4.35	21.64	24.2
B-16	5.6	19/19	1/2	4.52/4.27	21.63	24.4
B-21	6/6	19/21	2/2	4.58/4.44	21.72	24.52
C- 2	6/6	19/19	2/2	4.35/4.24	21.71	24.54
October 13, 1970, Event 2						
A- 1	5	5	1	3.24	22.70/22.56	23.9/24.0
A- 3	5	9	1	3.25	22.61/22.60	24.2/24.2
A- 4	4/5	6/9	1/1	3.33/3.31	22.60/22.65	24.18/24.31
A- 5	5/5	10/11	1/1	3.46/3.25	22.64/22.62	24.22/24.24
B- 1	5/6	10/13	2/2	4.08	22.82	24.48
B-11	6/6	18/18	2/2	4.10	22.44	24.17
B-16	6/6	16/15	2/2	3.96/4.10	22.12/21.68	24.80/24.76
B-21	6/7	16/15	2/2	4.77/4.24	22.24	24.72
C- 1	6	18	2/2	4.42/4.24	22.16/22.68	24.88/24.72
October 17, 1970, Event 3						
A- 4	6	16	1	—	18	approx. 15
A- 7	8	14	1	—	18	
B-11	5	22	2	—	18	

Station	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
December 15, 1970, Event 4						
B- 1	1	2	0	8.35	6.6	20.00
B- 2	3	7	1	8.24	6.5	20.32
B- 3	1	1	0	7.93	7.0	19.65
B- 4	1	2	0	7.65	7.0	19.65
B- 5	2	2	0	8.35	7.2	20.01
B- 6	3	5	0	8.22	7.0	20.49
B- 7	2	2	0	7.87	6.8	19.85
B- 8	3	7	1	8.29	7.0	20.55
B- 9	2	2	0	8.22	7.0	19.71
B-10	2	2	0	8.01	6.2	19.78
B-11	3	11	1	8.12	7.2	20.66
B-12	2	2	0	8.27	7	20.05
B-13	2	4	0	7.47	7	19.20
B-14	2	2	0	8.15	6.5	19.86
B-18	3	12	1	6.70	7.2	20.75
January 18, 1971, Event 5						
A- 1	2	5	1	9.49	2.2	14.18
A- 2	2	3	1	9.52	2.8	15.33
A- 5	2/2	10/2	1	9.55/9.55	2.4	15.93
A- 7	2/2	7/7	1/1	7.84/7.78	2.8	16.26
B- 1	2/2	12	1/1	8.78/8.69	2.8	16.64
B-11	4/4	13/15	1/1	8.28/8.02	2.8	16.56
B-16	4/4	13/13	1/1	8.21/8.26	3.0	16.74
C- 2	4/4	14/31	4/4	7.35/7.98	3.1	17.31
January 28, 1971, Event 6						
A- 4	2/2	16/12	1/1	8.41/8.43	0.0	28.40
A- 7	2	11	1	7.78	-0.5	
A-11	2/1	21/25	1/1	7.92/8.55	+0.5	
March 6, 1971, Event 7						
A- 1	4	0	0	7.35	8.44	10.9
A- 5	2/2	0	0	7.0/7.74	7.28/7.64	11.23/13.10
A- 6	2/2	0	0	8.82/8.29	7.31/6.76	12.8/13.64
A- 7	1/3	0	0	6.83/7.76	6.8/7.11	13.25/13.21
B- 1	1/1	0	0	8.61/-	7.17	13.34
B-16	2/1	0	0	8.64/8.19	7.03/6.32	11.00/13.63
B-21	3/1	0/3	0	7.81/8.04	6.8/6.5	11.43/13.12

Station	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
May 11, 1971, Event 8						
A- 7	2	13	0	5.55	22.5	15.9
B- 1	2			5.6	21.4	16.4
B-16	3	13	0	5.65	21.4	17.1
B-21	5	10	0	4.81	19.3	18.19
C- 2	5	13	0	5.8	19.1	18.2
C- 4	7	11	0	4.97	18.95	18.3
D- 1	5	13	0	5.85	19.0	18.7
D- 3	3	12	0	5.6	18.62	18.5
D- 5	4	11	0	5.85	19.6	18.4
D- 7	2	10	0	5.95	17.9	18.4
D- 9	1	10	0	5.95	17.9	18.4
D-10	-	13	0	6.0	17.5	18.3

May 18, 1971, Event 9

Station B-16

Time (E.D.S.T.)	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
1023	4	10	1	4.06		
1155	5	14	1	4.76/4.34		Approx.
1400	5	13	1	5.88		18^o/oo
1700	5	13	2	5.95		

Station	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
June 10, 1971, Event 10						
B-21	5	17	2	5.88	25	12.88/13.45
C- 1	4	20	2	5.7	25	13.42
C- 2	5	23	2	5.7	24.92	13.52
C- 3	5	18	2	5.7	24.5	13.36
C- 4	5	18	2	6.0	24.0	14.4
D- 1	12	28	2	5.9	24	14.13
D- 2	4	23	2	7.0	24	14.45
D- 3	4	20		7.7	24	14.27
D- 4	5	24		6.4	24.1	14.20
D- 5	5	26		6.7	24.1	14.08
D- 6	4	26		6.0	24.1	14.01

Station	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
D- 7	4	25		6.0	24.1	14.04
D- 8	4	26		6.0	24.1	14.04
D- 9	4	25		5.7	23	14.6
D-10	20	31		4.9/5.3	23.3	14.29
D-11	4	26		6.3	23.5	13.86
June 26, 1971, Event 11						
B-20	—	10	2	3.6	27.5	15.1
C- 2	5/5	—	2/1	4.7	26.7/26.7	14.1/15.1
D- 1	5	10/12	1/2	5.3/2.9		15.3
D- 4	2/4	10/10	1	5.0/3.4		14.6/14.3
D- 5	2	14	1	5.0/4.1		14.5
D-10	19	15	1	4.6/3.9	24.5	13.3
July 13, 1971, Event 12						
B-16	9/7	4/2	1/1	4.7/3.6	26.14/26.14	18.03/18.35
B-17	7/7	2/2	1/1	4.9/3.98	26.4/26.0	18.50/18.64
B—1	7	2/6	1	4.0	26.25	18.53
B- 2	7/7	2/6	1	4.3/3.4	26.5/26.0	18.58/18.68
B- 4	8/8	6/4	1	4.3/3.2		18.35
B- 1	11/7	4/2	1	3.6/3.5	26.65/25.95	18.15/18.58
B- 3	5/5	4/2	1	6.0/4.4		17.98
B- 5	4	21	1	6.8/4.3		
B- 7	4/4	21/21	1	6.4/4.0		
B- 9	5	21	1	5.4/4.4	26.0	18.8
B-10	4/4	21/21	1	5.9/6.7	26.1	18.59
July 29, 1971, Event 13						
B-16	10/12	0	0	3.9/4.1		
B-20	8/8			4.3/4.3		
C- 3	7/10					
C- 4	10/8			3.4/3.2		
D- 1	8/6			3.8/6.0		
D- 3	11/2			3.9/6.2		
D- 5	6/2			4.1/6.0		
D- 7	8/6			4.2/3.9		
D- 9	8/1			3.9		
D-11	5/3			4.8/4.5		

Time	Tide	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
August 4-5, 1971, Event 14							
Station B-18							
0850	E	8/6	8/8	0/0	3.98/ 3.28	26.38/ 25.70	20.72/ 20.92
1240	E	16/12	24/0	1/1	6.56/ 6.7	27.84/ 26.86	20.56/ 21.0
1455	F	8/24	0/39	0/3	9.49/ 9.21	29.0/ 28.4	20.52/ 20.76
1830	F	7/6	0/0	0/0	6.98/ 5.91	28.2/ 27.8	20.94/ 21.56
2040	E	2/4	2/2	0/0	5.37/ 5.41	27.46/ 27.80	21.3/ 22.22
0100	E	7/7	0/0	0/0	5.79/ 5.58	27.26/ 27.28	21.32/ 21.44
0340	F	10/8			4.75/ 4.6	27.30/ 27.04	20.51/ 21.24
0640	F	6/4			4.6/ 4.05	26.64/ 26.68	21.0/ 22.16
Station C-4							
0920	E	24/10	2/10	0/3	4.4/ 4.04	25.84/ 25.46	21.44/ 21.64
1220	E	20/9	10/10	0/0	5.10/ 4.40	26.6/	22.38/ 22.32
1517	F	8/8	0/13	0/1	5.51/ 5.65	27.92/ 26.8	21.54/ 22.5
1815	F	7/8	0/0	0/0	6.28/ 5.58	27.00/ 25.62	22.04/ 22.68
2100	E	2/5	2/2	0/0	5.86/ 5.17	26.7/ 25.92	21.44/ 22.18
0415	F	7/6			4.47/ 4.47	26.68/ 25.86	21.18/ 22.94
0715	F	5/4			4.82/ 5.03	25.74/ 25.72	22.58/ 23.06
Station D-10							
0945	E	7/5	3/7	1/1	4.89/ 4.05	25.76/ 24.20	21.66/ 24.08
1145	E	4/5	2/9	1/1	4.47/ 3.49	25.82/ 24.36	21.66/ 23.78
1544	F	20/4	8/19	0/2	5.30/ 5.30	27.46/ 26.48	20.82/ 22.12

Time	Tide	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
1745	F	2/3	8/20	0/0	5.58/ 5.30	27.66/ 27.20	20.68/ 21.48
2130	E	5/5	8/10	0/0	5.58/ 4.43	27.18/ 24.76	21.30/ 23.56
2345	E	7/4	5/10	0/0	5.17/ 4.19	26.46/ 25.42	21.30/ 23.26
0455	F	4/6			4.47/ 4.47	25.52/ 25.42	22.52/ 23.04
0743	F	2/2			4.89/ 4.75	25.66/ 25.62	22.30/ 22.46

Station	PO_4	NO_3	NO_2
October 20, 1971, Event 15			
A- 1	5/5	11/15	3/3
A- 7	5/5	16/13	3/3
B- 1	4/4.5	15/15.5	3/3
B- 6	4/4	21/18	3/3
B-11	4/5	18/19	3/3
B-16	5/4	16/19	3/3
B-20	4/8	19/34	3/4
B-21	4/4	19/16	3/3
C- 4	5/4	21/19	3/3

Time (E.S.T.)	PO_4	NO_3	NO_2	Oxygen	Temperature
November 13, 1971, Event 16					
Station B-16					
0650	4.3/4.6	36.7/36.7	4.4/4.5	5.93	12.9
0910	4.4/4.6				
1130	4.2/4.1			6.11	
1235	4				
1435	3.9				13.5
1628	4.4				13.9
1835	4.3	27.3	5.0		13.9

Time (E.S.T.)	PO_4	NO_3	NO_2	Oxygen	Temperature
Station B-17					
0710	4.1/4.8	37.5/35.2	4.6/4.6	5.60	13.5
0903	4.5/5.3				
1120	4.1/4.2			6.63	
1230	4.1				
1430	3.8				14.0
1625	4.1				14.0
1830	4.4	29.0	4.9		13.9
Station B-18					
0640	4.1	29.5	5.7	5.68	13.0
0855	4.2				
1010	4.9			6.61	13.5
1225	5.3				
1425	4.1				15.5
1615	4.6				14.0
1825	4.5	32.3	4.9		

Time (E.S.T.)	Tide	PO_4	NO_3	NO_2	Oxygen	Temperature	Salinity
January 11-12, 1972, Event 17							
Station B-16							
1055	E	5.9	26/24	1.3/ 4.1	6.75/ 7.01	10.9	16.2
1210	E	4.6	20/17	1.9/ 2.0	6.85/ 6.8	10.5	16.4
1410	F	5.2	22/24	1.8/ 2.8	6.90/ 7.01	11.2	16.5
1610	F	5.6	22/22	2.0/2.8	———	11.2	17.0
1910	E	6.9	25/10	1.8/ 4.7	7.20/ 6.27	11.3	17.4
2110	E	6.7	22/12	2.5/2.8	———	11.3	16.9
2320	E	5.9	20/8	1.3/ 1.6	7.07/ 6.33	11.2	16.8
0110	F	5.4	23/28	1.6/1.6	———	11.1	16.8
0310	F	5.6	20/7	1.9/ 1.3	6.90/ 6.73	11.1	16.8
0610	F	6.9	22/18	1.8/ 0.6	6.35/ 6.01	———	18.1
0910	E	5.7	25	2.0	6.61	———	18.1
1100	E	4.8	28	2.3	6.58	10.6	18.1

APPENDIX B

Mean monthly rainfall, in inches, and the mean monthly sewage pumping rate for the Lamberts Point Plant and the Army Base Plant (Hampton Roads Sanitation District, Norfolk, Virginia) for the sampling period 1970-1972. The sewage pumping rate is expressed as million gallons per day.

Month and Year	Rain	Sewage Pumping Rate Lamberts Point	Sewage Pumping Rate Army Base
October, 1970	1.30	21.6	11.6
November	2.34	19.4	11.1
December	3.01	21.9	10.7
January, 1971	4.03	25.9	11.3
February	3.59	29.9	12.8
March	3.88	30.3	14.0
April	2.18	31.3	14.2
May	4.46	27.4	13.0
June	2.16	26.9	11.7
July	4.81	27.2	11.7
August	4.63	27.8	11.8
September	5.46	29.4	12.2
October	10.12	38.0	17.6
November	0.97	30.0	13.7
December	1.44	25.4	12.1
January, 1972	2.94	26.6	13.2

APPENDIX C

Sewage pumping rate fluctuations, in million gallons per day, over a twenty-four hour period, August 4-5, 1971 and January 12-13, 1972 for the Lamberts Point Sewage Plant (Hampton Roads Sanitation District, Norfolk, Virginia).

Time	August 4-5, 1971	January 12-13, 1972
0100	22	23
0200	16	17
0300	10	17
0400	10	17
0500	18	16
0600	10	16
0700	10	17
0800	17	29
0900	25	27
1000	26	32
1100	30	32
1200	30	32
1300	29	31
1400	29	30
1500	28	27
1600	26	27
1700	26	27
1800	26	27
1900	26	27
2000	26	27
2100	26	27
2200	26	27
2300	26	27
2400	26	24
mean	27.9	27.4

APPENDIX D

Concentration of dissolved inorganic phosphate, in microgram-atoms per liter, in the final, primary treated sewage effluent, the sewage pumping rate, in million gallons per day, and the rate of flow of phosphate from the outfall, in kg/hr, from the Lamberts Point Sewage Plant (Hampton Roads Sanitation District, Norfolk, Virginia) on March 30, 1972.

Time (hours, E.S.T.)	Phosphate	Sewage Pumping Rate	Rate of flow of phosphate from the outfall
Midnight	205	27	28.9
0100	294	17	
0200	264	17	23.1
0300	262	17	
0400	171	16	13.1
0500	146	16	
0600	146	15	16.6
0700	268	16	
0800	185	23	18.5
0900	108	27	
1000	106	31	24.9
1100	195	31	
1200	130	31	24.1
1300	175	30	
1400	166	29	25.0
1500	185	26	
1600	195/208	27	28.1
1700	195/207	27	
1800	203/195	27	28.8
1900	244/185	27	
2000	185	27	25.5
2100	181	27	
2200	164	26	18.8
2300	116	26	
range	116-294		

APPENDIX E

Processed observed data for the 24 hour stations. Dissolved inorganic phosphate, in microgram-atoms per liter, tidal stage, expressed as 1 to less than 2 for flood and 2 up to, but not including 3, for ebb, computed rate of phosphate from the Lamberts Point sewer outfall, in kg/hr, wind component (p. this thesis) and time for August 4-5, 1971, combined stations (B-18 + C-4) and January 12-13, 1972, station (B-16).

Observed dissolved inorganic phosphate	Tidal Stage	Rate of dissolved inorganic phosphate from the sewage outfall	Wind component	Time Station (E.D.S.T.)
August 4-5, 1971				
3.5	2.0	24	.552	2100/C-4
14.5	2.7	24	.997	1220
17.0	2.3	22	.297	0920
7.0	2.2	20	.297	0850/B-18
14.0	2.6	24.5	.912	1240
3.0	2.0	24.0	.791	2040
7.0	2.6	27.6	.845	0100
4.5	1.7	17	11.9	0715/C-4
6.5	1.3	15	.540	0415
7.5	1.58	29	.714	1815
7.5	1.07	26.4	.100	1517
9.0	1.1	15.9	.540	0340/B-18
5.0	1.75	17.2	10.3	0640
6.5	1.6	28.8	.931	1830
16.0	1.0	26.5	.641	1455
				(E.S.T.)
January 12-13, 1972				
5.2	1.2	25	.864	1410/B-16
5.6	1.7	29	.532	1610
5.4	1.0	25.6	.769	0110
5.6	1.3	20.6	.769	0310
6.9	1.75	16	.101	0610
5.7	2.4	20	10.2	0910
4.8	2.5	24.8	5.70	1100
5.9	2.7	24.8	.843	1055
4.6	2.8	24.4	.013	1210
6.9	2.2	28	.063	1910
6.7	2.4	24	.494	2110
5.9	2.75	20	.041	2320

APPENDIX F

Combined Values for Dissolved Inorganic Phosphate, Rainfall, Water Temperature, and Wind Direction, Expressed as Cosine Theta, for the Combined Sections (A + B + C) Comprising the Lafayette River and Section D, the Elizabeth River, During the Sampling Interval, 1970-1972

Statistical values for phosphate (microgram-atoms per liter) and water (degrees Centigrade) are listed in the following sequence: mean, standard deviation, number of measurements, and range.

Month Year Event	Dissolved inorganic phosphate	Wind Direction (Cos θ)	Rain (Inches)	Water temperature
Lafayette River (Sections A + B + C)				
October	5.0	.21	1.3	21.75
1970	1.1			1.40
1, 2, 3	N=50			N=28
	3-8			18-22.7
December	2.2	.47	3.01	6.94
1970	.8			.41
4	N=16			N=16
	1-3			6.2-8.0
January	2.6	.74	4.03	1.98
1971	1.0			1.31
5, 6	N=19			N=11
	2-4			-0.5-3.0
March	1.9	.74	3.88	7.1
1971	1.0			.66
7	N=13			N=12
	1-4			6.3-8.4
May	4.3	.79	4.46	20.44
1971	1.6			1.51
8, 9	N=10			N=6
	2-7			18.95-22.5
June	4.9	.62	2.16	25.54
1971	.4			1.25
10, 11	N=7			N=8
	4-5			24-27.5
July	8.2	.88	4.81	26.2
1971	1.5			0.2
12, 13	N=17			N=7
	7-12			26-26.5
August	8.6	.31	4.63	26.85
1971	5.5			0.93
14	N=30			N=28
	2-24			25.7-29

Month Year Event	Dissolved inorganic phosphate	Wind Direction (Cos θ)	Rain (Inches)	Water temperature
October 1971 15	4.6	.38	10.12	21.75 1.40 N=28 18-22.7
November 1971 16	4.4 0.4 N=27 3.9-4.8	.92	2.34	13.8 .76 N=12 12.9-15.5
January 1972 17	5.8 1.33 N=22 5.2-6.9	.74	4.03	10.97 .29 N=10 10.5-11.3
Elizabeth River (Section D)				
May 1971 8	3.0 1.6 5 1-5		4.46	18.6 .665 8
June 1971 10, 11	5.7 5.5 16 2-20		2.16	24.24 1.134 15
July 1971 12, 13	5.4 2.6 22 1-11		4.81	26.1 .104 4
August 1971 14	5.3 4.2 16 2-20		4.63	25.9 1.07 16

APPENDIX G

Seasonal Dissolved Inorganic Phosphate, Water Temperature, in Degrees Centigrade, Rain, and Wind Direction for the Lafayette River for 1970 to 1972.

The values are the composite means of the values in Sections A, B, and C. Mean dissolved phosphate (microgram-atoms per liter) and mean water temperature in degrees Centigrade are listed with their standard deviations, number of samples, and ranges of values.

Season Date Event(s) Section(s)	Mean dissolved inorganic phosphate	Mean water temperature	Total seasonal rain (inches)	Wind direction (mean Cos Θ) resultant wind (degrees) range
Fall 1970 1,2,3 A & B	5.3 1.1 32 3 to 8	21.74 1.40 28 18 to 22.8	1.3	0.21/050°
Winter 1970-71 4,5,6 A & B	2.4 0.9 35 1 to 4	4.93 2.63 27 -.5 to 8	3.52 range 1.3 to 10.12	0.616/280° range 270-290°
Spring 1971 7,8,9 A,B,C	3.0 1.7 23 1 to 5	8.9 5.18 72 6.8 to 22.5	4.17	0.04/268° range 190/290°
Summer 1971 10,11,12 13,14 A,B,C	8.0 4.4 54 2 to 24	26.7 1.8 48 23.5 to 29	3.86 range 2.16-4.81	0.815/117° range 060-180°
Fall 1971 15,16 A	4.5 0.7 45 4 to 5	13.8 0.6 13 12.9 to 15.5	5.45 range .97	a. 0.21/050°
Winter 1972 17 B	5.8 1.3 22 2.6 to 8.6	10.97 .29 10 10.5 to 11.3	2.94	b. 0.616/280°

a. No data available, assumed same as Fall, 1970.
b. No data available, assumed same as Winter, 1970-71.

APPENDIX H

Seasonal Oxygen Saturation Values for Sections A, B, C, and D For 1970-1971

Season	Sections A	B	C	D
Fall, 1970 & 1971				
mean percent saturation	69	82	82	-
standard deviation	7.4	4.7	2.5	-
p greater than 0.05 confidence limits	±4.2	±2.7	±3.5	-
number of observations	14	14	4	-
Winter, 1970 & 1971				
mean percent saturation	106	103	97	-
standard deviation	5.23	7.15	11	-
p greater than 0.05 confidence limits	±5.2	±2.9	±21	-
number of observations	6	25	3	-
Spring, 1971				
mean percent saturation	100	105	95	102
standard deviation	9.30	4.6	1.6	15.2
p greater than 0.05 confidence limits	±7.6	±5.3	±3.0	±15.2
number of observations	8	5	3	6
Summer, 1971				
mean percent saturation	-	81	92	96
standard deviation	-	12	23	20
p greater than 0.05 confidence limits	-	±6.7	±19	±5.4
number of observations	-	15	8	53