U.S. ENVIRONMENTAL PROTECTION AGENCY
Annapolis Field Office
Annapolis Science Center
Annapolis, Maryland 21401

# TECHNICAL REPORTS

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Chesapeake Technical Support Laboratory
Middle Atlantic Region
Federal Water Pollution Control Administration
U.S. Department of the Interior

Technical Report No. 29

# STEP BACKWARD REGRESSION

by

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August 1969

*Revised by Paul R. Dorn

Johan A. Aalto, Chief, CTSL
Norbert A. Jaworski, Chief, Engineering Section
Richard Burkett, Draftsman

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PROGRAM: STEP BACKWARD REGRESSION

ABSTRACT: This program performs a multiple regression analysis and provides related statistics on a STATPAC data matrix or on a subset of that matrix formed by the selection of rows and columns of the matrix. If desired, the regression may proceed stepwise where, at each step, the least significant independent variable is deleted from the regression equation. The regression residuals may also be computed.

RESTRICTIONS:

The input matrix may have a maximum size of 99999 rows and 199 columns. The maximum size of the subset selected for a regression analysis is 99999 rows and 99 columns.

## PROGRAM RUN PREPARATION:

The following is a complete deck setup for this program:

1. JOB card
2. System control cards
3. Header card
4. Column selector cards*
5. Row selector cards*
6. Minimum number of variables card *
7. Residual start card*
8. Delimeter

*Optional--see the individual sections on the various cards.

If more than one run is to be performed, repeat cards 3-7 as necessary; the final card should be delimiter card.

JOB CARD:

The JOB card cannot be catalogued and is installation as well as machine dependent. Below is the specification for the 360/Model 65 located in the Department of the Interior building, in Washington, D.C. The structure of the JOB card changes occasionally, and one should check with the computer center before using the below form.

Card 1 -

| Card Columns | Contents |
|---|---|
| 1 - 2 | // |
| 3 | Center Code:<br>D = Denver, Colorado<br>F = Flagstaff, Arizona<br>I = Crystal Plaza, Virginia<br>M = Menlo Park, California<br>R = Rolls, Missouri<br>W = Washington, D.C. |
| 4 - 5 | Agency Code |
| 6 - 8 | User registration code. |
| 9 - 10 | User's ID. May be changed by the user as desired. Do not use the same two characters for different jobs run during the same day. |
| 11 | Blank. |
| 12 - 14 | JOB (i.e. the word JOB). |

| Card Columns | Contents |
| --- | --- |
| 15 | Blank. |
| 16 | ( (Left parenthesis). |
| 17 - 20 | Program Number |
| 21 | , (Comma). |
| 22 - 25 | Auxiliary account number. |
| 26 | , (Comma). |
| 27 - 30 | Estimated execution time in minutes. Requires four numeric digits. |
| 31 | , (Comma). |
| 32 - 35 | Estimated lines of print expressed in thousands of lines. Requires four numeric digits. |
| 36 | , (Comma). |
| 37 - 40 | Estimated number of cards to be punched. Requires four numeric digits. |
| 41 | , (Comma). |
| 42 | Reserved for future use; must be a 1 punch. |
| 43 | , (Comma). |
| 44 | Reserved for future use; must be a 1 punch. |
| 45 | , (Comma). |
| 46 | Type of Run:<br>C = Compile only<br>T = Test of program<br>P = Production use of program |

| Card Columns | Contents |
|---|---|
| 47 | , (Comma). |
| 48 - 49 | Number of lines per page. A value of zero suppresses page overflow tests. If this field (and the preceding comma) is eliminated, a default option of 61 lines per page is used. In this case the following fields are shifted left 3 columns. (Except columns 62-72.) |
| 50 | ) (Right parenthesis). |
| 51 | , (Comma). |
| 52 | ' (Apostrophe). |
| 53 - 61 | Name of the user. |
| 62 | ' (Apostrophe). |
| 63 | , (Comma). |
| 64 - 71 | Blank. |
| 72 | X (The letter X). |

Card 2 -

| Card Columns | Contents |
|---|---|
| 1 - 2 | // |
| 3 - 15 | Blank. |
| 16 - 25 | MSGLEVEL=1 |
| 26 | , (Comma). |
| 27 - 33 | CLASS=C |
| 34 - 72 | Blank. |

SYSTEM CONTROL CARDS:

Cards 1 & 2:

(a) If the object deck is used -

```
1
//bEXECbLINKFORT,REGION.GO=252K,TIME.GO=J
//LKED.SYSINbDDb*
```

where J is the time required to run the program(in minutes). The 'b' stands for a blank space. Next comes the object deck (including its delimiter).

(b) If the source deck is used -

```
1
//bEXECbFORTGCLG,PARM.FORT='DECK',REGION.GO=252K,TIME.GO=J
//FORT.SYSINbDDb*
```

where J is as before. Next comes the source deck (including its delimeter).

Cards 3 & 4:

(a) If the data resides on the disc SYSDK -

```
1                                                PASS
//GO.FT10F001bDDbDSN=&NAME,UNIT=SYSDY,DISP=(OLD,DELETE,DELETE),
//bDCB=(RECFM=VB,LRECL=RRR,BLKSIZE=BBBB)
```

where &NAME is the name of the storage space. (The '&' signifies the storage is temporary--it only exists for the extent of the job.) PASS is used if the data file is used later on; otherwise use DELETE.

The letters 'RRR' and 'BBBB' are computed as follows:

RRR = 8M + 24 where M = number of columns in the data matrix.

BBBB = K(RRR) + 4 where K is an integer chosen so that the positive difference (7200-BBBB) is as small as possible.

(b) If the data resides on magnetic tape -

```
1
//GO.FT10F001bDDbUNIT=2400,LABEL=(,SL),VOLUME=(,RETAIN,,,SER=YYYYYY),
//bDCB=(RECFM=VB,LRECL=RRR,BLDSIZE=BBBB),

//bDISP=(OLD,KEEP),DSP=STAPAC
```

where 'YYYYYY' in the first tape card represents a six digit input tape number (leading zeros must be given).

The letters 'RRR' and 'BBBB' are as before.

When a tape is used, a tape setup card is required. Its form is:

| Card Columns | Contents |
|---|---|
| 1 - 9 | /*MESSAGE |
| 10 - 12 | Blank. |
| 13 - 20 | The same characters as in columns 3-10 of the JOB card. |
| 21 - 22 | Blank. |
| 23 - 27 | SETUP. |
| 28 - 29 | Blank. |
| 30 - 36 | The number of the tape used. |
| 37 - 38 | /9 |

If the tape is written on as well as read, in column 39, place an R (for ring in). This card should be placed right after the JOB card. (This card's format is particular to the 360/65 in Washington, D.C.)

Card 5:

```
1
//GO.SYSINbDDb*
```

**HEADER CARD:**

| Columns | Format | Entry | Description |
|---|---|---|---|
| 1-30 | 7A4,A2 | TITLE | Up to 30 characters of alphanumeric information used to title the output for this data set. It is also used when listing the total number of plots created. It is not used on the graph. |
| 31-38 | 2A4 | INPUT ID | Up to 8 characters of alphanumeric information used to identify the input data set. |
| 39-43 | I5 | INPUT N | The number of rows in the input data matrix. (Right justified.) |
| 44-46 | I3 | INPUT M | The number of columns in the input data matrix. (Right justified, 199.) |
| 47-56 | 10I1 | OPTION | See the following sheet. |
| 73-77 | I5 | PRON | The number of pairs of row numbers needed to select the desired rows of the input matrix. If blank, all rows are included. If not blank, this number must be right justified and row selector cards must be included. |
| 78-80 | I3 | PROM | The number of pairs of column numbers needed to select the desired columns in the input data matrix. (If blank, all columns are included. If not blank, this number must be right justified and column selector cards must be provided.) |

OPTIONS -

OPTION( 1) - 0 - No stepwise deletion of variables
1 - Deletion of least significant variable occurs until the program reaches minimum specified.

OPTION( 2) - 0 - No action taken.
1 - Residual analysis performed starting with all variables present; continues until stepwise deletion stops.

OPTION( 3) -2 - Residual analysis performed starting with number of variables specified on Residual start card.

OPTION( 4) - 0 - Indeterminants not allowed in the selected data
1 - Observations having indeterminants in selected data are skipped.

OPTION( 5) - 0 - No action taken
1 - Residual analysis doen using antilog transform of dependent variable.

OPTION( 6) - NOT USED

OPTION( 7) - NOT USED

OPTION( 8) - NOT USED

OPTION( 9) - 0 - Input tape unit is 10.
1-9 This is the input tape unit.

OPTION(10) - 0 - Use the variable identifiers on the STATPAC tape
1 - Read in new variable identifiers from cards.

**COLUMN IDENTIFIER CARDS:**

These cards are used only if OPTION(10)=1 on the header card. They permit the user to associate an eight character identifier with each column in the data matrix. Ten identifiers can be used per card; if more than ten identifiers are needed, they are continued on another card. The numbers above the eight card column fields indicate the columns in the data matrix the identifiers are associated with. One identifier must be specified for each column in the output data matrix.

## ROW SELECTOR CARDS:

These cards are used only if PRON on the header card is not blank. The number entered in the field PRON specifies how many pairs of row numbers are used to select desired rows of a data matrix. Each pair specifies the rows FROM and including the first member of the pair TO and including the last member of the pair will be selected. The pairs must be entered starting in the left most field of the card and continuing across eight pairs per card If more pairs are used, continue on another card. The first member of the pair is entered under the word "FROM" and the second member of the pair entered under "TO." Except for the selection of a single row (where the "TO" portion is left blank) the row numbers must form an increasing sequence, i.e., rows must be selected in the order they appear in the data matrix.

<u>COLUMN SELECTOR CARDS</u>:

These cards are used only if PRON on the header card is not blank. The number entered in the field PRON specifies how many pairs of column numbers are used to select desired columns of a data matrix. The instructions for their use is identical to the select row cards except that thirteen pairs per card are used and the columns need not be selected in increasing order.

MINIMUM NUMBER OF VARIABLES CARD:

This card is used if OPTION(1) is non-zero. It gives the minimum number of variables (including the dependent variable) at which stepwise deletion is to cease.

Its format is:

| Columns | Format | Entry | Description |
|---|---|---|---|
| 1 - 4 | I4 | K | The minimum number of variables (including the dependent variable on which the regression is to be performed. The stepwise deletion stops when M' is less than K. (K must be punched right justified.) |

RESIDUAL START CARD:

This card is used if OPTION(2) is a two, and OPTION(1) is non-zero. It gives the number of variables (including the dependent variables) at which residual analysis is to be performed. Its format is the same as the **MINIMUM NUMBER OF VARIABLES CARD.**

OUTPUT:

Output to this program is a printed table of means, standard deviations, variance-covariance, the correlation matrix, multiple correlation coefficients (and degrees freedom), regression coefficients, regression weights, regression constants, standard errors of the regression weights and tests of significance, variables deleted (if any), residuals and sums of the squares of the residuals if requested, and the standard error of the estimate of the dependent variable.

Appendix: Sample Output

```
DCOSS   REGRESSION

      TITLE                               INPUT ID        N      M     ***** OPTIONS  ****
FLOW (Q) VERSUS PH     (63-99)            DATA           443     13     0 1 1 0 0 0 0 0 0 0

NUMBER OF SELECTED VARIABLES =     2

SELECTED VARIABLE INDICES
       1            9

SELECTED VARIABLE IDENTIFIERS
     PH           FLOW

NUMBER OF SELECTED OBSERVATION PAIRS =      1

SELECTED OBSERVATION PAIRS
     5-   23
```

```
00055   REGRESSION

      TITLE                          INPUT ID        N     M     ***** OPTIONS ****
FLOW (Q) VERSUS PH     (68-83)      DATA            44[illegible]    1[illegible]     [illegible]

TOTAL NUMBER OF OBSERVATIONS =     19
NUMBER OF VALID OBSERVATIONS =     16

MEANS
   0.2647D 01   0.2167D 01
STANDARD DEVIATIONS
   0.9211D 00   0.1713D 01
```

```
00095 REGRESSION.....FLOW (Q) VERSUS PH     (68-69)

VARIANCE-COVARIANCE
ROW NUMBER       1
   0.84850 00  -0.55420 00
ROW NUMBER       2
  -0.55420 00   0.29350 01
```

```
DC095 REGRESSION.....FL N (2) VERSUS PH     (68-69)

CORRELATION MATRIX
ROW NUMBER      1
   0.10000 01  -0.35120 00
ROW NUMBER      2
  -0.35120 00   0.10000 01
```

```
DC095 REGRESSION.....FLOW (L) VERSUS PH    (68-69)

VALUE OF DETRIMINANT =    0.2059E-83
MULTIPLE CORRELATION COEFFICIENT =     0.3512
TEST OF SIGNIFICANCE OF MULTIPL  CORRELATION COEFFICIENT =     0.1403E 01 DEGREES OF FREEDOM =     13
REGRESSION WEIGHTS
  -0.3512E 00
REGRESSION COEFFICIENTS
  -0.1689E 00
REGRESSION CONSTANT =   0.3056E 01
STANDARD ERROR OF REGRESSION WEIGHTS
  2.5965E-01
TEST OF SIGNIFICANCE OF REGRESSION WEIGHTS
 -1.3525E 00
SUM OF THE SQUARES OF THE RESIDUALS =   1.1157E 01
STANDARD ERROR OF THE ESTIMATE OF THE DEPENDENT VARIABLE =   9.2642E-01
```

00095 REGRESSION.....FLOW [illegible]

| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | REL. ERROR | DATA TYPE NORMAL |
|---|---|---|---|---|---|---|
| 5 | CFS 2 | 2.0000E 00 | 1.9608E 00 | 3.9248E-02 | 1.9624E-02 | |
| 6 | CFS 2 | 1.7000E 00 | 2.4707E 00 | -7.7065E-01 | -4.5332E-01 | |
| 7 | CFS 2 | 1.9000E 00 | 2.6595E 00 | -7.5950E-01 | -3.9974E-01 | |
| 8 | CFS 2 | 5.8000E 00 | 2.8672 00 | 2.9328E 00 | 5.0565E-01 | |
| 10 | CFS 2 | 2.5000E 00 | 2.3007E 00 | 1.9932E-01 | 7.9726E-02 | |
| 11 | CFS 2 | 3.0000E 00 | 2.7729E 00 | 2.2713E-01 | 7.5728E-02 | |
| 12 | CFS 2 | 2.7000E 00 | 2.9994E 00 | -2.9944E-01 | -1.1090E-01 | |
| 13 | CFS 2 | 2.8000E 00 | 2.9428E 00 | -1.4278E-01 | -5.0994E-02 | |
| 14 | CFS 2 | 2.3000E 00 | 3.0183E 00 | -7.1832E-01 | -3.1231E-01 | |
| 15 | CFS 2 | 2.4000E 00 | 3.0372E 00 | -6.3721E-01 | -2.6550E-01 | |
| 16 | CFS 2 | 2.2000E 00 | 2.5235E 00 | -3.2353E-01 | -1.4706E-01 | |
| 17 | CFS 2 | 2.6000E 00 | 2.5840E 00 | 1.6037E-02 | 6.1681E-03 | |
| 18 | CFS 2 | 2.4000E 00 | 2.4518E 00 | -5.1766E-02 | -2.1569E-02 | |
| 19 | CFS 2 | 2.6000E 00 | 2.7917E 00 | -1.9170E-01 | -7.3731E-02 | |
| 20 | CFS 2 | 2.3500E 00 | 2.1307E 00 | 2.1928E-01 | 9.3312E-02 | |
| 22 | CFS 2 | 3.1000E 00 | 2.8390E 00 | 2.6109E-01 | 8.4221E-02 | |

| MAXIMUM VALUE | MINIMUM VALUE | RANGE | MEAN ERROR | ABSOLUTE MEAN ERROR | ABSOLUTE MEAN PERCENTAGE ERROR |
|---|---|---|---|---|---|
| 5.799999E 00 | 1.700000E 00 | 4.099999E 00 | 7.748604E-07 | 4.868634E-01 | 1.687225E-01 |

INDEPENDENT VARIABLES LEFT IN THE EQUATION ARE -
9 ( FLOW )

# RELATIVE CONTRIBUTIONS OF NUTRIENTS TO THE POTOMAC RIVER BASIN FROM VARIOUS SOURCES*

Technical Report No. 31

January 1970

Chesapeake Technical Support Laboratory
Middle Atlantic Region
Federal Water Pollution Control Administration
U.S. Department of the Interior

# RELATIVE CONTRIBUTIONS OF NUTRIENTS TO THE POTOMAC RIVER BASIN FROM VARIOUS SOURCES*

Technical Report No. 31

Norbert A. Jaworski
and
Leo J. Hetling**

January 1970

* Presented at the Cornell Agricultural Waste Management Conference, January 19-21, 1970, Rochester, New York

** Director, Research Unit, Division of Environmental Health Services, New York State Department of Health

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# INTRODUCTION

The upper Potomac estuary is highly eutrophic. During the summer months, large blooms of nuisance blue-green algae, mainly microcystis, occur in the fresh water portion of the upper estuary. A relationship between high nutrient content and the accelerated eutrophication in the Potomac estuary has been established [1].

To aid in developing the water resources of the Potomac River Basin, an investigation was initiated in 1966 to determine nutrient sources including temporal and spatial distributions. The analyses was expanded in 1968 to determine the amount of nutrients entering the Potomac Basin from all major wastewater discharges. The scope of the program was expanded to include several other basins in the Middle Atlantic Region during 1969.

# A DESCRIPTION OF THE POTOMAC RIVER BASIN

The Potomac River Basin has a drainage area of 14,670 square miles and encompasses parts of Pennsylvania, Maryland, West Virginia, and Virginia and all of the District of Columbia. The major sub-basins, including their drainage areas, are:

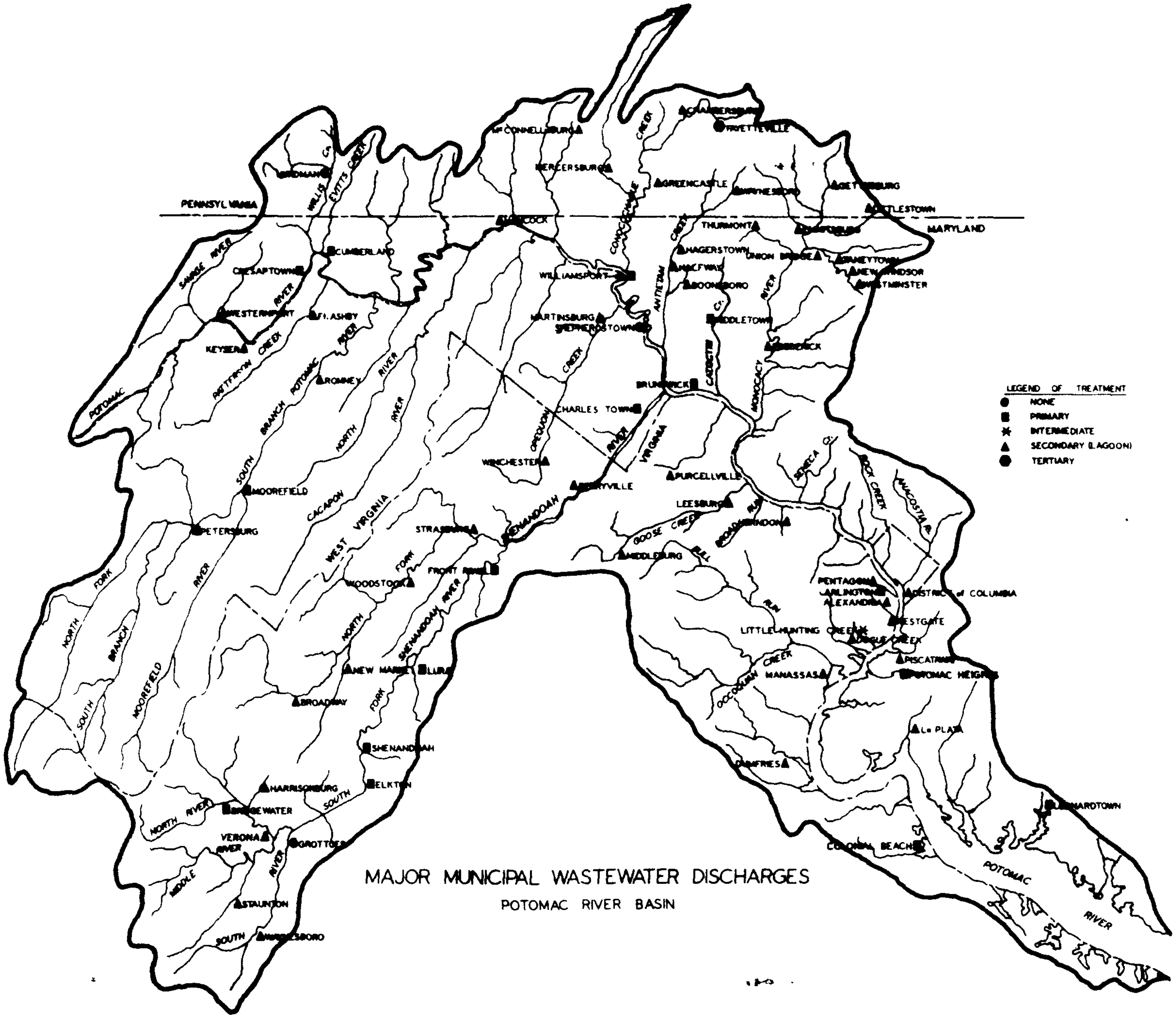
| | Sub-Basin | Drainage Area (square miles) |
|---|---|---|
| (1) | Shenandoah River | 3,054 |
| (2) | South Branch | 1,493 |
| (3) | North Branch | 1,328 |
| (4) | Monocacy River | 970 |
| (5) | Cacapon River | 683 |
| (6) | Conococheague Creek | 563 |
| (7) | Opequon Creek | 345 |
| (8) | Antietam Creek | 292 |

A map of the basin is presented in Figure I.

Of the 3 million people living in the basin, about 2.5 million, or 83 percent, live in the Washington, D. C. metropolitan area. The industrial development is primarily concentrated in the North Branch of the Potomac near Luke and Cumberland, Maryland, and in the South Fork of the Shenandoah near Front Royal and Waynesboro, Virginia.

Land use in the sub-basins is either predominately forest, agricultural or urban. In the entire Potomac Basin, it has been estimated that the land use is 5 percent urban, 55 percent forest and 40 percent agricultural including pasture lands.

The Potomac and its tributaries are characterized by flash floods and extremely low flows. The average discharge of the Potomac River at Washington, D. C. is about 11,000 cubic feet per second (cfs).




MAJOR MUNICIPAL WASTEWATER DISCHARGES
POTOMAC RIVER BASIN

Figure 1

# NUTRIENT SOURCES

## A. Sampling Programs

During the 1966 calendar year, a 40-station stream sampling network was monitored weekly for nitrogen and phosphorus as shown in Figure 2. Weekly analyses of nutrients from 13 wastewater discharges in the upper basin were initiated during the latter part of 1966.

During 1968, all municipal and all bio-degradable industrial wastewater discharges with a flow greater than 0.5 million gallons per day (mgd) were sampled.

In 1969, a sampling network, as shown in Figure 3, was developed to determine the nutrient loading into the Chesapeake Bay. The weekly analysis included two forms of carbon, three of phosphorus and four of nitrogen taken at sampling stations just above the non-tidal portions of the respective basins.

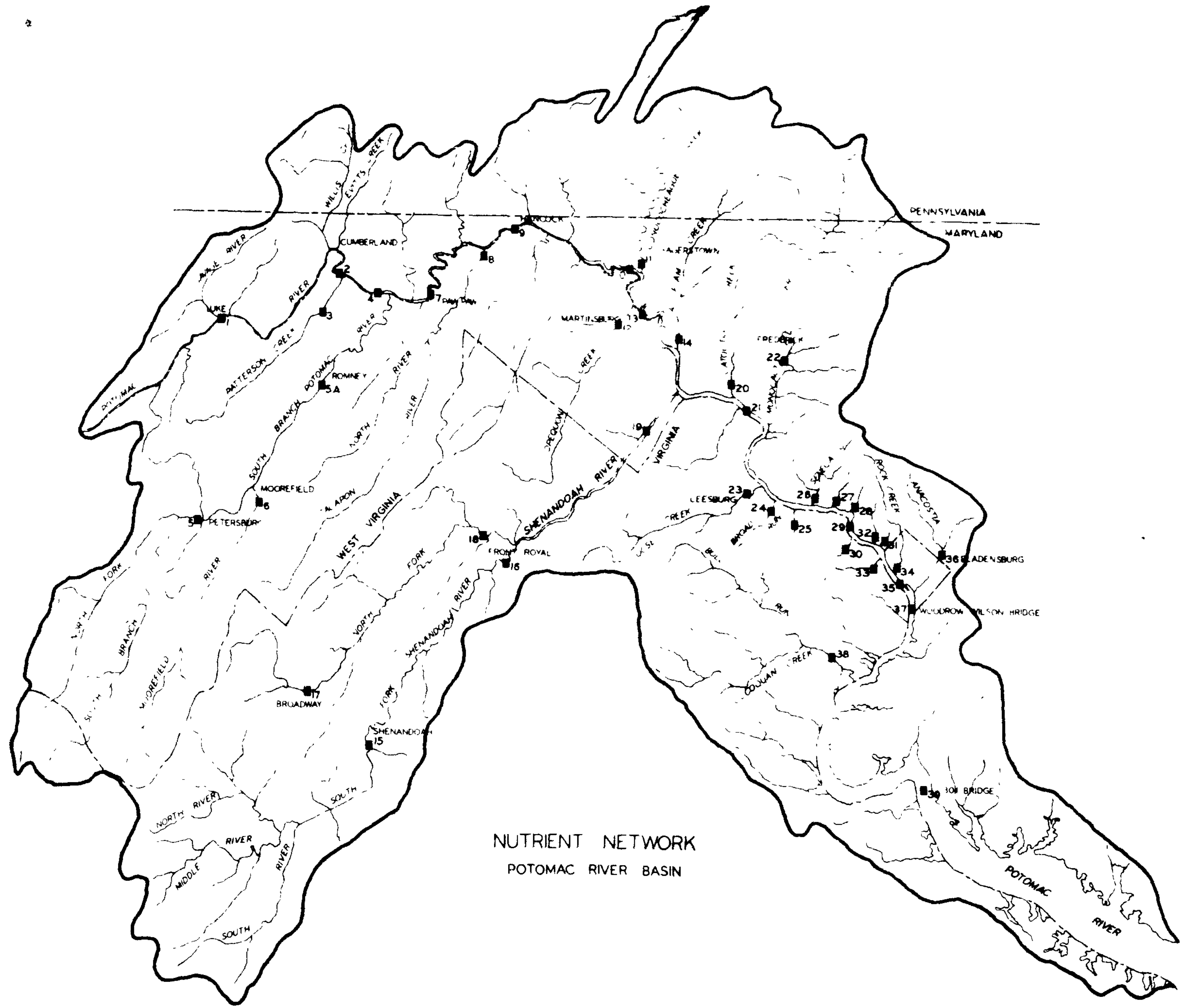

PENNSYLVANIA
MARYLAND
CUMBERLAND
HANCOCK
MARTINSBURG
FREDERICK
ROMNEY
MOOREFIELD
PETERSBURG
WEST VIRGINIA
VIRGINIA
SHENANDOAH RIVER
FRONT ROYAL
LEESBURG
BROADWAY
SHENANDOAH
ROCK CREEK
ANACOSTIA
BLADENSBURG
WOODROW WILSON BRIDGE
POTOMAC RIVER
NUTRIENT NETWORK
POTOMAC RIVER BASIN

Figure 2

## CHESAPEAKE BAY NUTRIENT INPUT STATIONS

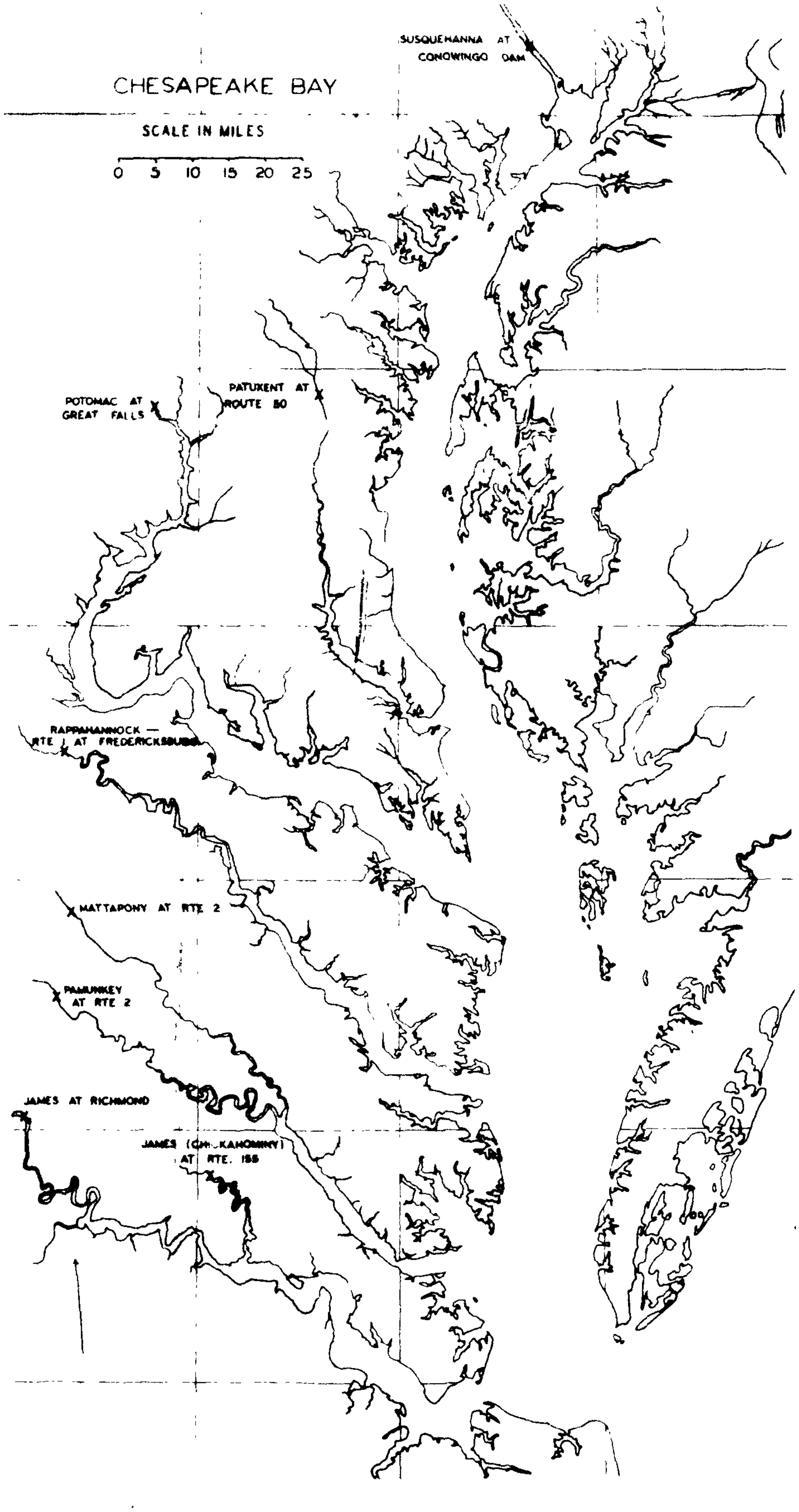



FIGURE 3

[illegible]

As of [illegible], there were a [illegible] wastewater discharges in the upper Potomac River basin. During 1968, 80,430 lbs/day of total phosphorus and [illegible] lbs/day total Kjeldahl nitrogen were discharged to the surface waters. As can be seen in Table I, the largest contribution to the Potomac estuary is from the Washington, D. C. area. For a sewered population of 2,903,500, this reduces to 0.024 and 0.020 lbs/capita/day of phosphorus and nitrogen, respectively.

Nutrient loadings from industrial wastewater discharges are about 7,700 lbs/day of total $PO_4$ and 4,600 lbs/day of TKN. The industrial contributions to wastewater nutrient loadings in the basin are about 10 percent of the total $PO_4$ ($TPO_4$) and about 7 percent of the total nitrogen. The amount of $NO_2$+$NO_3$ nitrogen in both the industrial and municipal wastewater discharges is insignificant.

# TABLE I

## NUTRIENT LOADINGS FROM WASTEWATER DISCHARGES BY SUB-REGIONS*

| Sub-Region | Population Served | LOADING AFTER TREATMENT BOD lbs/day | TKN lbs/day | $TPO_4$ lbs/day |
|---|---|---|---|---|
| North Branch | 79,200 | 55,300 | 1,750 | 4,850 |
| South Branch and Upper Region | 17,300 | 2,720 | 370 | 460 |
| Opequon | 34,800 | 3,470 | 480 | 1,100 |
| Conococheague and Upper Middle Region | 26,900 | 4.250 | 710 | 1,050 |
| Antietam and Middle Region | 61,500 | 7,980 | 890 | 2,380 |
| Shenandoah | 108,500 | 31,800 | 4,890 | 6,360 |
| Catoctin Creeks Md. and Va. | 5,400 | 740 | 110 | 220 |
| Monocacy | 62,500 | 4,220 | 1.380 | 1,830 |
| Lower Fresh Water Region | 7,400 | 200 | 100 | 180 |
| Potomac Estuary | 2,500,000 | 130,000 | 53,000 | 62,000 |
| TOTAL | 2,903,500 | 240,680 | 63.680 | 80,430 |

* A Sub-region may include discharges to the small tributaries and to the main stem of the Potomac.

C. Land Runoff and Other Sources

To determine the amount of nutrients entering the Potomac from land runoff, analyses of loadings from areas with three distinct land uses (forest, agricultural, and urban) were made [2]. Using the Catoctin Creek (Maryland) watershed basin as primarily agricultural, the Patterson Creek watershed as forested, and Rock Creek watershed as urban, the effect of land uses on the contribution of nutrients to surface waters is illustrated in Figures 4 and 5. These three areas receive a relatively small wastewater volume.

On an annual basis, the concentration of nutrients was consistently higher from agricultural areas. As summarized in Table II, it can be seen that the runoff from agricultural areas yields about twice the nitrogen and phosphorus as does the forested area.

Summary of the nutrient data for the major sub-basins, as presented in Table III, indicates that the phosphorus concentrations were at least three times greater in the Monocacy River, Opequon Creek, and Antietan Creek sub-basins than in the remaining five sub-basins. These three sub-basins, while primarily agricultural, also receive considerable quantities of municipal wastewater. These higher concentrations are also reflected in large $PO_4$ yields of from 3.6 to 4.8 lbs/day/sq. mi., as shown in Table III.

The Conococheague, Antietam, Opequon, and Monocacy sub-basins had average concentrations of $NO_2$+$NO_3$ nitrogen of 1.4 mg/l and greater. The Conococheague and Monocacy sub-basins had nitrite and nitrate yields of over 10 lbs/day/sq.mi., almost twofold larger than that of the remaining four sub-basins. This is mainly from agricultural drainage.

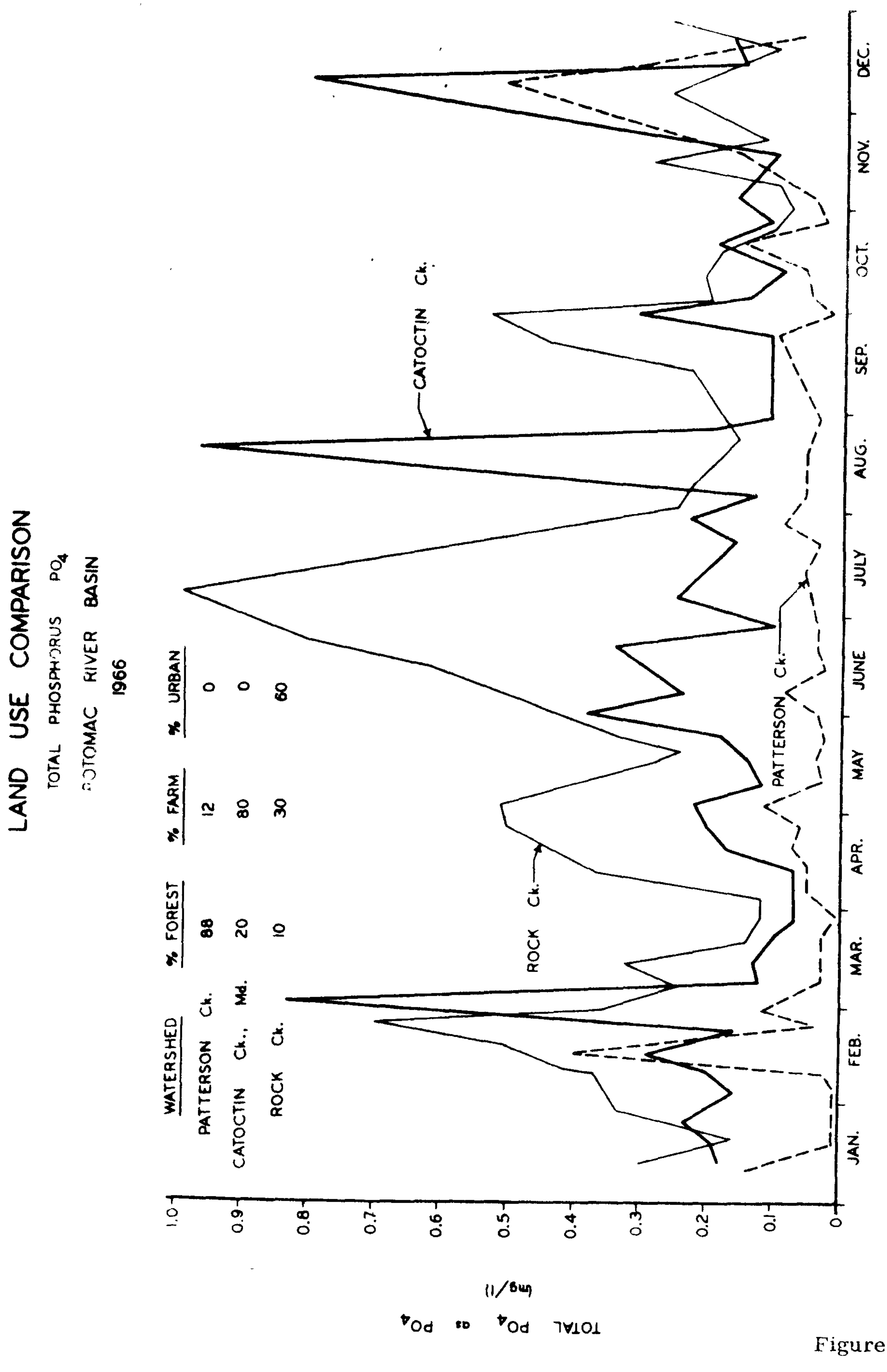

LAND USE COMPARISON
TOTAL PHOSPHORUS PO4
POTOMAC RIVER BASIN
1966
WATERSHED | % FOREST | % FARM | % URBAN
PATTERSON Ck. | 88 | 12 | 0
CATOCTIN Ck., Md. | 20 | 80 | 0
ROCK Ck. | 10 | 30 | 60
CATOCTIN Ck.
ROCK Ck.
PATTERSON Ck.
JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEP. OCT. NOV. DEC.
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
TOTAL PO4 as PO4 (mg/l)

Figure 4

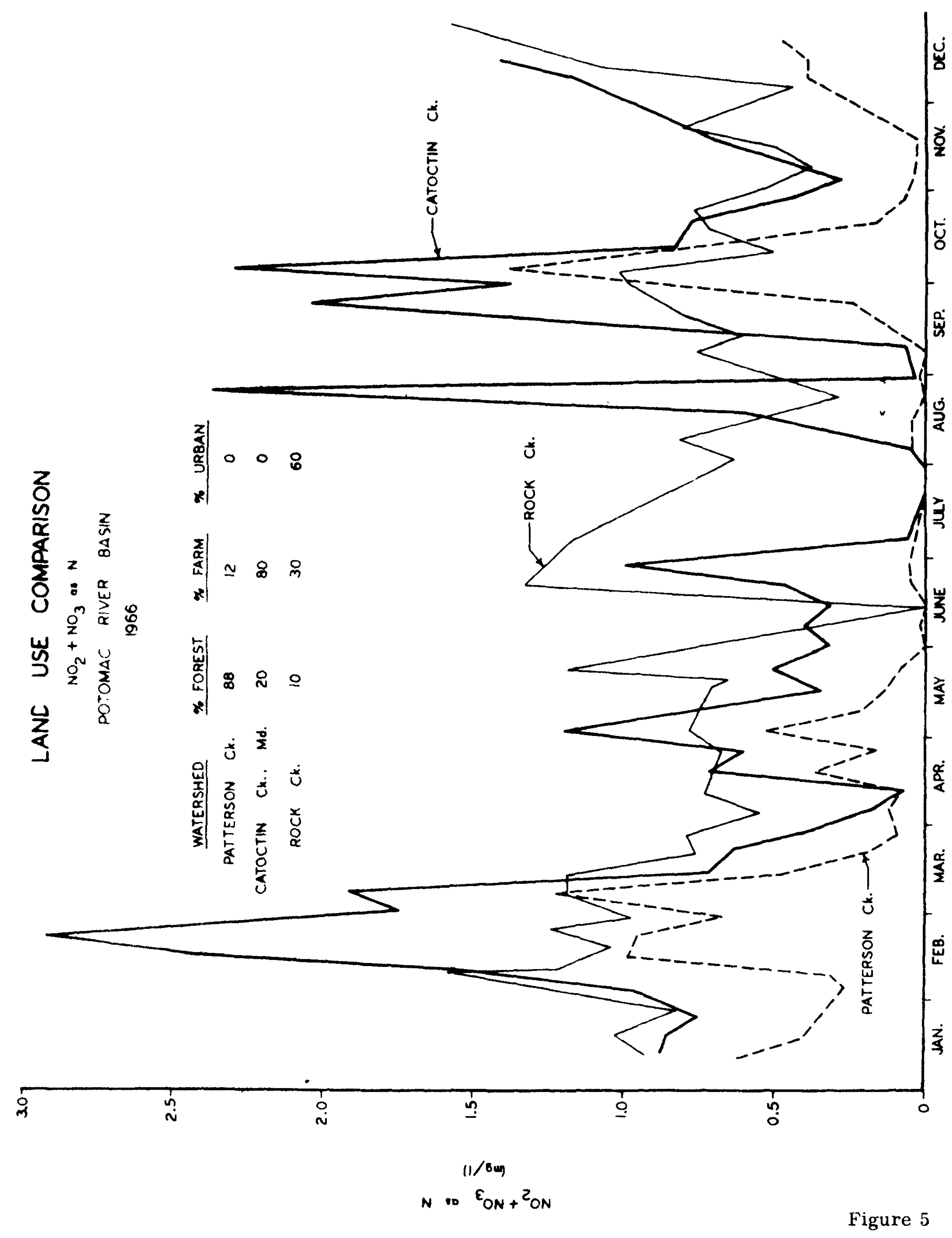

LAND USE COMPARISON
$NO_2 + NO_3$ as N
POTOMAC RIVER BASIN
1966
WATERSHED
PATTERSON Ck.
CATOCTIN Ck., Md.
ROCK Ck.
% FOREST
88
20
10
% FARM
12
80
30
% URBAN
0
0
60
CATOCTIN Ck.
ROCK Ck.
PATTERSON Ck.
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
AUG.
SEP.
OCT.
NOV.
DEC.
0
0.5
1.0
1.5
2.0
2.5
3.0
$NO_2 + NO_3$ as N
(mg/l)

Figure 5

TABLE II

NUTRIENT LOADINGS FROM WATERSHEDS WITH VARYING LAND USE

1966 Data

| Watershed and Land Use | Drainage Area (sq.mi.) | $TPO_4$ as $PO_4$ (lbs/day/sq.mi.) | $NO_2+NO_3$ as N (lbs/day/sq.mi.) | TKN as N (lbs/day/sq.mi.) |
|---|---|---|---|---|
| Patterson Creek (Forest) | 279 | 0.5 | 2.0 | 0.4 |
| Catoctin Creek (Agric.) | 109 | 1.3 | 6.0 | 0.7 |
| Rock Creek (Urban) | 77 | 1.1 | 2.7 | 0.7 |

TABLE III

COMPARISON OF ANNUAL AVERAGE NUTRIENT CONCENTRATIONS
AND LOADINGS
1966

Major Sub-basins of Upper Potomac River Basin

| Sub-basin (Station) | Drainage Area | TPO₄ as PO₄ | | | $NO_2+NO_3$ as N | | | TKN as N* |
|---|---|---|---|---|---|---|---|---|
| | (sq.mi.) | (mg/l) | (lbs/day) | (lbs/day/sq.mi.) | (mg/l) | (lbs/day) | (lbs/day/sq.mi.) | (mg/l) |
| North Branch (Oldtown, Md.) | 1,328 | .532 | 2,551 | 1.92 | .378 | 3,267 | 2.46 | .784 |
| South Branch (Romney, W.Va.) | 1,450 | .092 | 1,535 | 1.06 | .296 | 3,655 | 2.52 | |
| Conococheague Cr. (Williamsport, Md.) | 469 | .327 | 1,226 | 2.61 | 1.593 | 5,317 | 11.34 | .019 |
| Antietam Creek (Antietam, Md.) | 283 | 1.996 | 1,353 | 4.78 | 1.429 | 1,321 | 4.67 | .536 |
| Opequon Creek (Martinsburg, W.Va.) | 309 | 1.511 | 1,109 | 3.59 | 2.149 | 1,817 | 5.88 | .264 |
| Shenandoah River (Bloomery, W.Va.) | 3,012 | .356 | 5,105 | 1.69 | .654 | 6,714 | 2.23 | .580 |
| Monocacy River (Frederick, Md.) | 813 | 1.176 | 3,385 | 4.16 | 1.744 | 8,661 | 10.65 | .693 |
| Potomac River (Great Falls, Md.) | 11,460 | .379 | 17,013 | 1.48 | .903 | 49,009 | 4.28 | .270 |

* Based on 6 months of sampling

The large variations in $NO_2+NO_3$ nitrogen can be attributed to high mobility of $NO_3$ ion as reported by Wadleigh [3] and Bailey [4]. Figure 6 for the South Branch station at Petersburg demonstrates that the concentration of nitrates is directly related to river discharge while concentrations of TKN and $PO_4$ are indirectly related.

For the 35 stations in the non-tidal portion of the basin, regression analyses were made using both linear and log transforms [5]. The log transforms appeared to yield the best correlation resulting in the following expression:

$$C = aQ^b$$

where:

$C$ = concentration of $PO_4$, TKN, or $NO_2+NO_3$ (mg/l)

$Q$ = stream flow (cfs)

$a$ = a constant

$b$ = an exponent

Using the slope of the concentration-discharge relationship (the exponent b) and knowing the specific location of the sampling point in relation to the municipal or industrial waste outfalls, a quantization of the sources of the nutrients can be obtained. For example, all stations, except one below an industrial outfall discharging nitrates, had a positive slope ranging from about 0.3 to 0.7 with an average of 0.5 suggesting that most of the inorganic nitrogen comes from land and other sources and not from wastewater discharges.

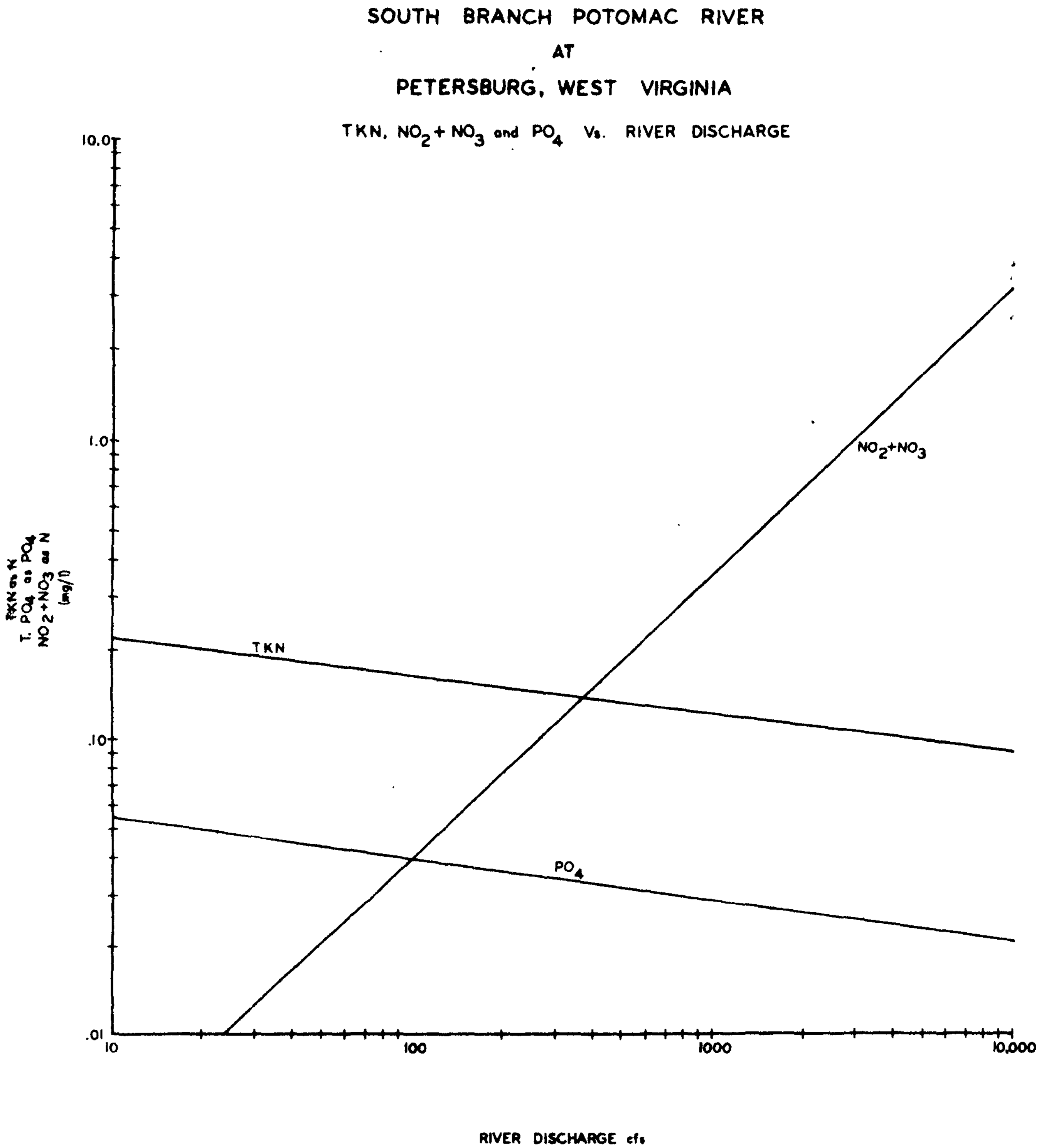

SOUTH BRANCH POTOMAC RIVER
AT
PETERSBURG, WEST VIRGINIA
TKN, NO2 + NO3 and PO4 Vs. RIVER DISCHARGE
T. PO4 as PO4
NO2 + NO3 as N
(mg/l)
10.0
1.0
.10
.01
10
100
1000
10,000
TKN
NO2+NO3
PO4
RIVER DISCHARGE cfs

Figure 6

The concentrations of phosphorus and TKN for most of the non-tidal stations had either slightly positive or negative slopes indicating a diluting effect. The correlation coefficients for these two parameters were low, probably due to seasonal and flushing effects which were not incorporated into the regression studies.

A review of the slopes of the concentration-flow relationships for stations above and below waste outfalls definitely supports the findings of Bailey [4] who indicated that (1) nitrate nitrogen has high mobility in soil, (2) $PO_4$ and TKN are not readily leached, and (3) nutrient concentrations appear to be affected by stream transport mechanisms.

Using the same land use designations that the U. S. Corps of Engineers developed in their 1958 study [6], the nutrient loading from land runoff was determined (Table IV). It should be noted that the largest contribution of nutrients, about 65 percent, is from agricultural runoff even though only 38 percent of the basin is farmed or in pasture lands.

TABLE IV

ESTIMATED NUTRIENT LOADINGS FROM LAND RUNOFF

Potomac River Basin
1966

| Land Use | Area | $TPO_4$ as $PO_4$ | | $NO_2+NO_3$ as N | | TKN as N | |
|---|---|---|---|---|---|---|---|
| | (sq mi) | (lbs/day/sq mi) | (lbs/day) | (lbs/day/sq mi) | (lbs/day) | (lbs/day/sq mi) | (sq mi) |
| Agriculture* | 5,840 | 1.3 | 7,592 | 6.0 | 35,040 | 0.7 | 4,088 |
| Forest | 8,100 | 0.5 | 4,050 | 2.0 | 16,200 | 0.4 | 3,240 |
| Urban | 730 | 1.1 | 800 | 3.0 | 2,190 | 0.7 | 511 |
| Total Basin | 14,670 | 0.84 | 12,442 | 4.98 | 53,430 | 0.53 | 7,839 |

*Agricultural use includes both crop land and pastures.

D. Relative Contribution of Loadings

Utilizing the wastewater data of 1968 and stream flow conditions of 1966, the total nutrient loadings to the surface waters of the basin have been estimated as presented in Table V. The delineation of the sources indicates the following:

1. Of the 92,872 lbs/day of total phosphorus as $PO_4$, 87 percent was from wastewater discharges.
2. About 67 percent of the total phosphorus was from wastewater discharges in the upper Potomac estuary.
3. The total loading of nitrogen as N was about 125,000 lbs/day, of which approximately 51 percent or 63,680 lbs/day originated from wastewater discharges.
4. About 43 percent of the total nitrogen loading was from wastewater discharges in the upper Potomac estuary.

The above delineation clearly indicates for the Potomac River basin the major sources of phosphorus is from wastewater. The major source of nitrogen in 1966 was also from wastewater discharge. Land runoff from the agricultural areas had the highest yield of nitrogen per square mile. Moreover, the concentration of nitrate-nitrogen appears also to be greatly affected by stream flow conditions.

Data for the first eight months of 1969 indicate that over 80 percent of phosphorus and 66 percent of the nitrogen entering the Potomac estuary was from wastewater discharges in the Washington, D.C. area [7]. Even though the first six months of 1969 had stream flows below normal with the latter period having above or normal flow conditions, the data supports the 1966 findings that the major source of nutrients in the Potomac is from wastewater discharges.

TABLE V

ESTIMATED TOTAL POTOMAC BASIN NUTRIENT LOADING
1966

| Source | $TPO_4$ as $PO_4$ (lbs/day) | % of total | $NO_2+NO_3$ as N (lbs/day) | % of total | TKN as N (lbs/day) | % of total |
|---|---|---|---|---|---|---|
| Wastewater | 80,430 | 87 | * | | 63,680 | 89 |
| Land Runoff | 12,442 | 13 | 53,430 | 100 | 7,839 | 11 |
| Total Basin | 92,872 | 100 | 53,430 | 100 | 71,519 | 100 |

* The amount of $NO_2+NO_3$ Nitrogen in the wastewater was insignificant.

E. Temporal Variations

An important aspect of the nutrient control problem is the annual variation in nutrient contributions from the various sources, especially from land runoff. The nitrate-nitrogen loadings from the years 1947-1967 for the Potomac River at Great Falls show a definite seasonal pattern (Figure 7). The seasonal loading variations closely parallel those of river discharge that is high in the spring months, low in the summer and fall, and somewhat higher than fall in the winter months.

The relationship between river discharge and nutrient loadings is vividly demonstrated in Figure 8 for the Potomac at Great Falls. During the high discharge rate in February and March of 1966, the $NO_2$+$NO_3$ and $TPO_4$ loadings were also the largest while in August, when the flow was very low, the nutrient loadings were likewise small.

In mid-September of 1966, there was considerable precipitation throughout the basin. This resulted in a high nutrient loading in September as also seen in Figure 8.

An important aspect of the temporal variations in nutrient loadings is nutrient transport. This is especially pronounced for phosphorus. As can also be seen in Figure 8, during August less than 100 lbs/day of $TPO_4$ entered the estuary even though over 18,400 lbs/day were discharged to surface waters from wastewater discharges. During low flow conditions, considerable amounts of phosphorus in the surface waters are either precipitated, adsorbed onto sediment particles or utilized by aquatic life. At times of high stream flows, much of the phosphorus is re-suspended and transported downstream.

The high loadings of $TPO_4$ in mid-September were due to flushing of the river channel system by the high stream flows. The high inorganic nitrogen loadings in September can be readily attributed to flushing of the land as previously indicated.

The various forms of phosphorus and nitrogen for the Potomac River at Great Falls during the first 10 months of 1969 are presented in Figures 9 and 10. Figure 9 shows that only about 25 percent of the total phosphorus is in the dissolved reactive form. This suggests that most of the phosphorus originating from the upper basin was or has become attached to silt particles.

Similar to Figures 6 and 7, the $NO_2$+$NO_3$ nitrogen as shown in Figure 10 demonstrates the dependence of this form of nitrogen on river discharge. Fraction analyses of the TKN form indicates that over 50 percent is in the particulate state.

The wide variations in nutrient loadings in the Potomac River at Great Falls demonstrates the need to sample at various river discharges continuously over an annual cycle before a delineation of nutrient sources can be made. Moreover, as shown in Figure 8, sampling only during summer flow conditions can yield misleading conclusions as to the temporal distribution, relative sources and transport mechanism of nutrients.

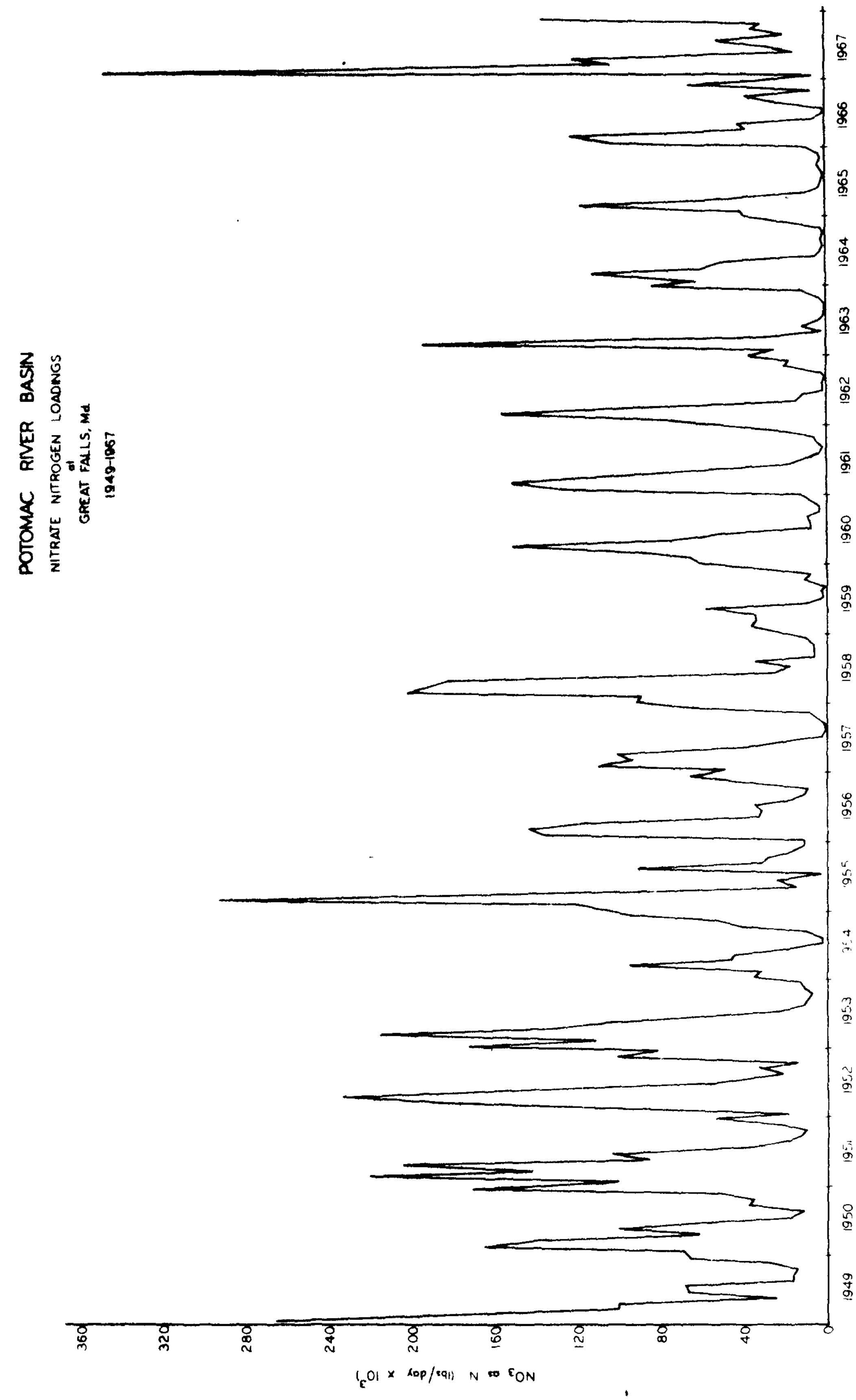

POTOMAC RIVER BASIN
NITRATE NITROGEN LOADINGS
at
GREAT FALLS, Md.
1949-1967
NO3 as N (lbs/day x 10^3)
0
40
80
120
160
200
240
280
320
360
1949
1950
1953
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967

Figure 7

# NUTRIENT LOADINGS and RIVER DISCHARGES

POTOMAC RIVER at GREAT FALLS, Md.

1966

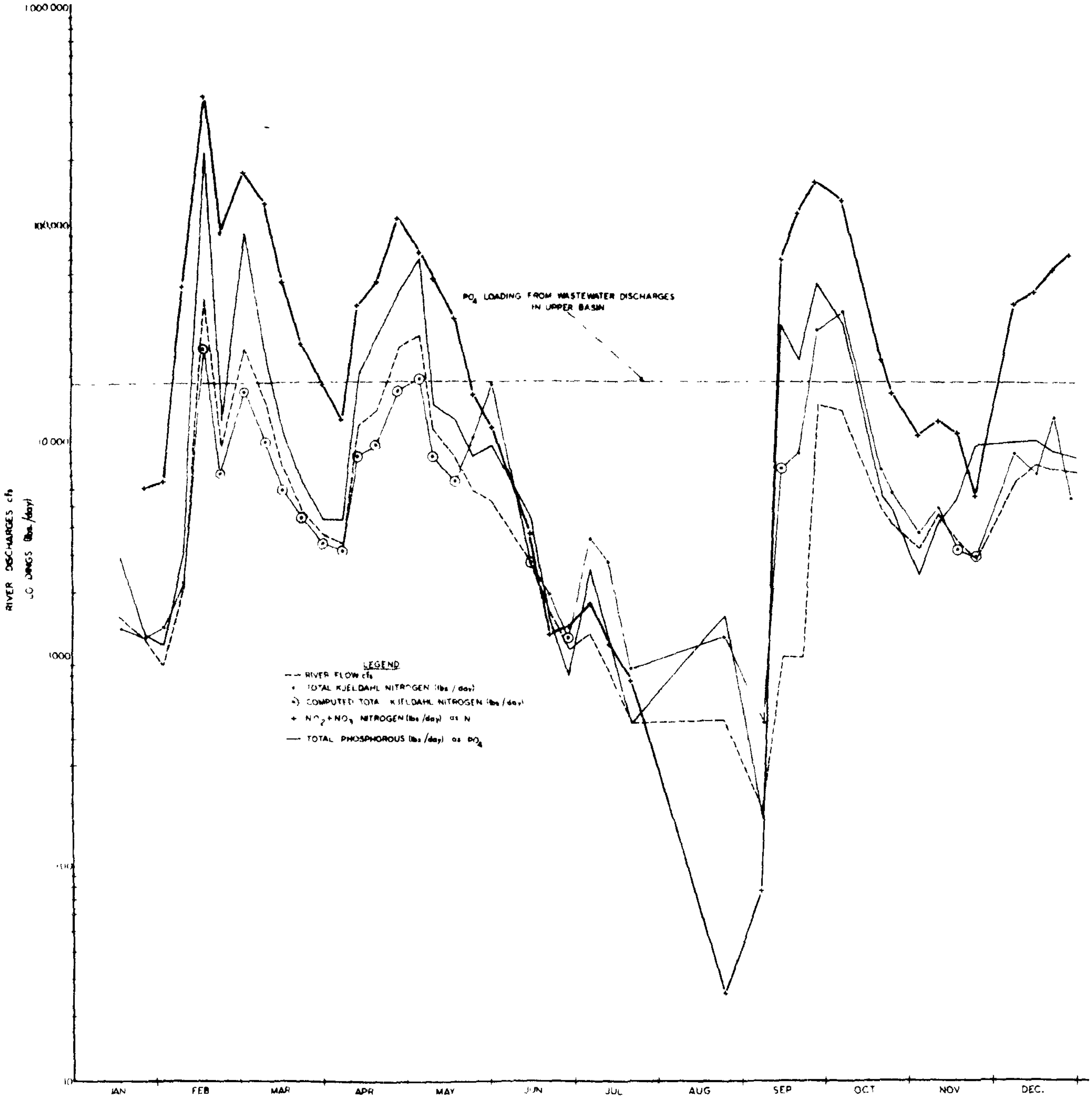



Figure 8

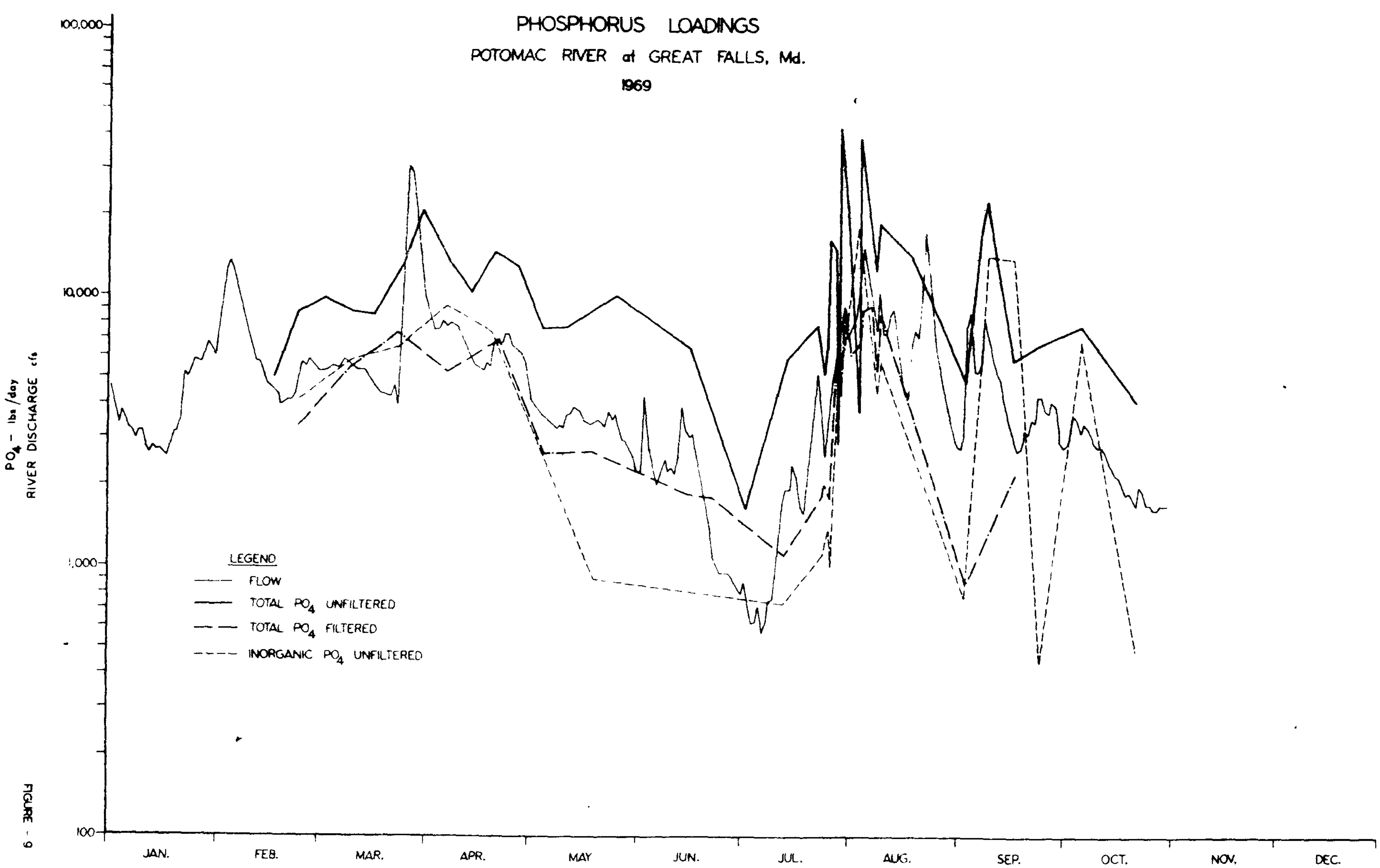

PHOSPHORUS LOADINGS
POTOMAC RIVER at GREAT FALLS, Md.
1969
100,000
10,000
1,000
100
$PO_4$ – lbs/day
RIVER DISCHARGE cfs
LEGEND
FLOW
TOTAL $PO_4$ UNFILTERED
TOTAL $PO_4$ FILTERED
INORGANIC $PO_4$ UNFILTERED
JAN.
FEB.
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE - 9

## NITROGEN LOADINGS
### POTOMAC RIVER at GREAT FALLS, Md.
### 1969

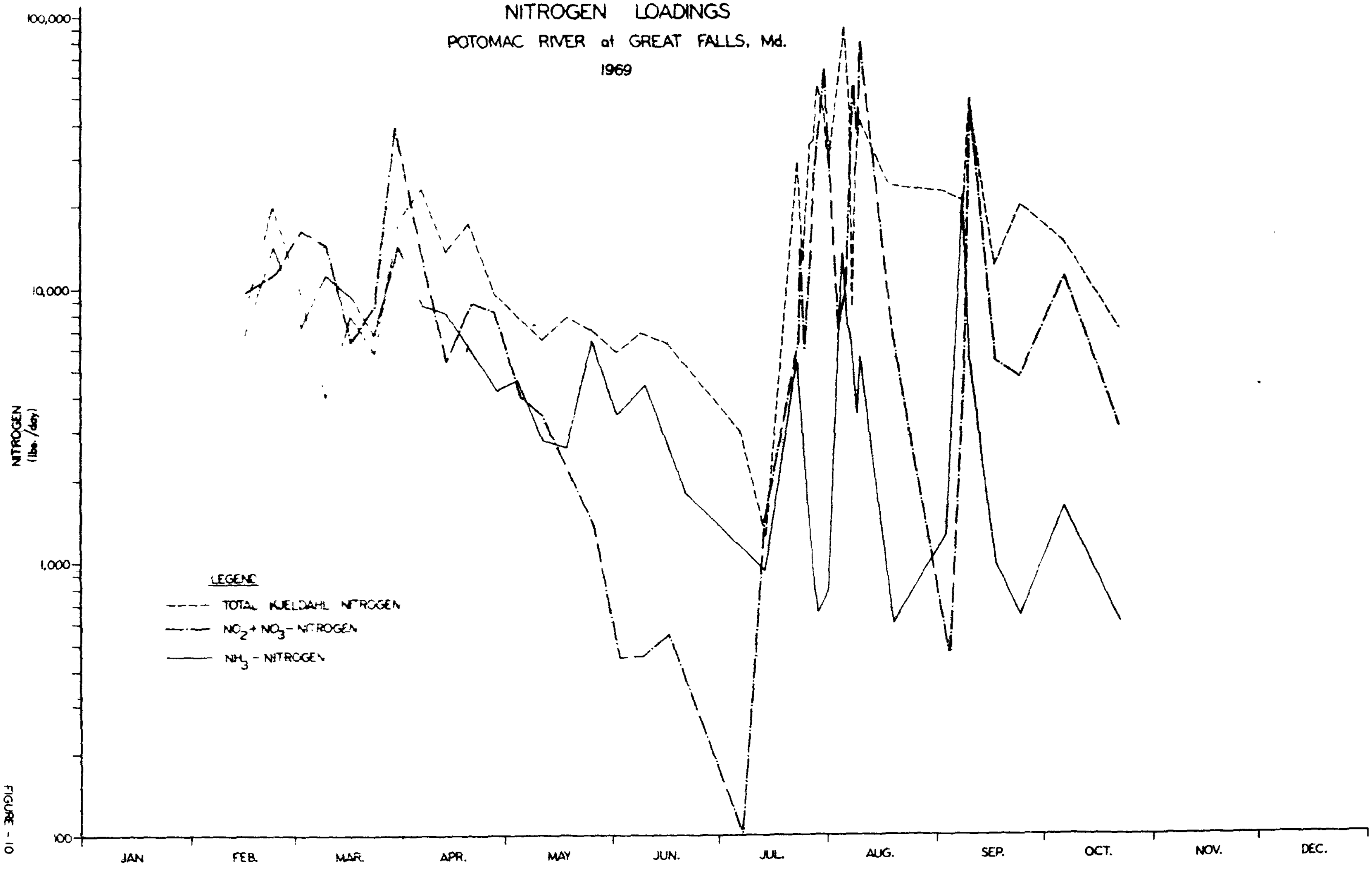



FIGURE - 10

F. Comparison to Other River Basins in the Middle Atlantic Region

Figures 11, 12 and 13 present a six month comparison of nutrient concentrations for five river basin systems as part of a nutrient input study of the Chesapeake Bay system. The mean monthly concentration of phosphorus is highest for the Patuxent Basin and lowest for the Susquehanna with the Potomac being second highest (Figure 11). Except for the Patuxent, all have concentrations usually less than 0.5 mg/l.

In terms of $NO_2$+$NO_3$ nitrogen, the Patuxent is the highest (Figure 12). This is mainly due to high ratio of sewage to stream flow in this small basin. The concentrations, usually less than 0.5 mg/l, were the lowest for the Rappahannock Basin with Potomac being comparable to the other basins of its size, ranging from about 0.5 to 0.75 mg/l.

TKN nitrogen concentrations in the Patuxent were the highest with the Potomac being second highest. For the three remaining basins, the concentration varied from about 0.3 to 1.0 mg/l.

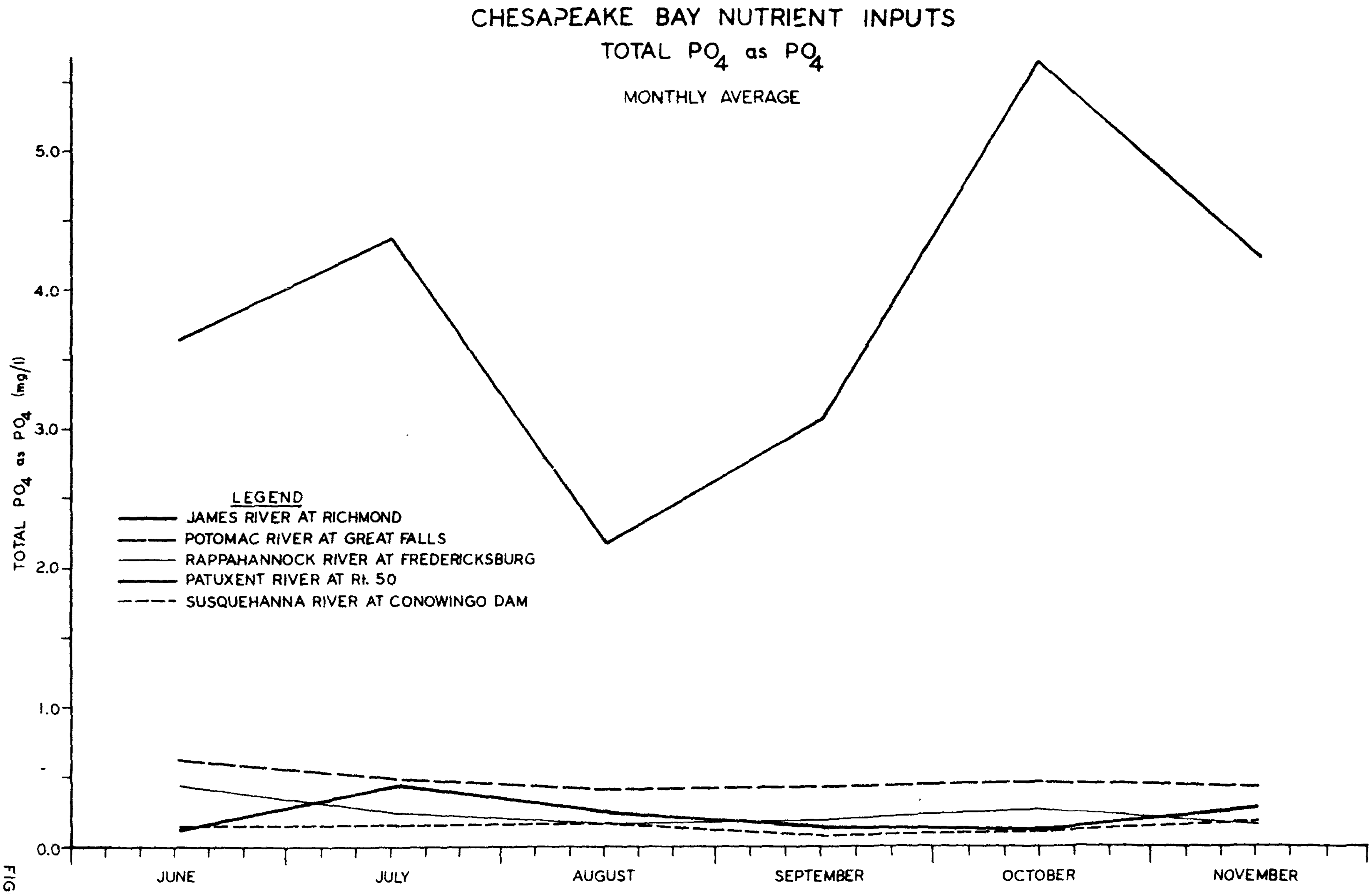

CHESAPEAKE BAY NUTRIENT INPUTS
TOTAL $PO_4$ as $PO_4$
MONTHLY AVERAGE
TOTAL $PO_4$ as $PO_4$ (mg/l)
5.0
4.0
3.0
2.0
1.0
0.0
LEGEND
JAMES RIVER AT RICHMOND
POTOMAC RIVER AT GREAT FALLS
RAPPAHANNOCK RIVER AT FREDERICKSBURG
PATUXENT RIVER AT Rt. 50
SUSQUEHANNA RIVER AT CONOWINGO DAM
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER

FIGURE - 11

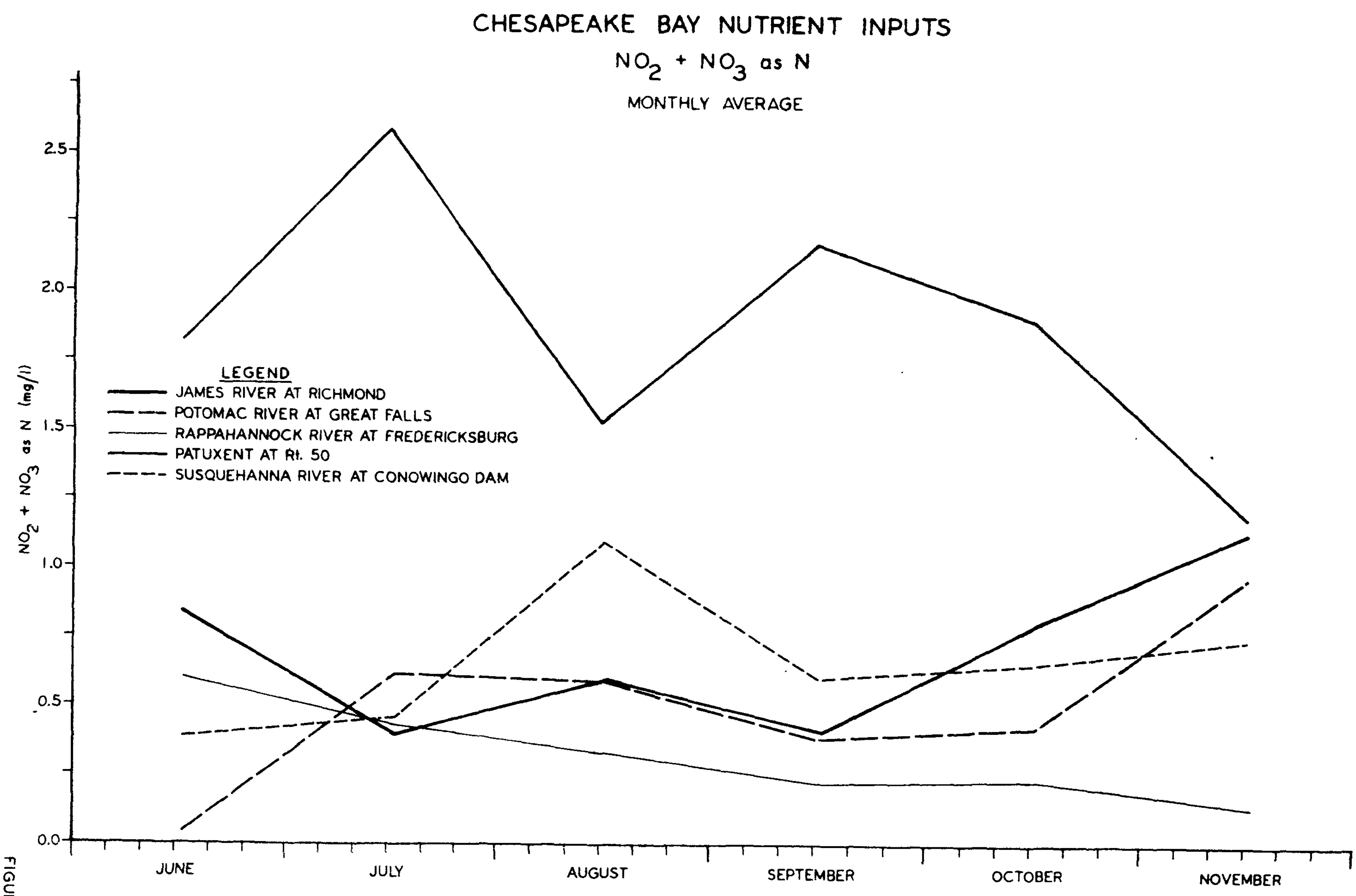
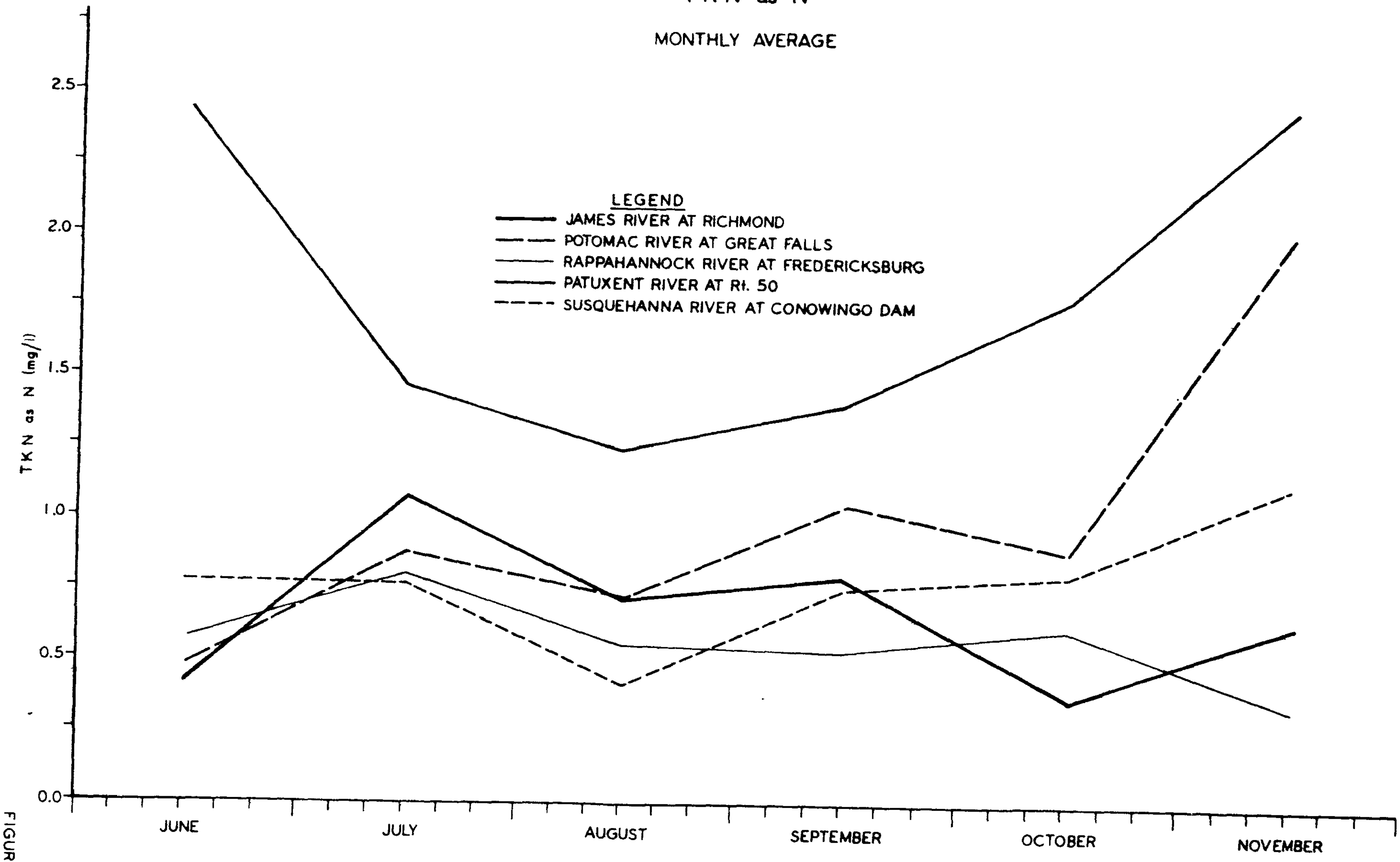

CHESAPEAKE BAY NUTRIENT INPUTS
$NO_2 + NO_3$ as N
MONTHLY AVERAGE
LEGEND
JAMES RIVER AT RICHMOND
POTOMAC RIVER AT GREAT FALLS
RAPPAHANNOCK RIVER AT FREDERICKSBURG
PATUXENT AT Rt. 50
SUSQUEHANNA RIVER AT CONOWINGO DAM
$NO_2 + NO_3$ as N (mg/l)
2.5
2.0
1.5
1.0
0.5
0.0
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER

FIGURE - 12



CHESAPEAKE BAY NUTRIENT INPUTS
TKN as N
MONTHLY AVERAGE
LEGEND
JAMES RIVER AT RICHMOND
POTOMAC RIVER AT GREAT FALLS
RAPPAHANNOCK RIVER AT FREDERICKSBURG
PATUXENT RIVER AT Rt. 50
SUSQUEHANNA RIVER AT CONOWINGO DAM
TKN as N (mg/l)
0.0
0.5
1.0
1.5
2.0
2.5
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER


FIGURE - 13

G. Hudson River Basin System

In order to determine if the relatively high percentage of nutrients from wastewater in the Potomac Basin was unique or whether it is more generally true that wastewater discharges are the most significant contributors of nutrients to the aquatic ecosystem in the Middle Atlantic Region, a comparison of the nutrient sources was made for the Hudson River Basin. This basin is relatively comparable to the Potomac in size, land use patterns and population (both over-all density and distribution). It is also more highly industralized.

A complete description of the Hudson River Basin and its nutrient loading was recently presented by Tofflemire and Hetling [8]. As a result of this study, it was estimated that the total phosphorus as $PO_4$ discharged to the Hudson River Basin above the New York City line is approximately 72,000 lbs/day, 73% of which is from wastewater discharges. The corresponding total for nitrogen as N is 125,570 lbs/day with 63% coming from wastewater.

A comparison of the Hudson River estimates with those found for the Potomac is given in Table VI. The Hudson results give added support to the Potomac findings that, for the large river basins in the Middle Atlantic Region, the major source of nutrients is wastewater discharges.

TABLE VI

COMPARISON OF NUTRIENT LOADINGS
IN HUDSON AND POTOMAC RIVER BASINS

Total Phosphorus as $PO_4$

| Source | Potomac Basin (lbs/day) | % | Hudson Basin (lbs/day) | % |
|---|---|---|---|---|
| Wastewater | 80,430 | 87 | 52,000 | 73 |
| Land Runoff | 12,442 | 13 | 19,420 | 37 |
| Total Basin | 92,872 | 100 | 71,600 | 100 |

Total Nitrogen as N

| Source | Potomac Basin | | Hudson Basin | |
|---|---|---|---|---|
| Wastewater | 63,680 | 51 | 78,500 | 63 |
| Land Runoff | 61,269 | 49 | 47,070 | 37 |
| Total Basin | 124,949 | 100 | 125,570 | 100 |

## SUMMARY AND CONCLUSIONS

Results of the initial phase of the nutrient investigations in the Potomac River system, which have been expanded to include other river basins and which are being continued by the CTSL, are summarized below:

1. The annual average concentration of phosphorus as $PO_4$ in the major sub-basins varied from a minimum of 0.09 mg/l in the South Branch to a maximum of 1.9 mg/l in the Antietam watershed.

2. The annual average concentration of $NO_2$+$NO_3$ nitrogen as N in the major sub-basins varied from 0.3 mg/l in the South Branch to 2.2 mg/l in Opequon Creek.

3. The annual average concentrations of phosphates, total Kjeldahl nitrogen (TKN) and $NO_2$+ $NO_3$ nitrogen in the freshwater stream flow entering the estuary near Washington, D. C., were 0.3, 0.3, and 0.9 mg/l, respectively.

4. About 92,700 lbs/day of total phosphorus as $PO_4$ entered the surface waters of the Potomac in 1966, of which 87 percent resulted from wastewater discharges.

5. The average 1966 loading of total nitrogen as N from all sources to the surface waters of the basin was about 125,000 lbs/day, of which 63,680 lbs/day, or 51 percent, were from wastewater discharges.

6. Seasonal variations in inorganic nitrogen loadings are much more pronounced when compared to phosphorus. This is mainly attributed

to a direct relationship between stream flow and inorganic nitrogen concentration for the stations in the non-tidal portion of the basin while phosphorus generally has an inverse relationship.

7. From an analysis of watersheds with varying land uses and receiving little or no wastewater discharges, the average annual yields per square mile for the entire basin was 0.8 lbs/day of phosphorus $PO_4$, 5.0 lbs/day of $NO_2$+$NO_3$ nitrogen as N, and 0.5 lbs/day of TKN.

8. Of the 61,270 lbs/day of total nitrogen from land runoff, about 35,000 lbs/day or 65 percent, were from agricultural areas which comprise only 38 percent of the total drainage area in the basin.

9. Nutrient yields were over twofold greater from areas which were predominately agricultural than from forested areas.

10. Similar to 1966 findings, data for the first eight months of 1969 corroborate that the major source of nutrients is from wastewater discharge with the largest contribution originating in the Washington, D. C. area.

11. During low flow conditions a significant proportion of the phosphorus entering the surface water from the various sources in the upper basin is retained in the stream channel. At high stream flow, it appears that a large proportion of this phosphorus is "flushed" out of the stream channel and transported downstream.

12. The wide variation in nutrient loadings clearly demonstrates the need to sample more frequently over a wide range of stream flows before a precise identification of nutrient sources can be made.

13. In the Hudson River Basin, wastewater discharge contributes about 73 percent of the phosphorus and 63 percent of the nitrogen.

14. A comparison of sources of nutrients in the Hudson River Basin to those found in the Potomac supports the contention that for large drainage basins in the Middle Atlantic Region the major source of nutrients to the aquatic ecosystem is from wastewater discharges.

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4. Bailey, G.W., "Role of Soils and Sediment in Water Pollution Control, Part One," Southeast Water Laboratory, FWPCA, March 1968.

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13. In the Hudson River Basin, wastewater discharge contributes about 73 percent of the phosphorus and 63 percent of the nitrogen.

14. A comparison of sources of nutrients in the Hudson River Basin to those found in the Potomac supports the contention that for large drainage basins in the Middle Atlantic Region the major source of nutrients to the aquatic ecosystem is from wastewater discharges.

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3. Wadleigh, C.H., "Wastes in Relation to Agriculture and Forestry," U.S. Department of Agriculture, Washington, D.C., March 1968.

4. Bailey, G.W., "Role of Soils and Sediment in Water Pollution Control, Part One," Southeast Water Laboratory, FWPCA, March 1968.

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Annapolis Field Office
Region III
Environmental Protection Agency

# MATHEMATICAL MODEL STUDIES OF WATER QUALITY IN THE POTOMAC ESTUARY

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# PREFACE

During 1969, two independent but coordinated studies were undertaken by the U. S. Department of the Interior, (FWQA)* and the Corps of Engineers to ascertain the feasibility of using the upper Potomac Estuary as a supplemental water supply source for the Washington Metropolitan Area. Another of the primary requirements for the FWQA study was determination of maximum allowable pollutant loadings to achieve and maintain the adopted water quality standards. Current water quality conditions in the upper estuary have been adequately defined by extensive sampling, but prediction of the effects of large freshwater withdrawals and the corresponding increases in wastewater flows on water quality was also required.

The Chesapeake Technical Support Laboratory (CTSL)** has employed mathematical modeling techniques to predict water quality behavior in the Potomac Estuary for various hydraulic conditions and wastewater loading schemes. While existing estuary models have proven to be flexible and versatile tools, verification for a particular system was necessary before reliable predictions could be made. This report presents CTSL's findings based upon simulation studies in the Potomac Estuary using two of the more commonly known mathematical models: (1) DECS III***, and (2) the FWQA Dynamic Estuary Model. The former model employs an average tidal solution whereas the latter is based upon a real-time solution.

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** Presently known as Annapolis Field Office

*** Hereafter referred to as the Thomann Model

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# CHAPTER I

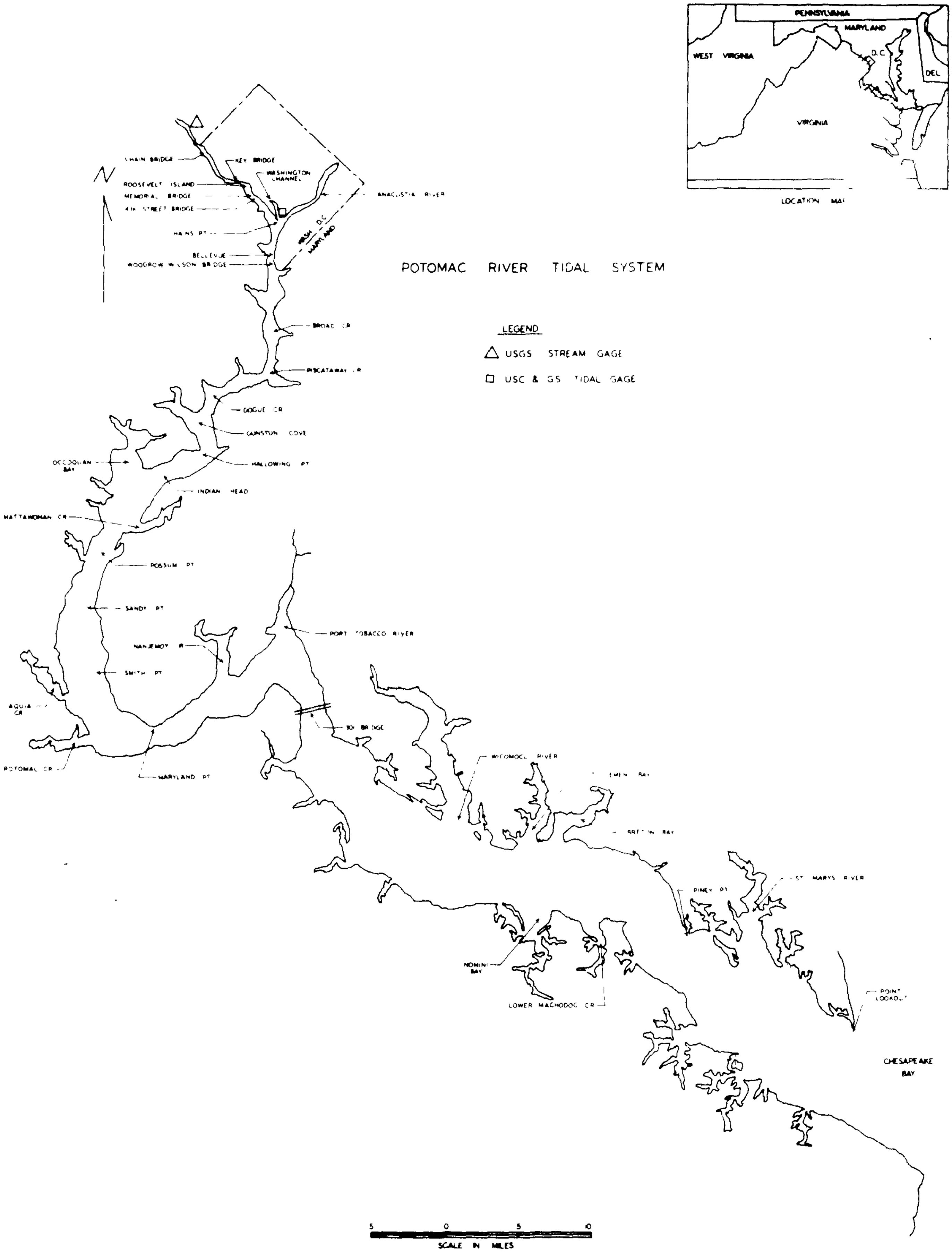
# INTRODUCTION

## A. PURPOSE AND SCOPE

Mathematical models are becoming an increasingly important "tool" for predicting, under a variety of conditions, water quality behavior in an estuary. The purpose of this report is to present recent CTSL studies on use of these models in the Potomac Estuary, specifically, the Thomann Model (time-dependent version) and the FWQA Dynamic Estuary Model.

Numerous computer runs were made with both models in an attempt to make a reasonably accurate simulation of dye profiles observed in the Potomac Estuary following a 13-day continuous release during November 1969 and of observed dye profiles in the Anacostia River following a 7-day continuous release during April 1970. In addition to model verification, consideration was given to: (1) a comparison of modeling approaches, (2) the limitations of each model, (3) input data requirements, and (4) a detailed sensitivity analysis to determine which input parameters had the greatest effect on model output. Hopefully, investigations of each of these factors will assist in future modeling efforts by defining the limitations and applicability of each model and also by indicating where expenditures for necessary data refinement are warranted.

While mathematical models have been developed for the entire Potomac Estuary, most studies in this report pertain to the 40-mile reach of the upper estuary extending from Key Bridge to Sandy Point (Figure I-1).




# POTOMAC ESTUARY

FIGURE I-1

## B. ACKNOWLEDGEMENTS

The assistance and cooperation extended by the personnel at the District of Columbia's Blue Plains Sewage Treatment Plant, the Washington Suburban Sanitary Commission, and the U. S. Geological Survey, Washington, D. C. contributed to successful completion of this study and is gratefully acknowledged.

# CHAPTER II

## SUMMARY AND CONCLUSIONS

In its continuing study of the Potomac Estuary, the Chesapeake Technical Support Laboratory (CTSL) has utilized mathematical models to predict water quality response to given hydrographic, demographic, and other physical, chemical, and biological constraints. In the course of model application, many problems associated with verification became evident almost immediately. The findings and conclusions which evolved during CTSL verification studies of both a nontidal model (Thomann) and a tidal or real-time model (FWQA Dynamic Estuary) for the Potomac are reported as follows:

1. The primary model verification effort involved simulation of a 13-day continuous dye release during November 1969 in which 4,454 pounds of diluted (6 percent) Rhodamine WT dye were discharged into the Potomac Estuary at the District of Columbia's Blue Plains Sewage Treatment Plant.

2. Using dispersion coefficients varying from 2.0 $mi^2$/day to 5.0 $mi^2$/day, the Thomann Model appeared to simulate the 1969 Potomac dye study satisfactorily in terms of peak concentrations and longitudinal dye distribution. Shortcomings found in the Thomann Model simulations were pronounced "peaking" during the early phase of the release and insufficient movement of peak dye concentration. Both of these problems were probably caused by the basic analytical (nontidal) solution employed by this model since refinement in the segmentation did not appear to overcome them.

3. A comparison of observed spatial profiles and those obtained from the Dynamic Estuary Model indicated that, except for minor differences in peak dye concentrations near the release point and the rate of downstream transport, the Dynamic Estuary Model was also adequately verified using the 1969 Potomac dye study data. For this verification, the dispersion coefficient ranged from about 1.0 to 2.0 $mi^2$/day depending on the existing tidal velocities and depths.

4. In order to define the mass transport characteristics of the Anacostia Tidal River better and also to provide data upon which confirmation of dispersion rates and other model input for this tidal system could be based, a 7-day continuous dye release was conducted during April 1970 at the Bladensburg Marina, above the D. C.-Maryland line.

5. With the exception of inadequate downstream movement of the simulated peak concentration, both the Dynamic Estuary and Thomann Models appeared to be capable of closely predicting the observed dye distribution in the Anacostia River.

6. A Potomac dye study conducted in 1965 was successfully simulated with both the Dynamic Estuary and Thomann Models. The substantially lower freshwater inflows which occurred during this study resulted in the use of lower dispersion coefficients (1.0 - 2.0 $mi^2$/day) for the Thomann Model. The dispersion coefficients remained the same in the DEM.

7. Based on all of the dye simulation studies, it can be concluded from the standpoint of model verification that, in general, maximum difficulty was experienced in the immediate area of the release point. However, this could have been expected since complete mixing had not yet occurred in the prototype but had to be assumed in both of the models (neither model can treat vertical concentration gradients), and because of the difficulty in selecting representative sampling points.

8. Chloride profiles observed in the Potomac Estuary during 1966 and 1969 were simulated using the Thomann Model. Historical station data, showing annual fluctuations in observed and predicted chlorides, indicated very good agreement when dispersion coefficients ranged between 1.5 - 14.0 $mi^2$/day during relatively low-flow periods and 2.0 - 20.0 $mi^2$/day during the higher flow periods of 1966 and when they ranged between 2.0 - 16.0 $mi^2$/day for the entire year of 1969.

9. The following conclusions can be drawn based upon the chloride simulations performed with the Thomann Model:

a. A considerable range in the dispersion coefficients can be expected where there are great salinity increases in a longitudinal direction. The pronounced gradients, rather than the actual salinity concentrations, require much larger dispersion coefficients for the Thomann Model if meaningful data are to be obtained.

b. Dependence of dispersion coefficients on freshwater inflow rates was not as evident for chloride as it was for dye simulations. In fact, an apparent anomaly appeared since maximum chloride intrusion occurred in the

Potomac Estuary during low-flow periods whereas the use of high dispersion coefficients normally associated with high-flow periods was required in the model to produce similar results. Thus, the dispersion term in the Thomann Model may have to be evaluated and related to flow in a different manner for constituents dispersing upstream than for those dispersing primarily downstream.

10. The observed chloride data, measured longitudinally during a period of relatively steady-state flow (July-December 1965), were simulated in the Dynamic Estuary Model. Special problems involving both the advection and dispersion components arose, probably as a result of the unusually high concentration gradients.

11. The following conclusions can be drawn based upon the chloride simulations performed with the Dynamic Estuary Model:

a. The dispersion term employed in the Dynamic Estuary Model ($C_4$) must be increased over an order of magnitude in the seaward portion of the model network to reflect the increasing chloride concentration gradients and to obtain sufficient mass transfer across the seaward boundary. The approximate range in dispersion coefficients used for simulation of chlorides was from 1.0 $mi^2$/day to 20.0 $mi^2$/day for representative depths and tidal velocities.

b. Determination of the proper amount of constituent advected from one node to another in the model becomes quite critical in areas with high concentration gradients. The quarter-point solution method for advective transport, which generally produces acceptable accuracy and low numerical mixing, did not yield satisfactory comparisons for chloride simulations in the Potomac. The use of a third-point advective concentration within a given channel was found to yield more favorable results.

12. Undoubtedly, many of the difficulties associated with application of either the Thomann or Dynamic Estuary Model to simulate the movement of chlorides are the result of representing a three-dimensional stratified system with a one-dimensional model. This further points out the importance of hydrodynamic behavior and the fallacy of using a model to solve a problem for which it was not designed.

13. In order to determine where additional refinement of model input may be warranted, a detailed sensitivity analysis of several factors pertinent to the Thomann and/or Dynamic Estuary Models was performed.

14. Based upon the results of this sensitivity analysis with the Thomann Model, the following represent a listing, in decreasing importance, of the sensitivity of each variable:

a. Dispersion coefficient (K),

b. Decay rate,

c. Segmentation, and

d. Proportionality factor ($\alpha$) used for advective transport.

15. Of the various input parameters investigated for the Dynamic Estuary Model, the decay rate and the solution technique for advective transport appeared to be the most sensitive in affecting the model's predictions. With the exception of simulating salinity (chlorides), the least sensitivity was identified with the dispersion coefficient.

While the hydraulic solution was relatively sensitive to the Manning roughness coefficients, the quality predictions were insensitive to them as well as to the tidal range specified at the seaward boundary. Based on limited data, it appeared that the Dynamic Estuary Model was considerably more sensitive to network detail than the Thomann Model.

16. Utilizing an approach where simulated data from both tidal and nontidal models were compared, relationships of dispersion coefficients (as used in the Thomann Model) to freshwater flows were formulated for the Potomac Estuary. For the flow range investigated (930 cfs to 20,000 cfs) it was determined that dispersion coefficients (K) varied directly with flow in accordance with the following equations:

Upstream from Blue Plains

$$K = 0.195\ Q^{0.34}$$

Blue Plains to Occoquan Bay

$$K = 0.027\ Q^{0.63}$$

where:

K = dispersion coefficient ($mi^2$/day) and

Q = freshwater flow (cfs).

17. The primary disadvantage of the Thomann Model or any nontidal model is the greater significance of dispersion coefficients for an estuarine system and the need to relate them to freshwater flows, salinity gradients, and other factors.

18. Another deficiency encountered with the Thomann Model, as evidenced by certain chloride simulations and the sensitivity analysis was

the apparent deemphasis of both tidal and nontidal advective transport as a result of the model's strong dependence on dispersion. Moreover, the fact that a flow sequence is routed through the system instantaneously indicates that the hydraulic conditions influencing advection are based strictly on a velocity (Q/A) relationship and not on volume displacement.

19. Other important disadvantages of the Thomann Model are its inability to (1) branch in a lateral direction and (2) link more than two constituents.

20. Significant advantages of the Thomann Model over the FWQA Dynamic Estuary Model as both models are presently programmed are (1) its less stringent input requirements, (2) its ability through the Namelist I/O option to change input variables, such as flow on a daily basis, and thereby readily simulate interseasonal conditions, and (3) the capability of running several alternative data decks back-to-back with a minimum of effort. In short, one can generate considerably more data in much less time with the Thomann Model.

21. In addition to more demanding input requirements, another disadvantage of the Dynamic Estuary Model is the fact that it is quite costly and time consuming to link different hydraulic conditions if simulation of seasonal or annual quality characteristics is desired.

22. Because the Dynamic Estuary Model is a "real-time" system, it can predict the effect of tidal exchange and excursion on the distribution of a pollutant as well as other intratidal cycle variations in water quality and it is significantly less dependent on an empirically derived dispersion term. Other major advantages of this model are its ability to branch in a lateral direction and thereby allow simulation of water quality behavior within embayments and to consider six separate constituents either dependently or independently of one another.

# CHAPTER III

## DESCRIPTION OF THE STUDY AREA

The Potomac River Basin, draining 14,170 square miles, is the second largest watershed in the Middle Atlantic States. Its tidal portion begins at Little Falls in the Washington Metropolitan Area and extends 114 miles southeastward to the Chesapeake Bay. The section of the estuary discussed in detail in this report is the 40-mile reach extending from Key Bridge in Washington to Sandy Point which is located downstream from Quantico, Virginia (Figure I-1).

The estuary is less than 200 feet wide near its upper end at Chain Bridge and widens to approximately 4,000 yards at Sandy Point. A shipping channel with a minimum depth of 24 feet is maintained from Washington to the Chesapeake Bay. The major embayments along the upper Potomac Estuary and their surface areas are:

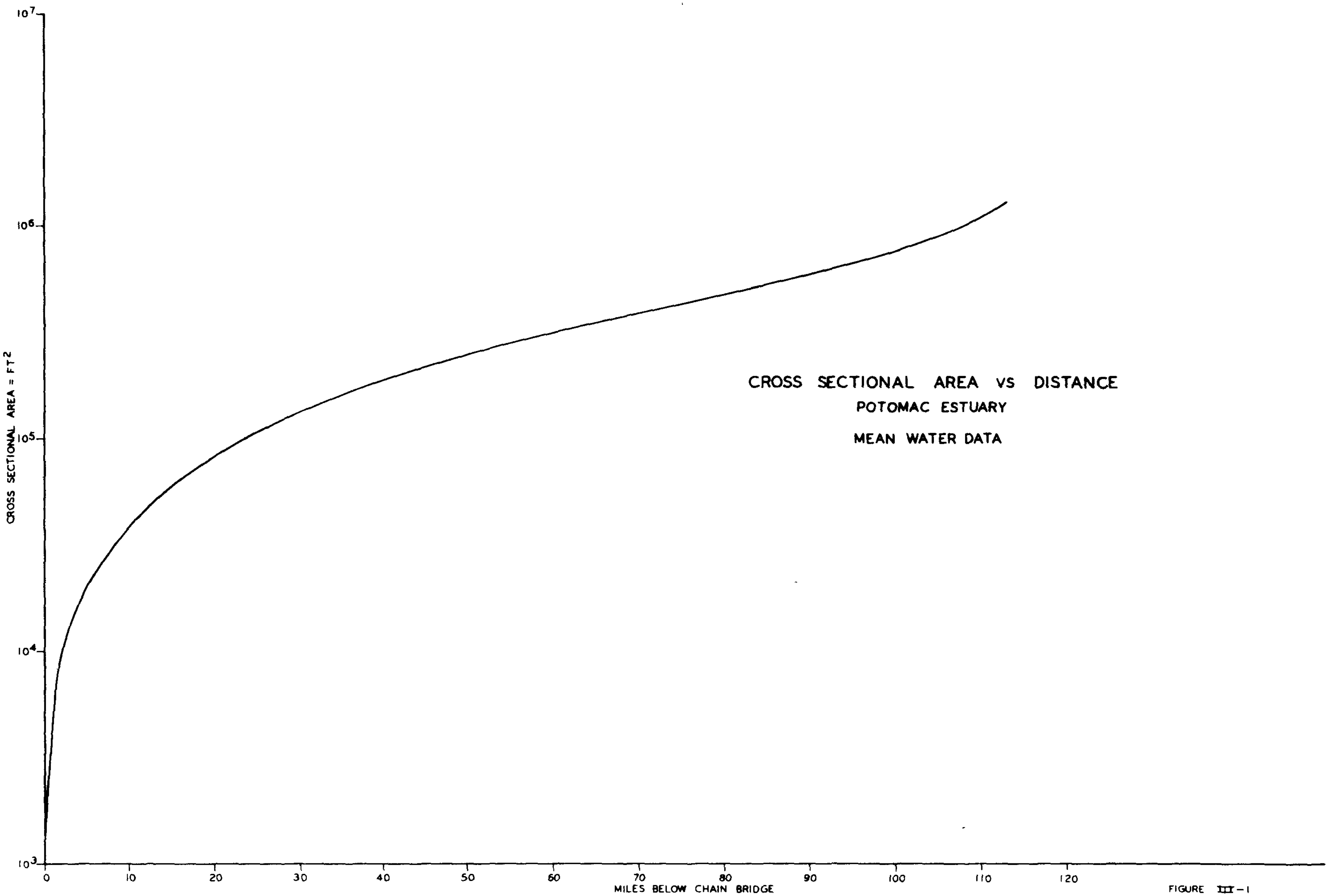
| Embayments | Surface Area |
| --- | --- |
| Occoquan-Belmont Bays | $218 \times 10^6$ ft$^2$ |
| Mattawoman Creek | $75 \times 10^6$ ft$^2$ |
| Gunston Cove | $65 \times 10^6$ ft$^2$ |
| Piscataway Creek | $36 \times 10^6$ ft$^2$ |
| Anacostia River | $31 \times 10^6$ ft$^2$ |
| Quantico Creek | $30 \times 10^6$ ft$^2$ |

Except for the main channel and a small reach below Chain Bridge where depths up to 80 feet occur, the estuary is relatively shallow with an average depth of about 15 feet. The embayments generally have average depths of 5 feet or less.

The upper 20 miles of the study reach (Chain Bridge to Marshall Hall) contain fresh water whereas the lower 20 miles (Marshall Hall to Sandy Point) form the transition zone from fresh to brackish water. The average tidal range at Washington is 2.9 feet, with high and low water occurring about +6 and +7 hours respectively.*

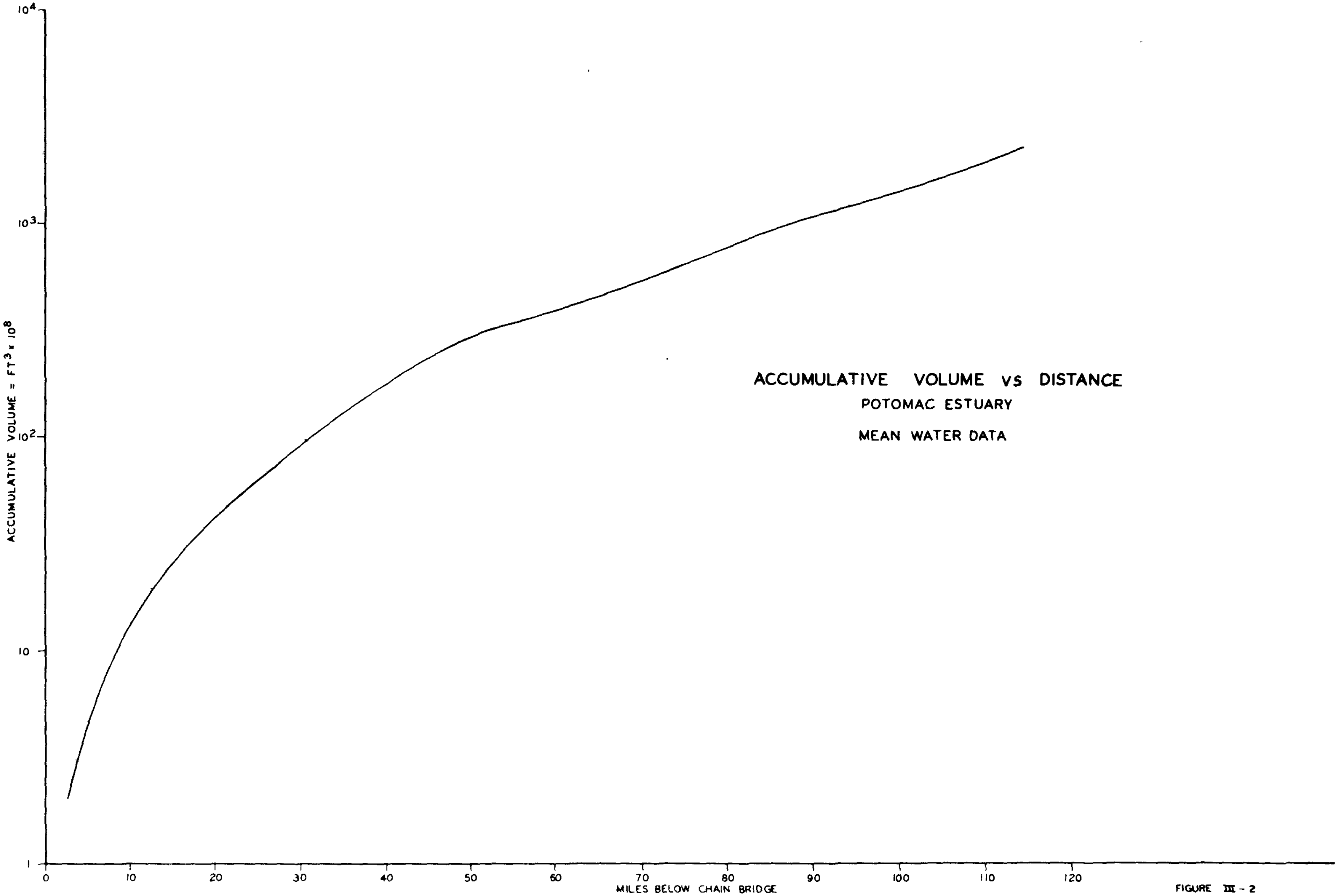
Physical data for the entire Potomac Estuary are summarized in Figure III-1 (cross-sectional area versus distance below Chain Bridge), Figure III-2 (accumulative volume versus distance below Chain Bridge), and Figure III-3 (accumulative surface area versus distance below Chain Bridge). More detailed information was recently published by CTSL in a separate report [1].

* Referenced to Piney Point (River Mile 99)



CROSS SECTIONAL AREA VS DISTANCE
POTOMAC ESTUARY
MEAN WATER DATA
CROSS SECTIONAL AREA = FT2
10^7
10^6
10^5
10^4
10^3
0
10
20
30
40
50
60
70
80
90
100
110
120
MILES BELOW CHAIN BRIDGE

FIGURE III-1



ACCUMULATIVE VOLUME vs DISTANCE
POTOMAC ESTUARY
MEAN WATER DATA
ACCUMULATIVE VOLUME = FT³ x 10⁸
10⁴
10³
10²
10
1
0
10
20
30
40
50
60
70
80
90
100
110
120
MILES BELOW CHAIN BRIDGE


FIGURE III - 2

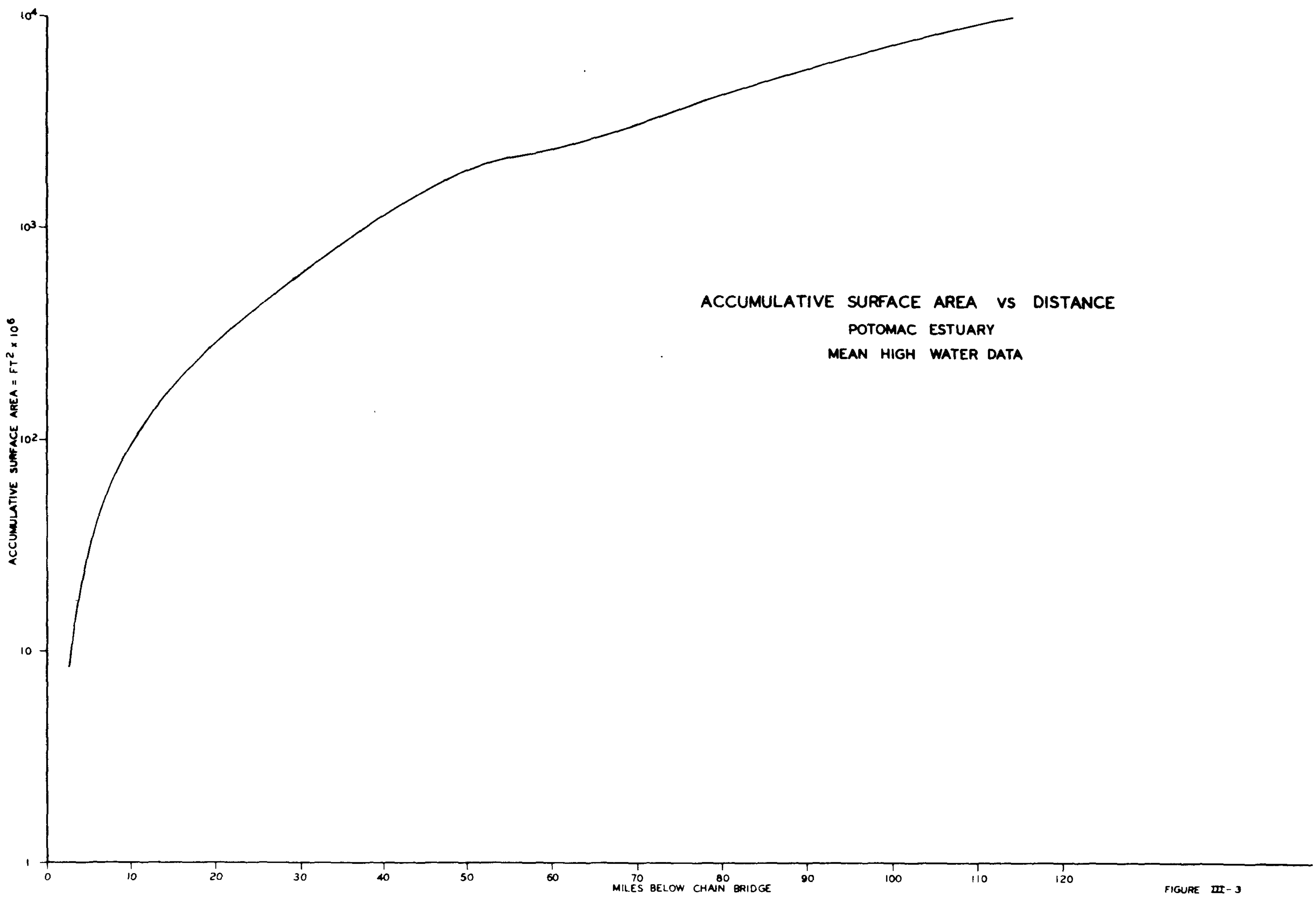

ACCUMULATIVE SURFACE AREA VS DISTANCE
POTOMAC ESTUARY
MEAN HIGH WATER DATA
ACCUMULATIVE SURFACE AREA = FT² x 10⁶
10⁴
10³
10²
10
1
0
10
20
30
40
50
60
70
80
90
100
110
120
MILES BELOW CHAIN BRIDGE

FIGURE III-3

# CHAPTER IV

# DESCRIPTION OF MATHEMATICAL MODELS

## A. THOMANN MODEL

The Thomann Model [4] was originally developed in 1963 as a one-dimensional, steady-state, BOD-DO model specifically for the Delaware Estuary. A time-dependent version of this model [5] and a chloride model [6] were developed in 1966-1967 by General Electric under contract to the Federal Water Pollution Control Administration.* Each of the above models was applied to the Potomac Estuary shortly after development.

The time-dependent Thomann Model employs a segmented network of the water body under consideration and utilizes a finite difference approach to solve the basic mass balance equations. For the case of BOD and DO, these equations can be written as follows:

$$[\![B]\!]\,[L_i] + \left[\frac{dL}{dt}_i\right] = [J_i]$$

$$[\![A]\!]\,[c_i] + \left[\frac{dc}{dt}_i\right] = [r_i\, c_{s_i} + P_i - d_i\, L_i]$$

where $[\![\ ]\!]$ denotes a square matrix of order n and [ ] denotes a column vector of dimension n (n is equal to the number of segments in the system).

The total number of equations and unknowns equals 2n. The components of matrices A and B are defined as:

$$A_{i,\, i-1} = B_{i,\, i-1} = \frac{\alpha_i\, Q_j + E_i}{V_i}$$

$$A_{i,\, i} = \frac{(\phi_i - \alpha_{i+1})\, Q_j - E_i - E_{i+1}}{V_i} - r_j$$

* Now Environmental Protection Agency

$$B_{i,\,i} = \frac{(\phi_i - \alpha_{i+1})\,Q_j - E_i - E_{i+1}}{V_i} - d_j$$

$$A_{i,\,i+1} = B_{i,\,i+1} = \frac{E_{i+1} - \phi_{i+1}\,Q_j}{V_i}$$

The remainder of the terms are defined below:

$L$ = BOD

$C$ = DO

$J_i$ = forcing function or loading in section i

$r_j$ = reaeration coefficient

$C_s$ = saturation value of DO

$d_j$ = decay coefficient

$P_i$ = other sources and sinks of oxygen

$V_i$ = volume of segment i

$Q_j$ = net flow

$E_i$ = eddy exchange coefficient

$\alpha_{i\,j}, \phi_i$ = advection factors

Of special importance are the eddy exchange coefficient and the advection factors. The eddy exchange coefficient is used to describe the tidal and other nonadvective effects on the transport of a constituent. Between sections i and i + 1, it can be computed as follows;

$$E_{i,\,j} = \frac{K_{i,\,j} \times A_{i,\,j}}{\frac{1}{2}(L_i + L_{i+1})} \times 27.878 \times 10^6$$

where:

$K_{i, j}$ = eddy diffusion coefficient between sections i and i + 1 ($mi^2$/day)

$A_{i, j}$ = cross-sectional area at the boundary of segments i and i + 1, and

$L_i$ = length of segment i

The purpose of the advection factor is to serve as a means of computing the concentration of a constituent at the interface of two segments by "weighing" the concentrations in these two adjacent segments. In order to guarantee positivity in the solution, the advection factor takes on the following definition:

$$\phi_{i, j} = \frac{1}{2} \left(\frac{E_{i-1, j}}{Q_{i-1, j}} + \frac{E_{i, j}}{Q_{i, j}}\right)$$

$$\text{if } \frac{E_{i-1, j}}{Q_{i-1, j}} > \frac{E_{i, j}}{Q_{i, j}} \text{ then } \phi_{i, j} = \frac{E_{i, j}}{Q_{i, j}}$$

$$\text{if } \phi_{i, j} > 0.5 \text{ then } \phi_{i, j} = 0.5$$

for the first section:

$$\frac{E_{o, j}}{Q_{o, j}} = 0.0$$

in which case $\alpha$ = 1.0 (pure advection). If the concentrations in the adjoining sections are to be weighed equally (pure dispersion both $\phi$ and $\alpha$ are 0.5.

The simultaneous, linear, first-order differential equations employed by the Thomann Model express the time rate of change of pollutant concentration as a function of the advection and dispersion components at each segment interface and sources and sinks within each segment. These equations are numerically integrated by a fourth-order Runge-Kutta procedure whereby the truncation error is kept within some preset allowable value by constant adjustment of the time step size. The solution yields a mean tide concentation of a particular constituent for every segment.

Since the Thomann Model does not have a "real-time" solution where tidal movement is explicitly considered in the mass transfer equations, the dispersion coefficient (K) must be an "all-inclusive" term that can grossly represent tidal behavior. Another source of uncertainty is numerical dispersion which is introduced by the assumption of a completely mixed finite volume.

B. FWQA DYNAMIC ESTUARY MODEL

The DEM represents the two-dimensional flow and mass transfer within an estuary by a network of interconnecting junctions and channels. Uniformity must be assumed only in the vertical direction. The hydraulic component of the model essentially solves the equations describing the propagation of a long wave (tidal) through a shallow water system. When the tidal conditions such as amplitude, period, etc. existing at the seaward boundary are known, this solution can be obtained from the one-dimensional form of the equations of motion and continuity. The equation of motion is:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - K/u/u - g\frac{\partial H}{\partial x}$$

where:

u = velocity along x axis

x = distance along x axis

H = water surface elevation

g = acceleration of gravity

K = frictional resistance coefficient

t = time

The equation of continuity can be expressed as:

$$\frac{\partial H}{\partial t} = -\frac{1}{b}\frac{\partial (uA)}{\partial x}$$

where:

b = mean channel width

A = cross-sectional area of the channel

The equation of motion is applied to the channel elements to predict velocity and flow and the continuity equation is associated with the junctions and accounts for tidal fluctuations in the water surface elevation (head) and corresponding changes in volume. Both of these differential equations are converted to finite difference form and solved by numerical integration techniques (predictor-corrector method) to yield a "real-time" hydraulic solution. The time step used is normally very small, i.e., 1-5 minutes, as dictated by the network and by numerical stability. The solution will converge for a given set of boundary conditions (including tides and freshwater flow rates) to a dynamic equilibrium having velocities, flows, and heads repeated at intervals equal to the specified tidal period.

The quality component of the FWQA model incorporates the two basic transport mechanisms; namely, advection and diffusion, and requires the dynamic steady-state hydraulic solution as input. Advective transport is primarily a hydraulic mechanism that moves the constituent in the direction of flow. It can be represented by the following two equations:

$$\frac{\partial c}{\partial t} = U \frac{\partial c}{\partial x}$$

or in terms of mass and in finite difference form

$$\frac{\Delta M}{\Delta t} = A\ U\ c^*$$

where:

$c^*$ = concentration in advected water

$U$ = channel velocity, and

$A$ = channel area

The determination of c* can present special problems such as computational instability and "numerical mixing." Previous studies have indicated that an advected concentration equal to that at one-quarter of the channel length, measured in the direction of decreasing gradient, generally proved satisfactory.

Diffusion (eddy) is represented in the model as a physical-chemical transport mechanism dependent only upon concentration gradients. Mathematically, it can be expressed as:

$$\frac{\partial c}{\partial t} = K \frac{\partial^2 c}{\partial x^2}$$

or again in terms of mass

$$\frac{\Delta M}{\Delta t} = KA \frac{\Delta c}{x}$$

where:

$\Delta c$ = concentration gradient within a channel

$x$ = channel length, and

$K$ = diffusion coefficient

The diffusion coefficient has a dimension of length squared over time and can be defined by the following equation:

$K = C_4/U/R$

where:

$C_4$ = a constant

$U$ = mean channel velocity, and

$R$ = hydraulic radius of channel.

As currently programmed, a maximum of six constituents can be handled simultaneously in the FWQA model. They may be either conservative or nonconservative and may be interrelated in any mathematically describable fashion. Recent modifications have enabled this model to quantitatively consider terms other than carbonaceous BOD oxidation and reaeration in the DO budget. For example, nitrification, benthic oxygen demand, and phytoplankton photosynthesis and respiration have also been included.

The model will compute constituent concentrations throughout the system by means of a numerical integration solution of the above finite difference equations describing advection and diffusion as well as those expressing degradation and the constituent's other sources and sinks. While maintaining mass continuity, the solution proceeds from channel to channel and junction to junction performing the appropriate transfers over a specified time step.

In order to minimize "induced dispersion" or numerical mixing, ample consideration should be given to the network layout and to selection of the time step. Ideally, the ratio of fluid displacement ($U\Delta t$) to the channel length ($x$) should approach unity.

# CHAPTER V

# MATHEMATICAL MODEL SIMULATIONS OF 1969-1970 DYE RELEASES

## A. THOMANN MODEL

### 1. Simulations and Verification

#### a. Potomac Dye Study

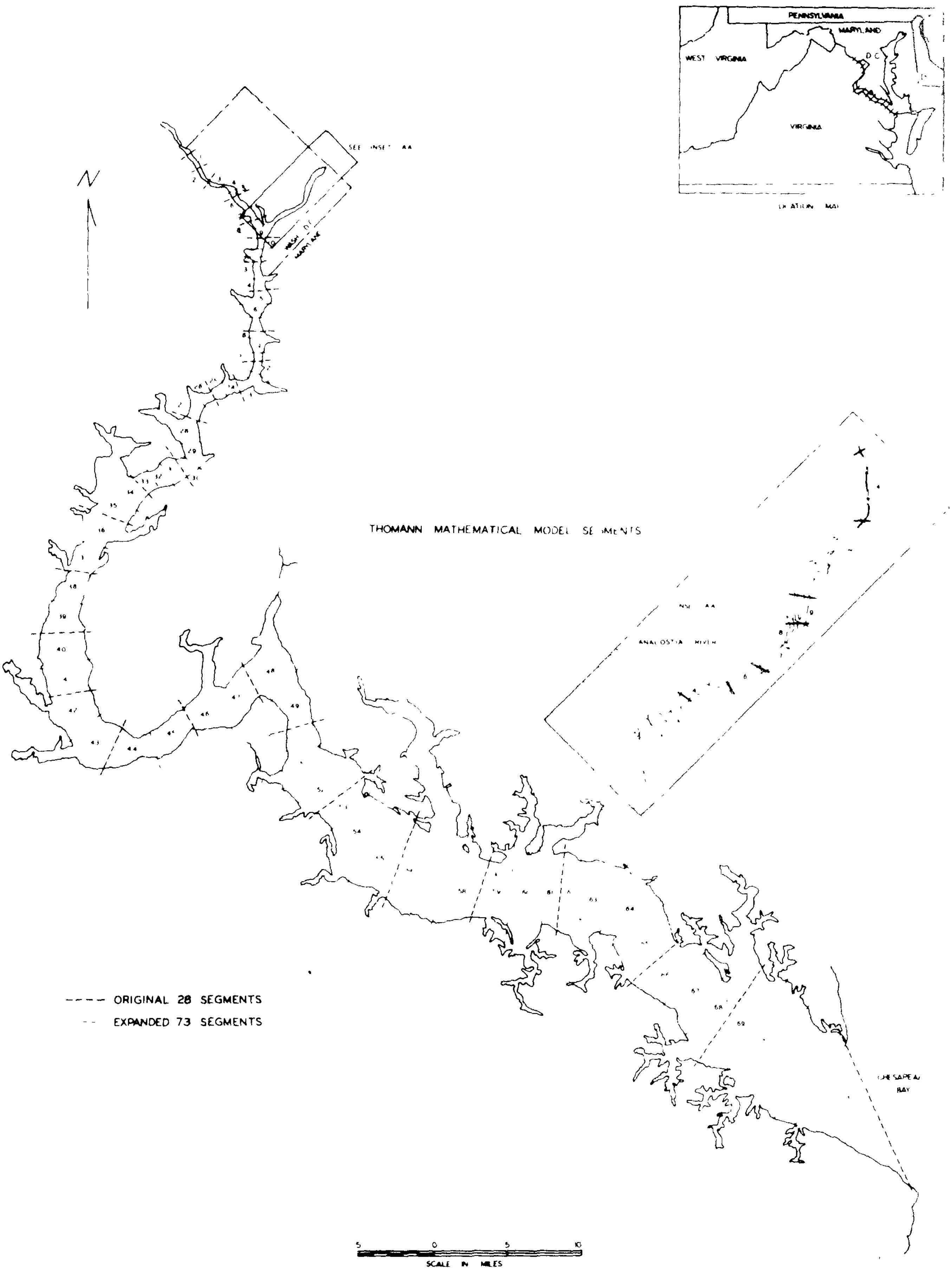
It should be noted at the outset that all mathematical model verifications involving the 1969 dye release data were based upon a dye loss rate of 0.03 per day as computed in Section A-3c of the Appendix. While other values for loss rate were considered in the Thomann and Dynamic Estuary models, the most favorable output was obtained with the 0.03 per day rate. Moreover,since neither background nor boundary data were collected prior to this dye study, the upper and lower boundary concentrations as well as a uniform background concentration of 0.1 ppb were arbitrarily specified in both models to compensate for differences between observed and discharged dye quantities. An evaluation of the sampling data collected from areas where dye was nonexistent and from background data collected during the 1965 Potomac dye study provided some insight into the magnitude of these concentrations.

The expanded segmented network used for the Potomac Estuary Thomann Model is shown in Figure V-1. Model simulations discussed in this section were made using the upper 35 segments between Chain Bridge and Mattawoman Creek.

During the simulation and verification studies, special consideration was given to the following:

1) Advection factors ($\phi$, $\alpha$), and

2) Dispersion coefficient (K).




# POTOMAC ESTUARY

FIGURE V-1

As described previously, the advective proportionality factors are used to determine the constituent concentration at a segment interface as a function of the concentrations in the adjoining segments. This concentration, when multiplied by a net flow across the interface, yields the quantity of constituent advected from one segment to another. Theoretically, $\alpha$ must range between 1.0 (nontidal or pure advection system) and 0.5 (pure tidal system with no net advective flow). In the original Thomann time-dependent model, $\phi$ was computed from the ratio E/Q, where E is the eddy exchange coefficient ($ft^3$/day) and Q is net flow and $\alpha$ was equal to 1 - $\phi$. Since there was no stipulation on the magnitude of $\alpha$, a program modification was made to maintain its value between these specified limits. A sensitivity analysis of $\alpha$ on model predictions is presented in Chapter VI.

The major problem involved with verifying the Thomann Model was estimating the longitudinal dispersion coefficient (K). This is a complex parameter affected by (1) freshwater inflow rates, (2) salinity gradients, (3) estuary geometry, and (4) tidal conditions.

The relationship between freshwater flow rates and dispersion coefficients is presented in Chapter VI. Salinity has a very pronounced effect on dispersion due to density gradients causing significant changes in the boundary shear velocity distribution. As reported by Harleman [7], dispersion coefficients calculated for freshwater and high salinity areas in a constant area estuary (Rotterdam Waterway) were 0.5 $mi^2$/day and 40 $mi^2$/day respectively.

The geometry of the channel and the tidal conditions also affect the extent of dispersion although quantitative relationships among the three have not been determined in this report. A sensitivity analysis of the dispersion coefficient in the Thomann Model is presented in Chapter VI.

In an attempt to verify the Thomann Model, several runs were made using the 1969 dye release data, each with different dispersion coefficients. The most favorable agreement between observed and simulated spatial profiles was noted utilizing the coefficients shown below:

| Segment Numbers | Time Period: November 1-5 | Time Period: November 6-30 |
|---|---|---|
| 1 - 13 (upstream of discharge) | K = 2.0 | K = 3.0* |
| 14 - 37 (downstream of discharge) | K = 3.0 | K = 5.0* |

* Dispersion coefficients were increased after November 5, to reflect the increased freshwater inflows and were increased farther downstream to reflect geometry and salinity changes.

The simulated spatial profiles obtained from the Thomann time-dependent model and the observed profiles at high- and low-slack tide are shown in Figures V-2 through V-6 for 5 different days of the study period. Major emphasis during model verification studies was placed upon closely simulating dye peaks, both spatially and in magnitude, and achieving similarly shaped curves. It was also important that simulated profiles generally fall within high- and low-slack water observed data since they do represent mean tide conditions. As can be seen in these figures, acceptable agreement between prototype and model data was generally obtained but certain discrepancies did arise. The primary shortcoming in the Thomann Model simulations appeared to be the pronounced "peaking" that occurred during the early period of the study. The simulated profiles for November 6 (Figure V-2), November 7 (Figure V-3), and November 10 (Figure V-4) show extremely sharp and somewhat greater peaks as compared to prototype data. Another difficulty encountered with some of the Thomann Model simulations was insufficient downstream movement of peak concentrations. This is evident in Figures V-3, V-5, and V-6.

A refinement in the estuary segmentation did not resolve the above problems. Increasing the dispersion coefficient lowered the peaks but the configuration of the curve was adversely affected for model verification. It appeared that all of the problems associated with simulation of dye peaks were created by the nontidal approach or the analytical mathematical solution of the basic equations employed by the Thomann Model.

A station history or temporal verification of the dye release data with the Thomann Model simulations discussed previously is shown for four selected sampling stations in Figure V-7.

## THOMANN MODEL DYE SIMULATION AND VERIFICATION

UPPER POTOMAC ESTUARY

NOVEMBER 6, 1969

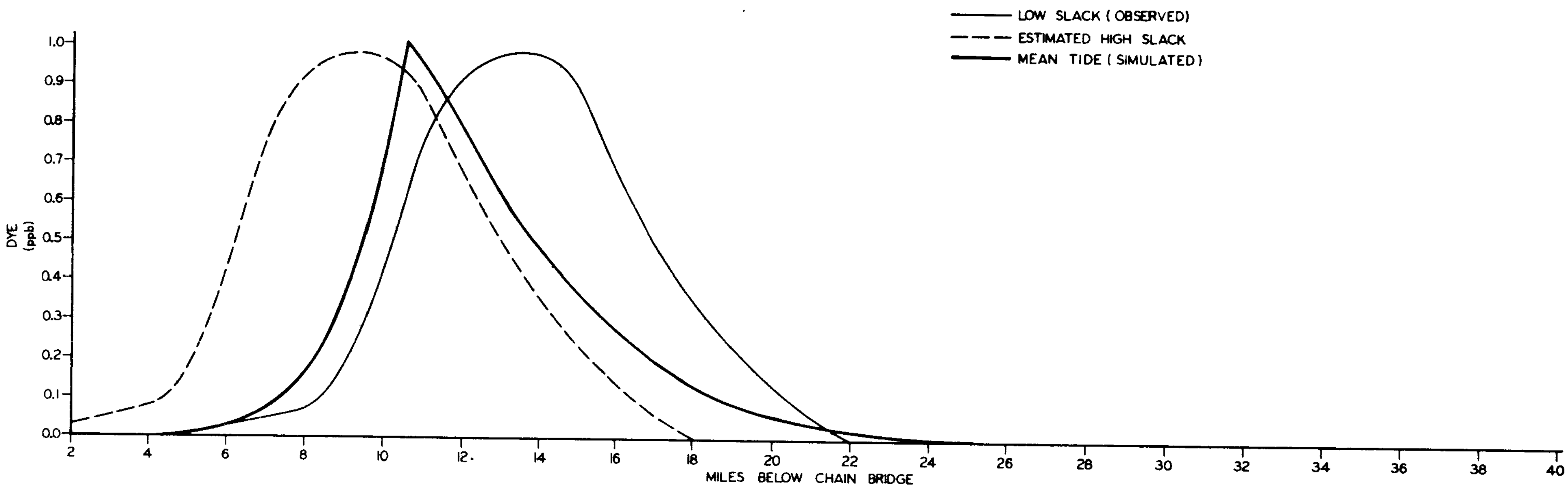



FIGURE V-2

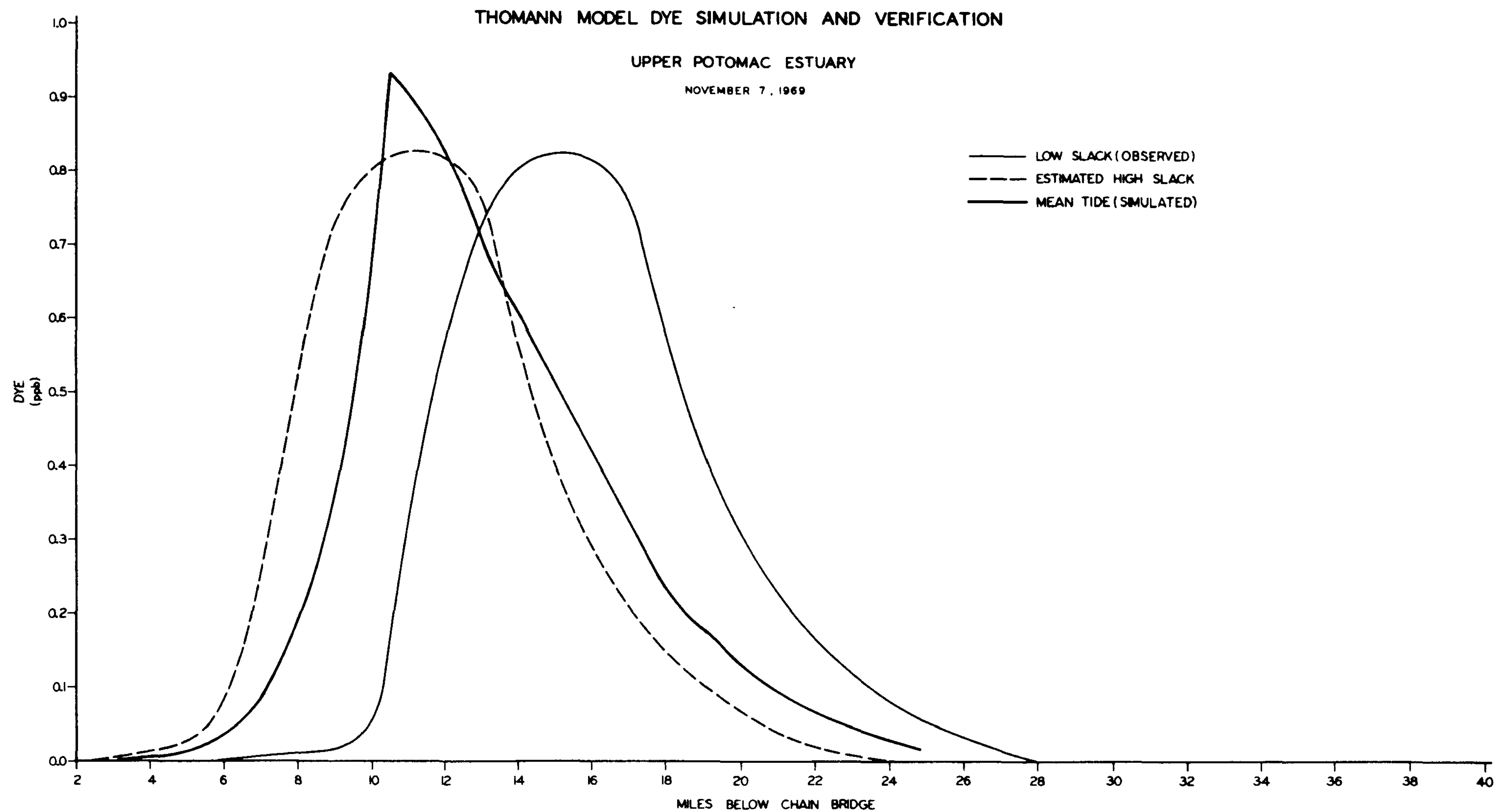

THOMANN MODEL DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 7, 1969
LOW SLACK (OBSERVED)
ESTIMATED HIGH SLACK
MEAN TIDE (SIMULATED)
DYE (ppb)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE

FIGURE V-3

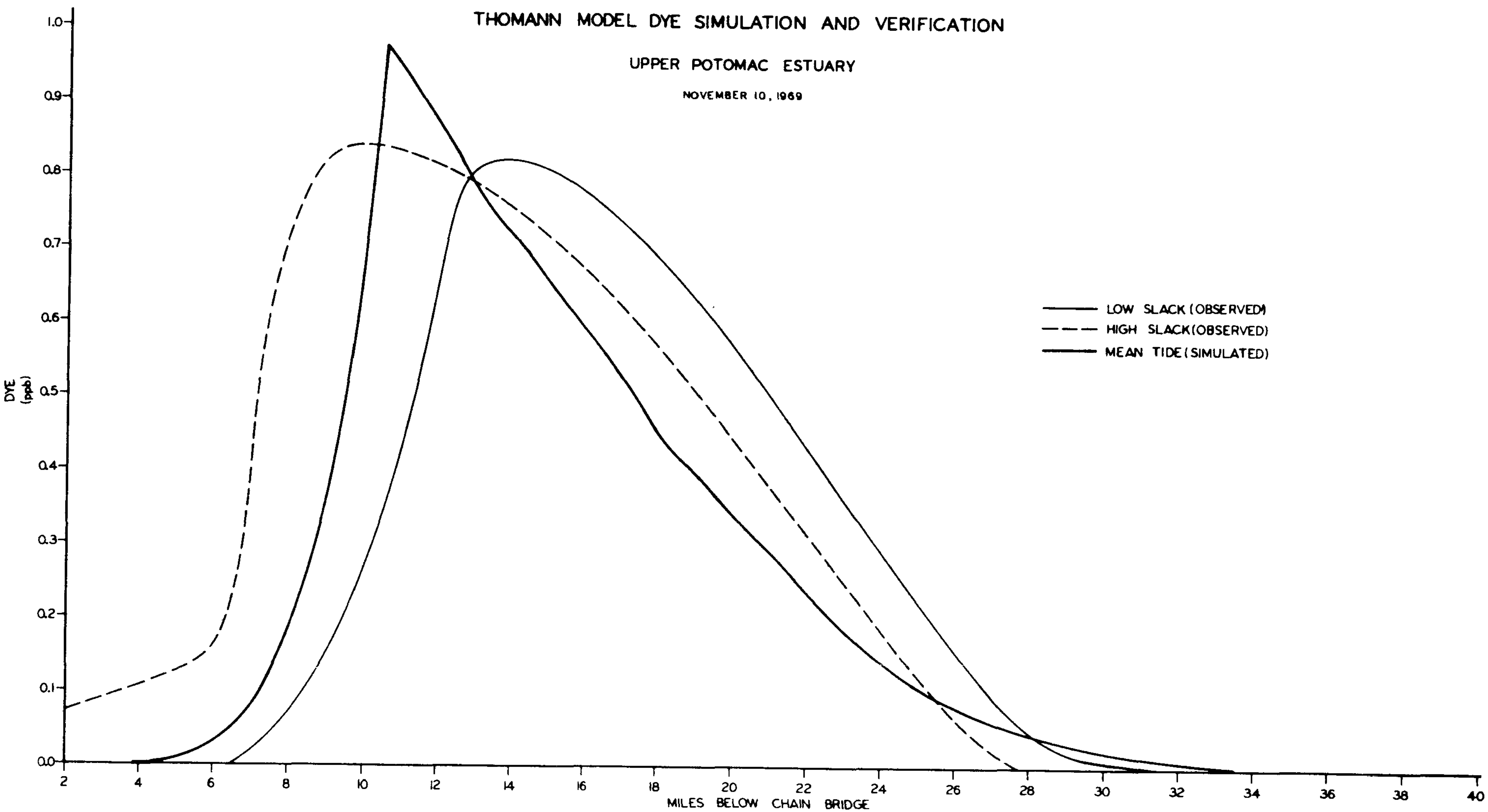

THOMANN MODEL DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 10, 1969
LOW SLACK (OBSERVED)
HIGH SLACK (OBSERVED)
MEAN TIDE (SIMULATED)
DYE (ppb)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE

FIGURE V-4

## THOMANN MODEL DYE SIMULATION AND VERIFICATION

UPPER POTOMAC ESTUARY

NOVEMBER 12, 1969

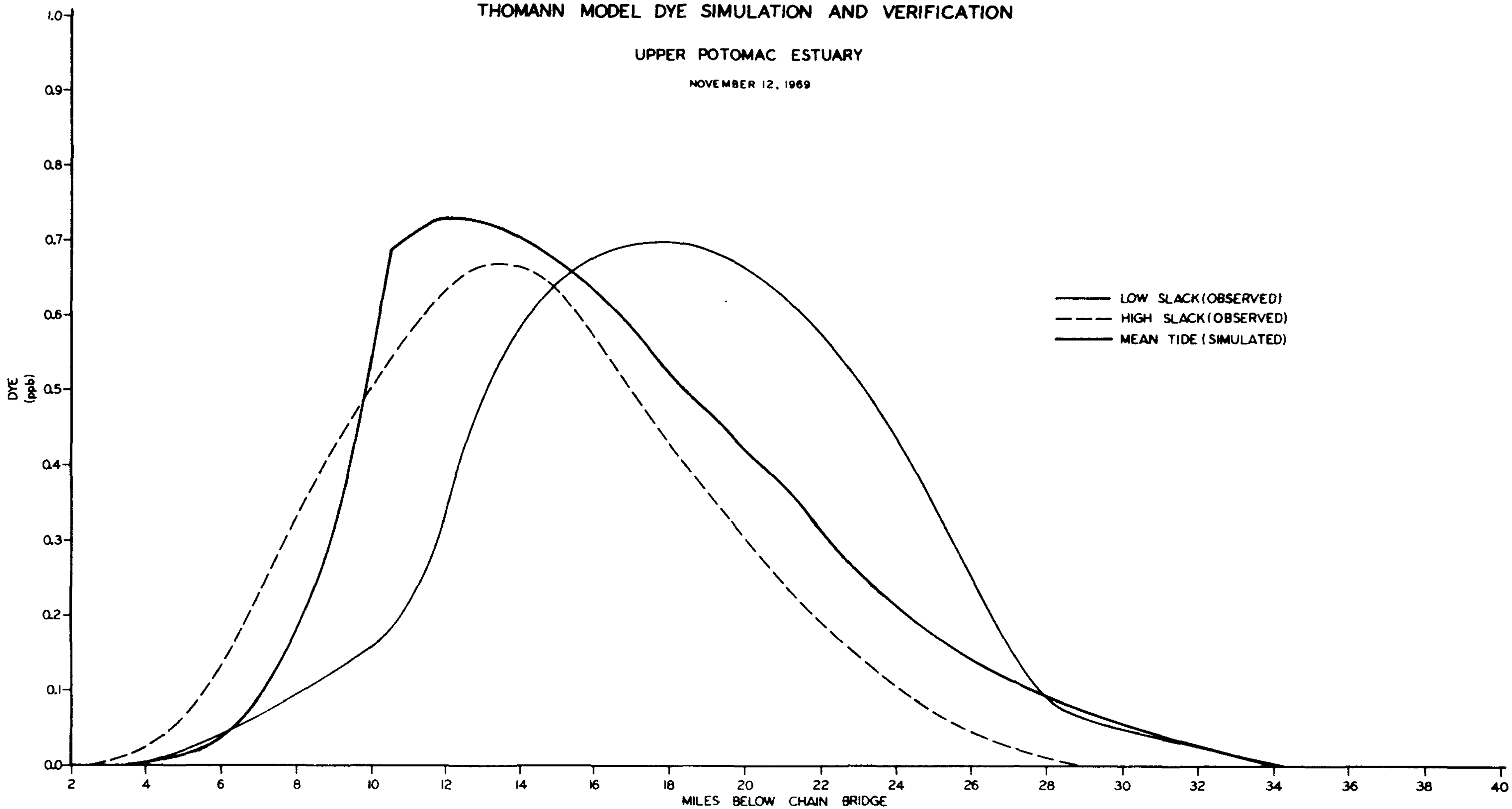



FIGURE V-5

## THOMANN MODEL DYE SIMULATION AND VERIFICATION

UPPER POTOMAC ESTUARY

NOVEMBER 17, 1969

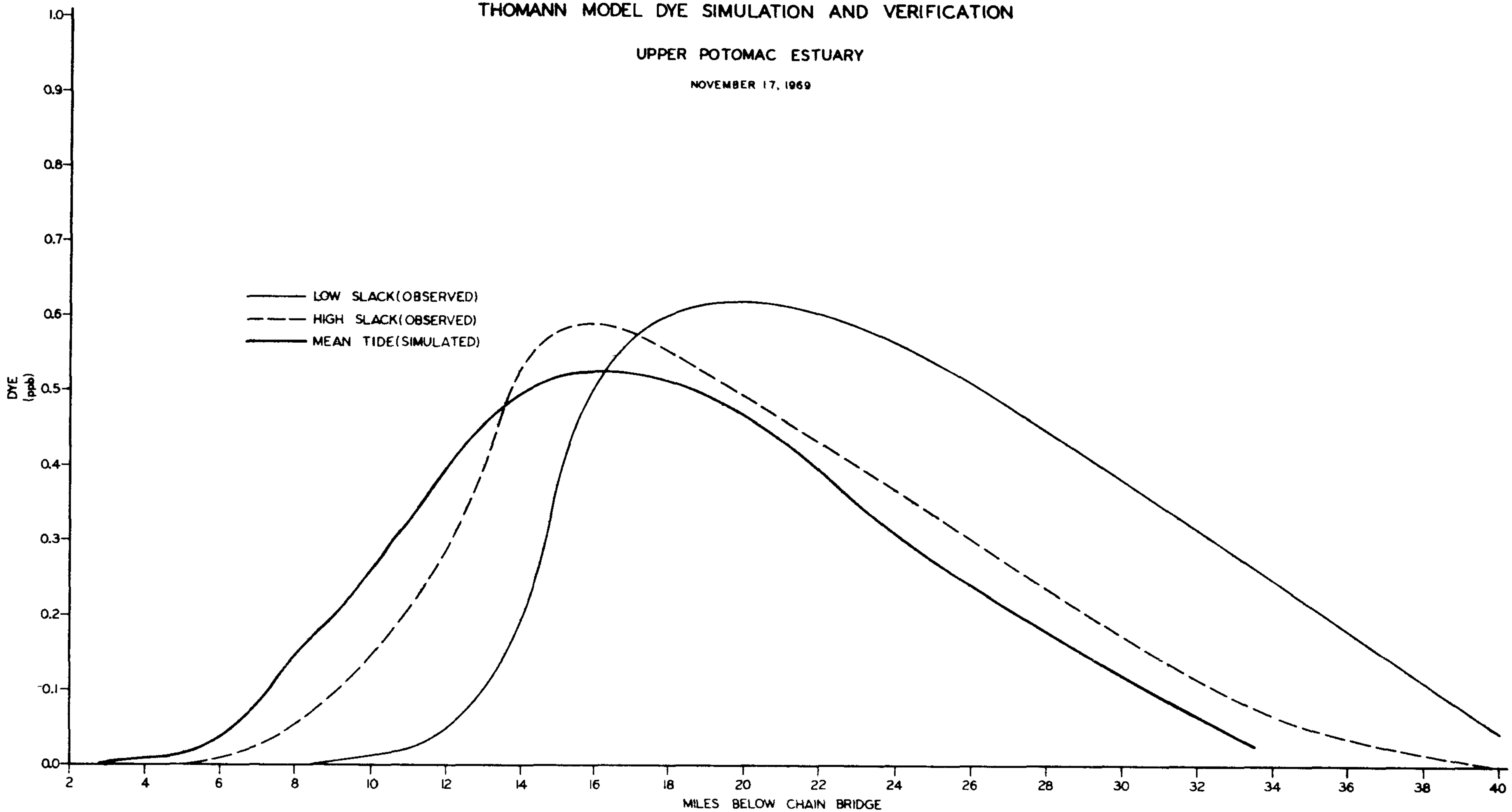



FIGURE V-6

# TEMPORAL DYE PROFILES
## UPPER POTOMAC ESTUARY
THOMANN MODEL

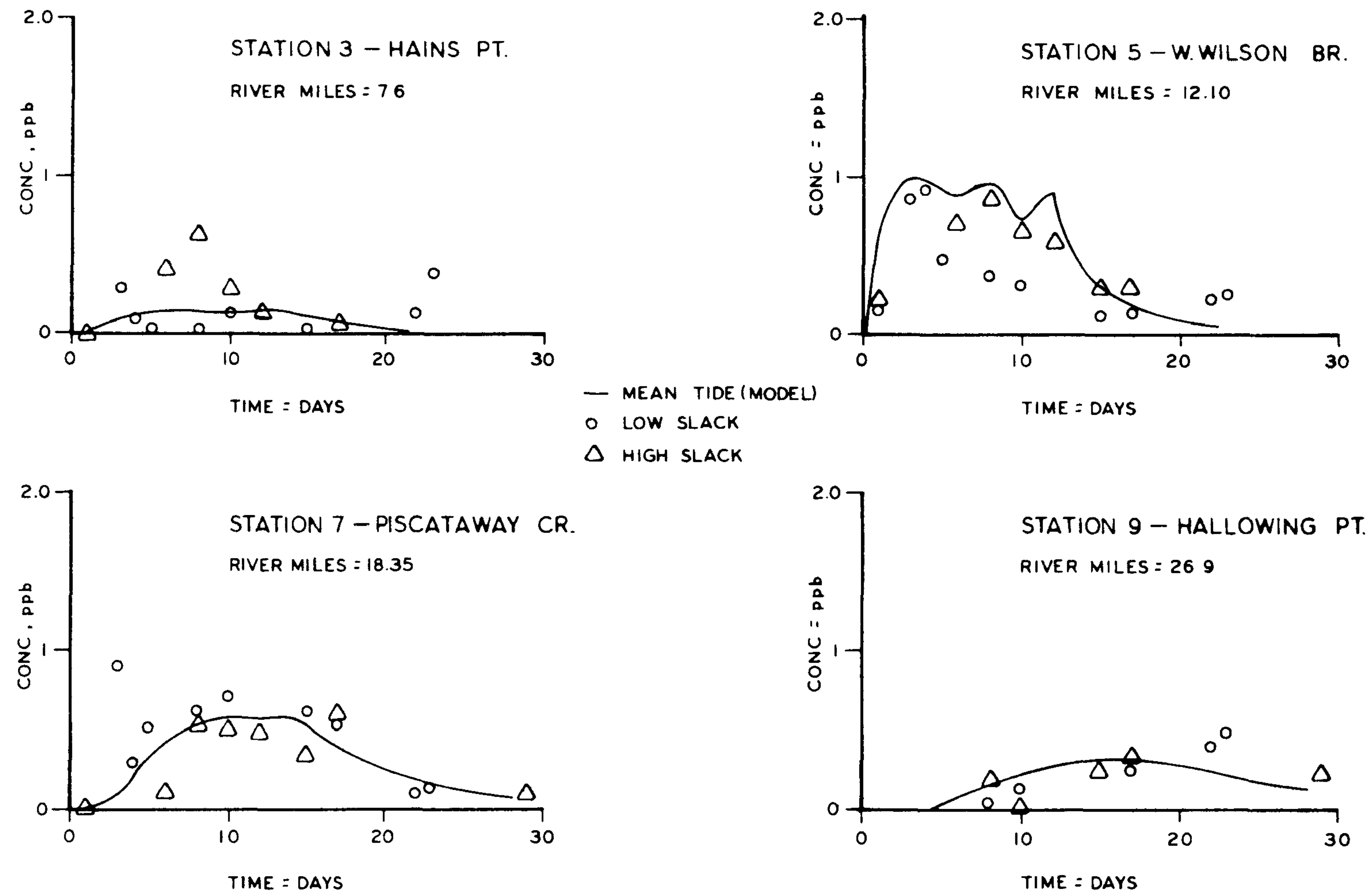



FIGURE V-7

b. Anacostia Dye Study

The segmented network applied to the Anacostia tidal system for modeling purposes is presented in Figure V-1. The problem of verifying the Thomann Model based upon 1970 Anacostia dye study data was again essentially one of evaluating a dispersion coefficient to yield the best agreement between observed and simulated data. The dye loss rate was specified as 0.05 per day for all simulation runs. After several trial runs, it appeared that a K value of 0.7 $mi^2$/day produced the most satisfactory results. Attempting to vary the dispersion coefficient longitudinally or relating it to freshwater flow, as was done with the Potomac, did not seem to improve the simulated data.

Observed spatial profiles and simulated data from the Thomann Model are shown in Figures V-8 through V-12. An analysis of these figures indicates that the basic configurations of the two curves are generally similar for various times in the study, especially those portions representing the leading edge of the dye cloud. Moreover, relatively close agreement was obtained between observed and simulated peak dye concentrations insofar as magnitude was concerned. Again, a major shortcoming of the Thomann Model predictions, which can be seen in several of the figures, was an insufficient rate of longitudinal peak movement.

The net advective transport of the dye cloud's centroid was not accurately simulated with the range of dispersion coefficients investigated. As was noted with the Potomac dye study, the effects of such factors as extreme and "flashy" flow variation and unusually high or

# THOMANN MODEL DYE SIMULATION AND VERIFICATION
## ANACOSTIA RIVER

APRIL 23, 1970

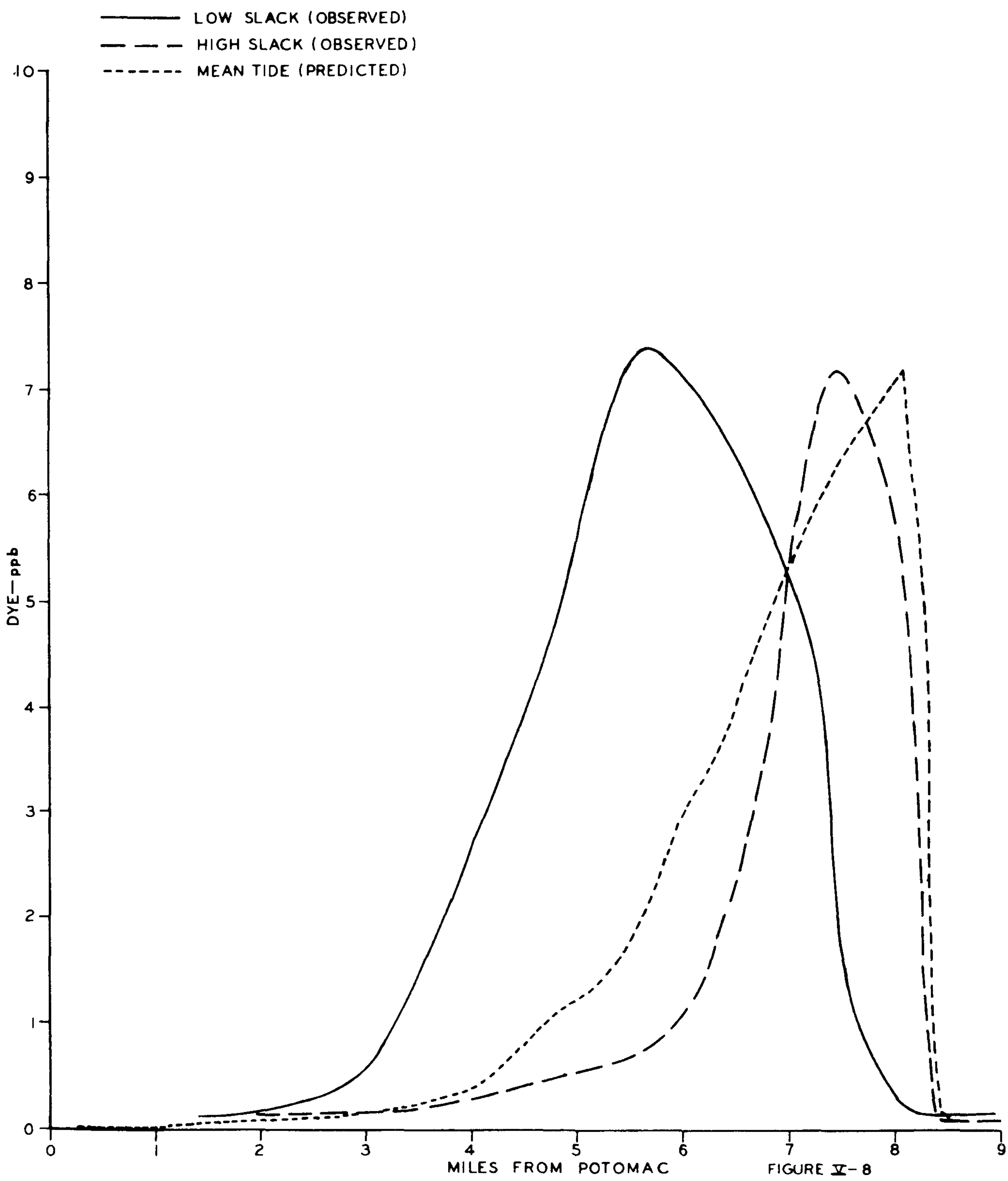



FIGURE V-8

# THOMANN MODEL DYE SIMULATION AND VERIFICATION

## ANACOSTIA RIVER

APRIL 27, 1970

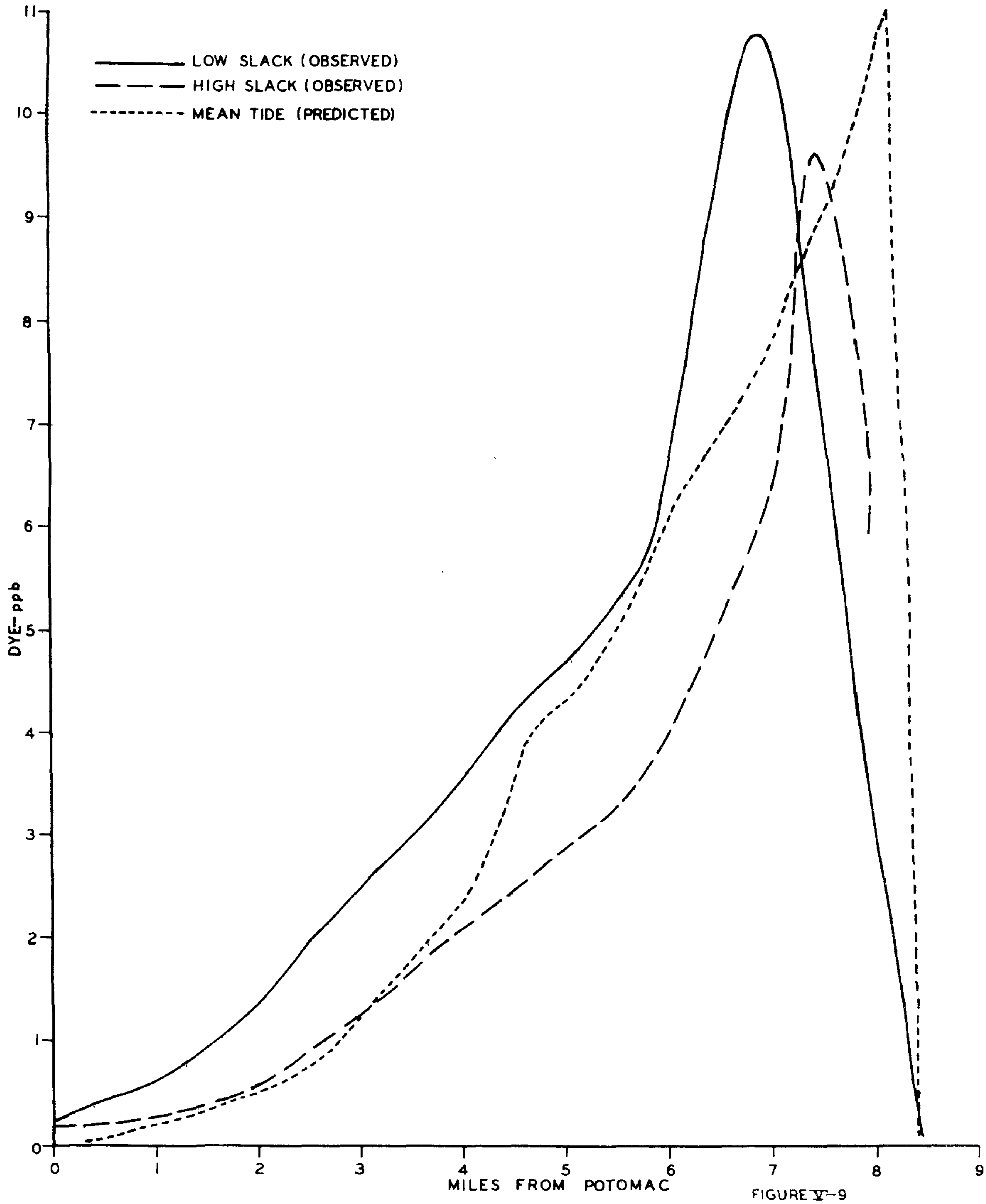



FIGURE V-9

## THOMANN MODEL DYE SIMULATION AND VERIFICATION

### ANACOSTIA RIVER

APRIL 29, 1970

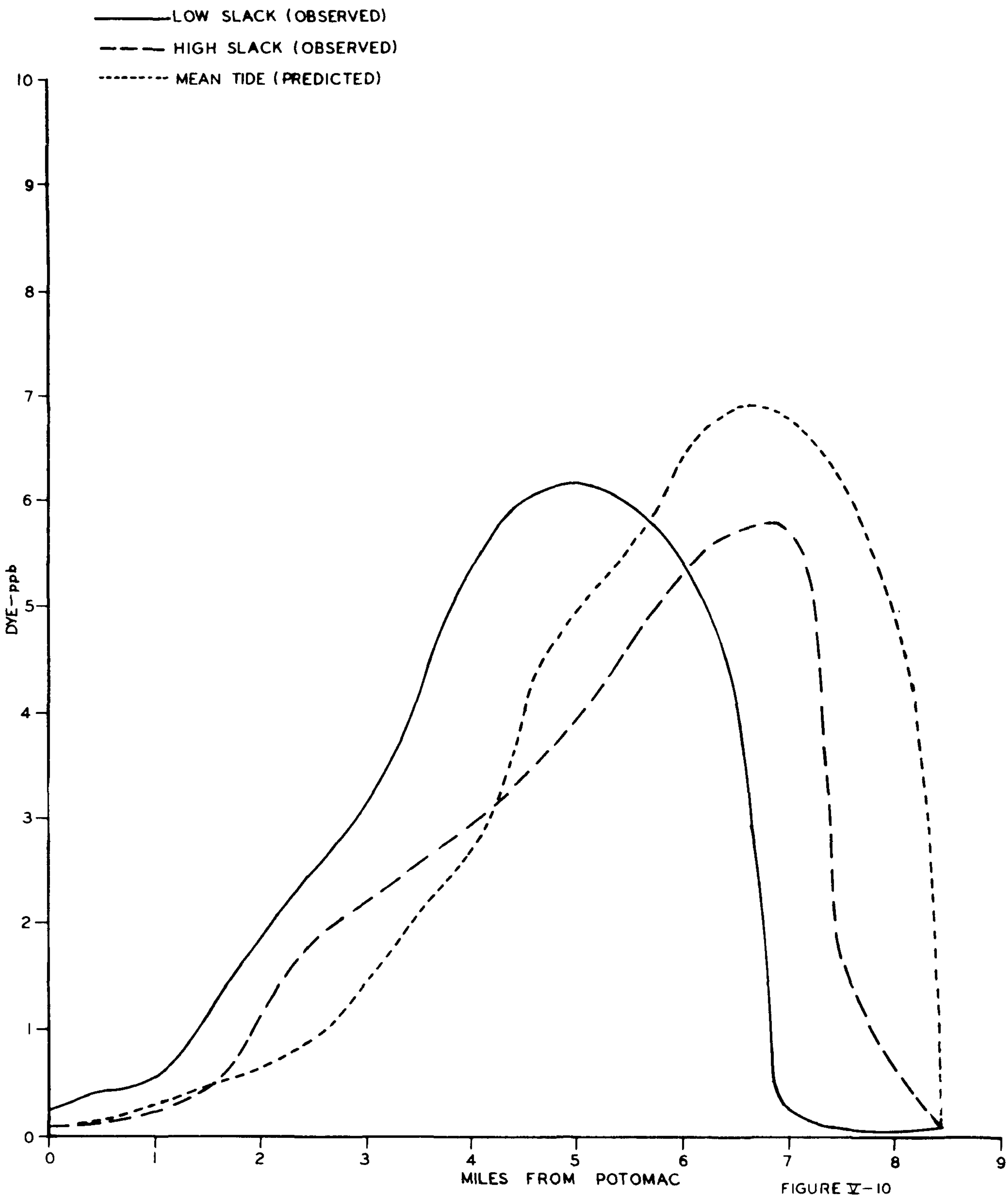



FIGURE V-10

# THOMANN MODEL DYE SIMULATION AND VERIFICATION

## ANACOSTIA RIVER

MAY 4, 1970

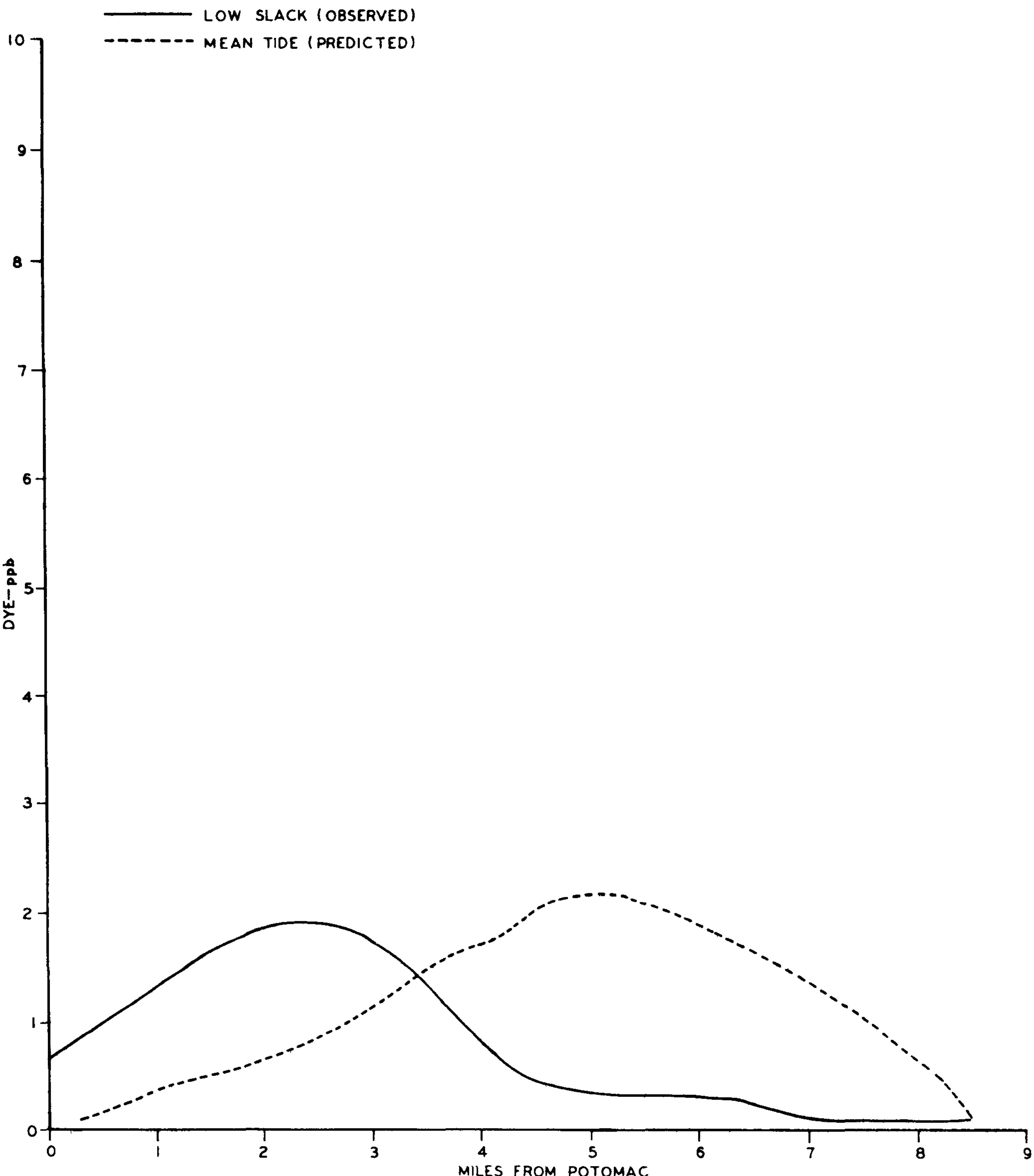



FIGURE V-11

# THOMANN MODEL DYE SIMULATION AND VERIFICATION
## ANACOSTIA RIVER
MAY 7, 1970

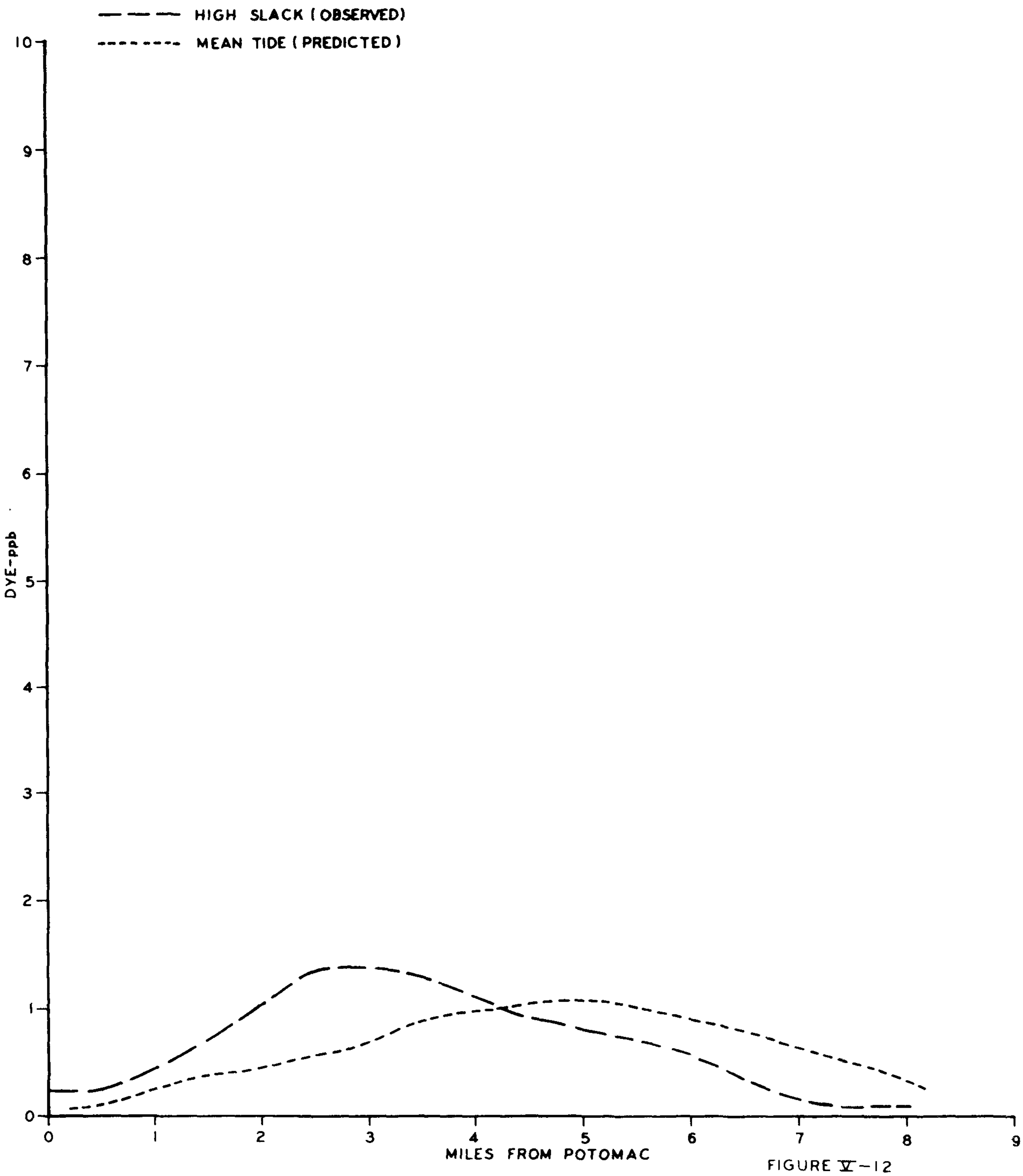



FIGURE V-12

low tides with the corresponding changes in tidal excursion and advection which generally accompany a long-term study are not adequately incorporated in the nontidal model and while the dispersion coefficient does exert considerable influence, there are limitations present.

## B. FWQA's DYNAMIC ESTUARY MODEL

### 1. Simulations and Verification

#### a. Potomac Dye Study

The network of junctions comprising the Dynamic Estuary Model for the main Potomac are basically the same as those shown in Figure V-1. The simulation data presented herein pertain to the 35 junctions upstream from Occoquan Bay.

The verification of the Dynamic Estuary Model based upon 1969 dye study data initially required a reliable representation of the hydrodynamics during the study period. For sake of convenience, only two hydraulic conditions were simulated. The period from November 1-5 assumed an average flow of 1,886 cfs. The remainder of November was assigned an average flow of 3,974 cfs. The actual tidal record at Piney Point, Maryland, (near the seaward boundary) was obtained from the U. S. Coast and Geodetic Survey for the month of November. A somewhat typical tide, having a period of 12.5 hours, was selected and assumed to recur continuously throughout the study period. Hydraulic runs using different Manning coefficients were tried until the simulated tidal data at Washington, including ranges and phasing, compared favorably with corresponding observed data. Predicted tidal data at intermediate stations throughout the estuary were also compared with observed data for hydraulic verification.

Insofar as the quality program is concerned, consideration was given to (1) appropriate dye loading rate, and (2) dispersion term $C_4$*. Since dye loading rates were computed for each 4-hour interval of the 13-day release period, a similar procedure was used in the model. Simulations were based on varying the dye concentrations in the effluent every 4 hours until the 13th day when the dye release was shut off entirely. While the dispersion coefficient is relatively unimportant in this model as compared to the Thomann Model, the initial value of 2.5 used for $C_4$ was considered too low and was subsequently increased an order of magnitude to 25. For a tidal velocity of 1.5 ft/sec and a channel depth of 15 feet, a $C_4$ of 25.0 would translate to a dispersion coefficient of 1.7 $mi^2$/day. This value yielded better results and additional refinement in the dispersion coefficient did not appear warranted.

The simulated dye profiles obtained from the Dynamic Estuary Model for the conditions and assumptions described above are shown in Figures V-13 through V-16. Also shown are high- and low-slack water sampling data for the same 4 days of the study period. The spatial profiles depicted in these figures indicate that the model was predicting dye movement and concentration buildups satisfactorily. While simulated

* As indicated previously, the actual dispersion coefficient is computed internally from the relationship

$$E = C_4 \; U \; d$$

where $C_4$ is a constant, U is the mean velocity, and d is the depth

FWQA DYNAMIC ESTUARY MODEL
DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 6, 1969

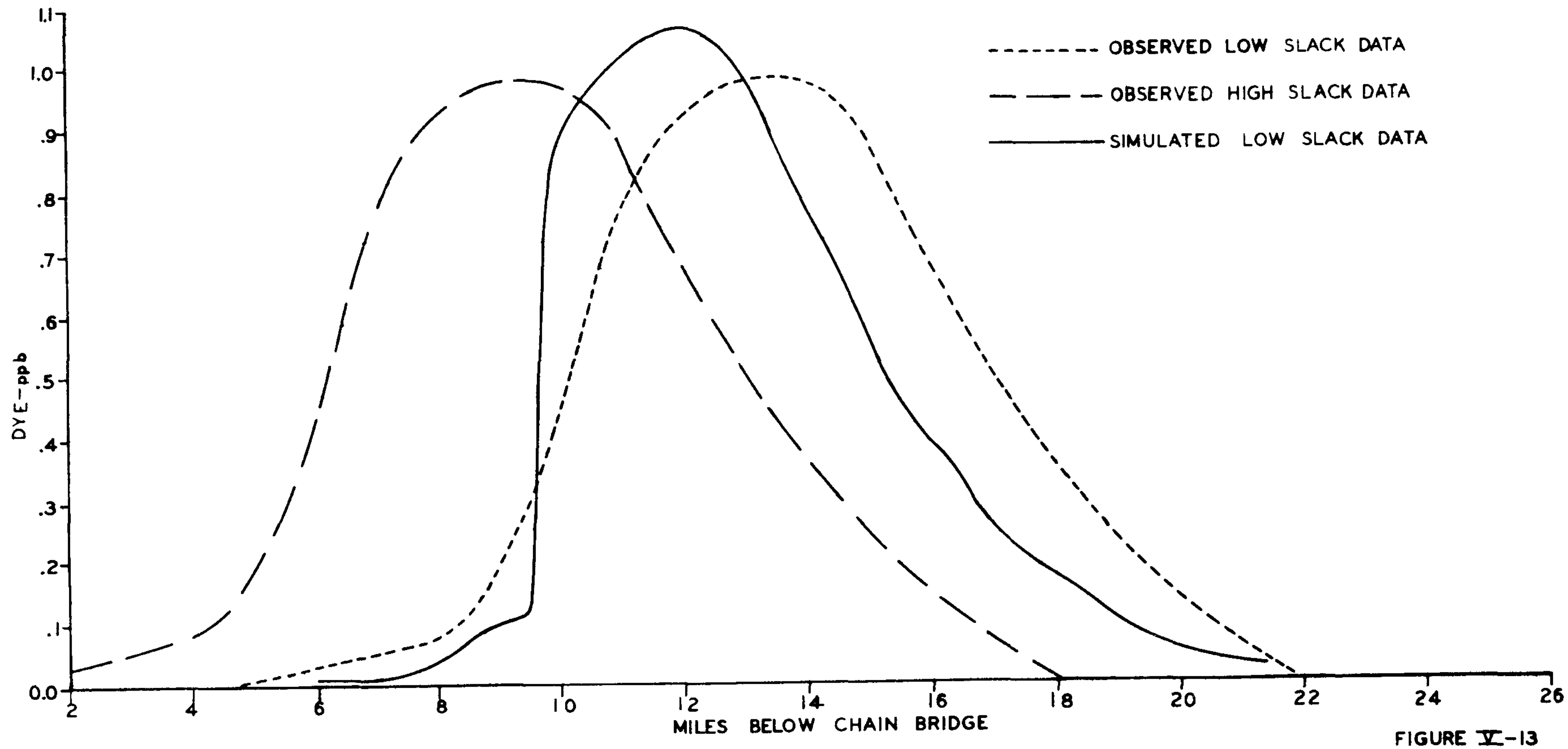



FIGURE V-13

FWQA DYNAMIC ESTUARY MODEL
DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 10, 1969

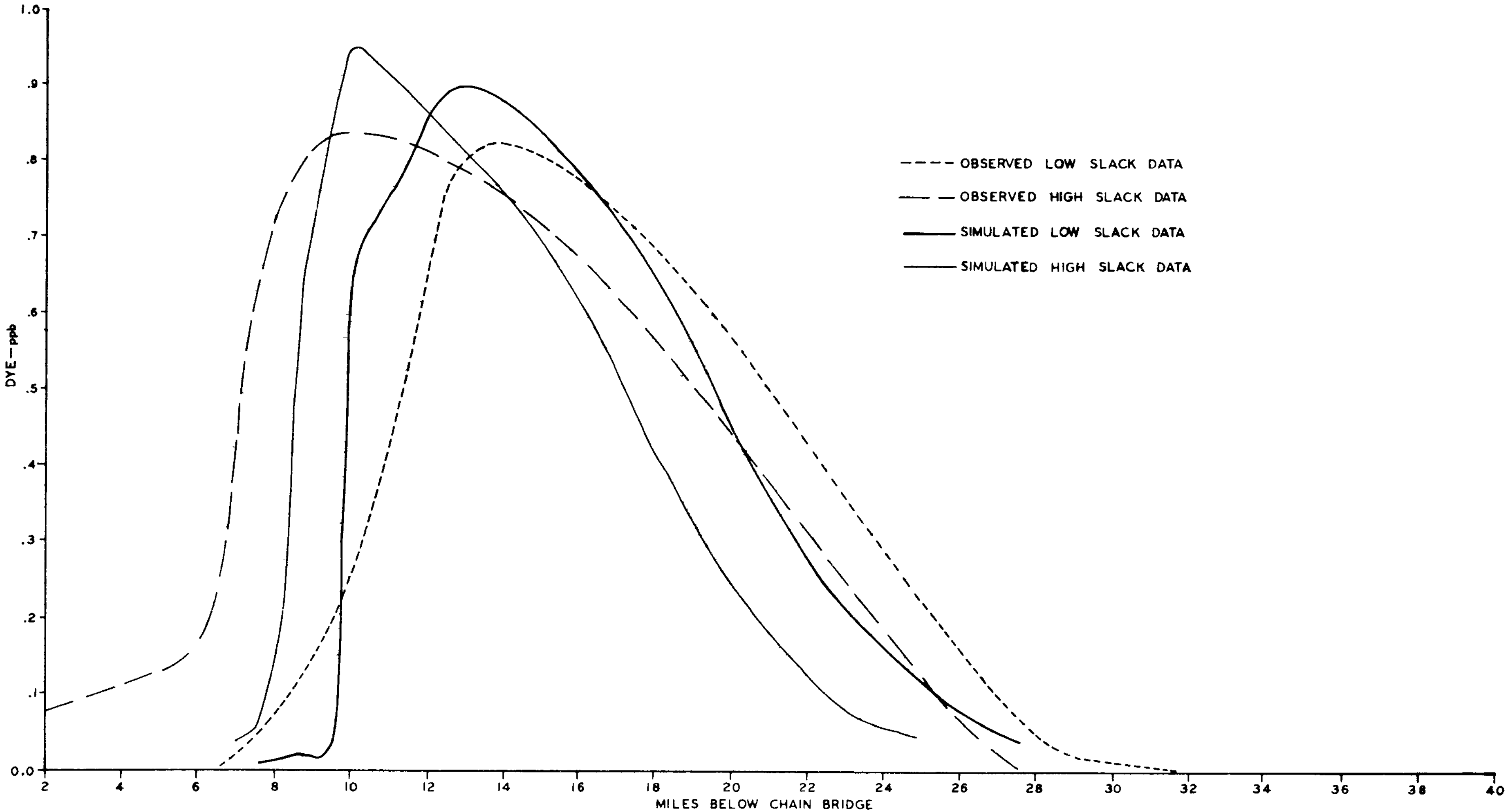



FIGURE V-14

FWQA DYNAMIC ESTUARY MODEL
DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 12, 1969

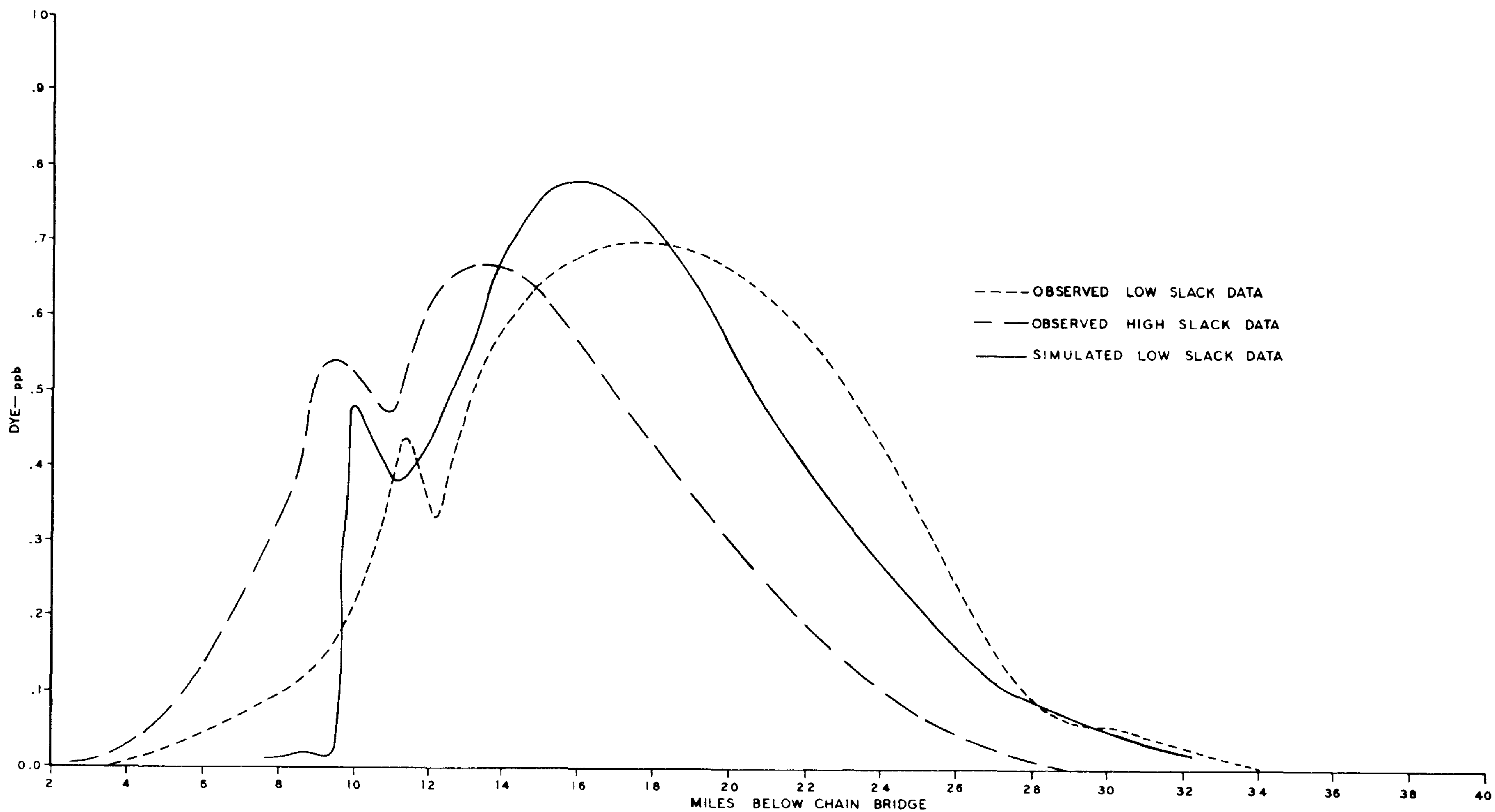



FIGURE V-15

FWQA DYNAMIC ESTUARY MODEL
DYE SIMULATION AND VERIFICATION
UPPER POTOMAC ESTUARY
NOVEMBER 17, 1969

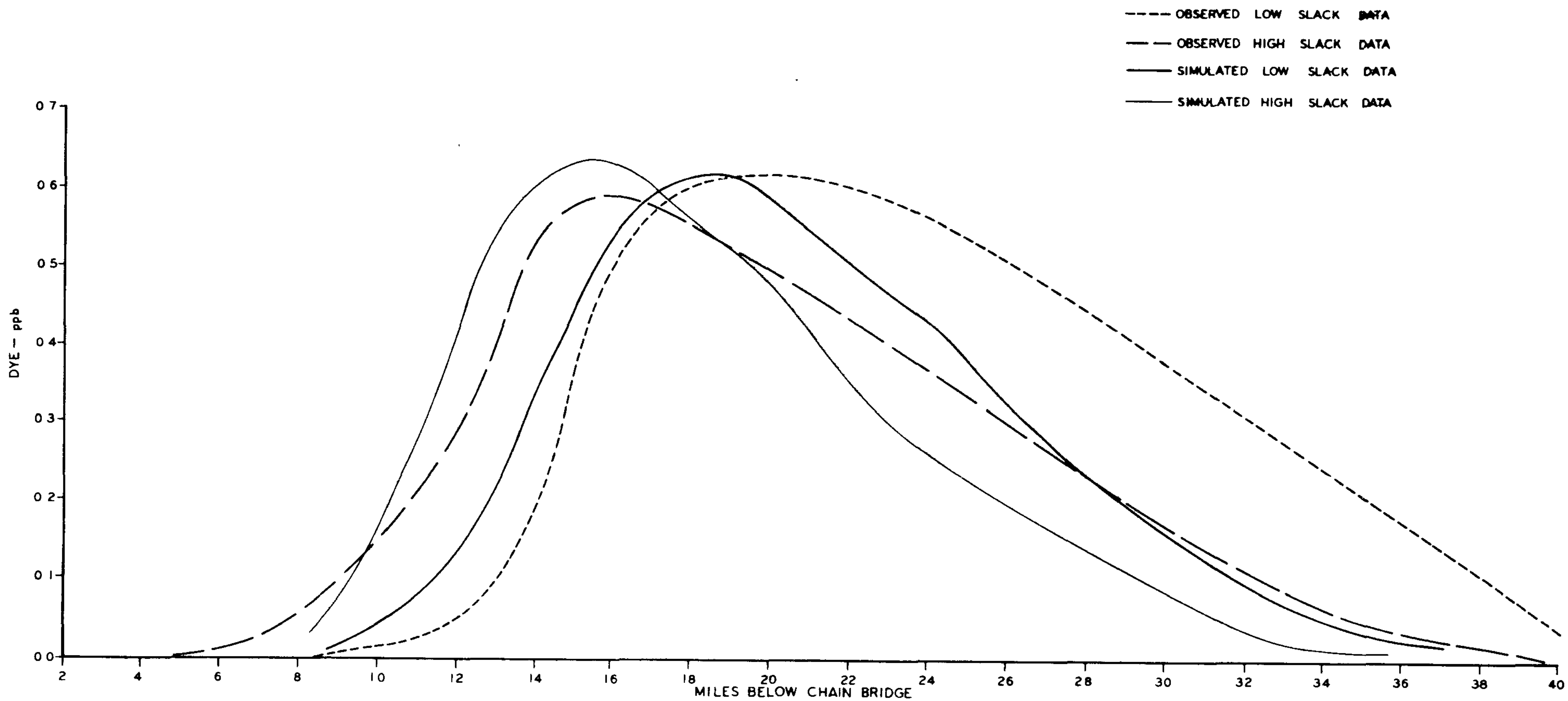



FIGURE V-16

TEMPORAL DYE PROFILES
UPPER POTOMAC ESTUARY
FWQA DYNAMIC ESTUARY MODEL
(HIGH WATER SLACK DATA)

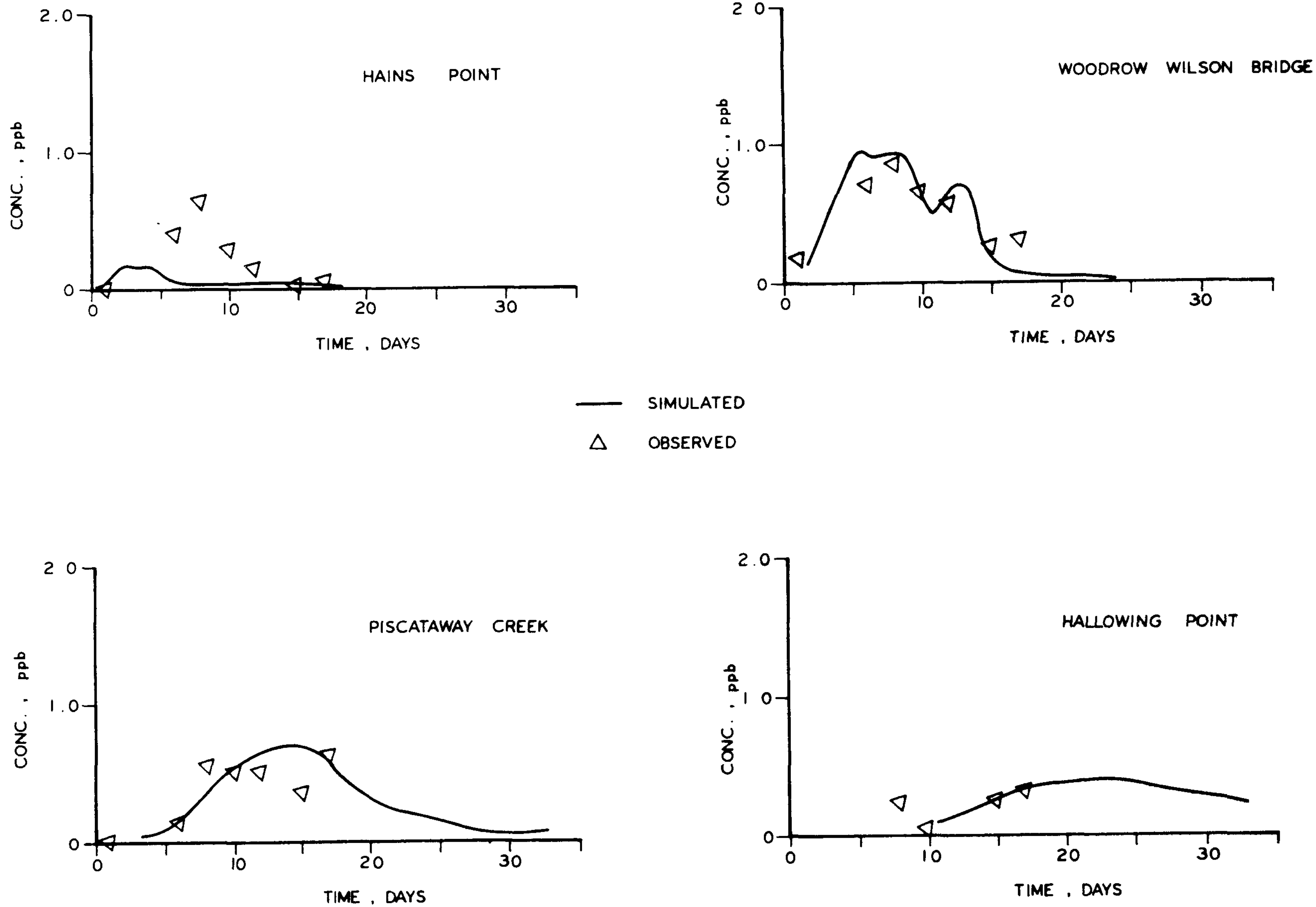



FIGURE V-17

# TEMPORAL DYE PROFILES
# UPPER POTOMAC ESTUARY
## FWQA DYNAMIC ESTUARY MODEL
(LOW WATER SLACK DATA)

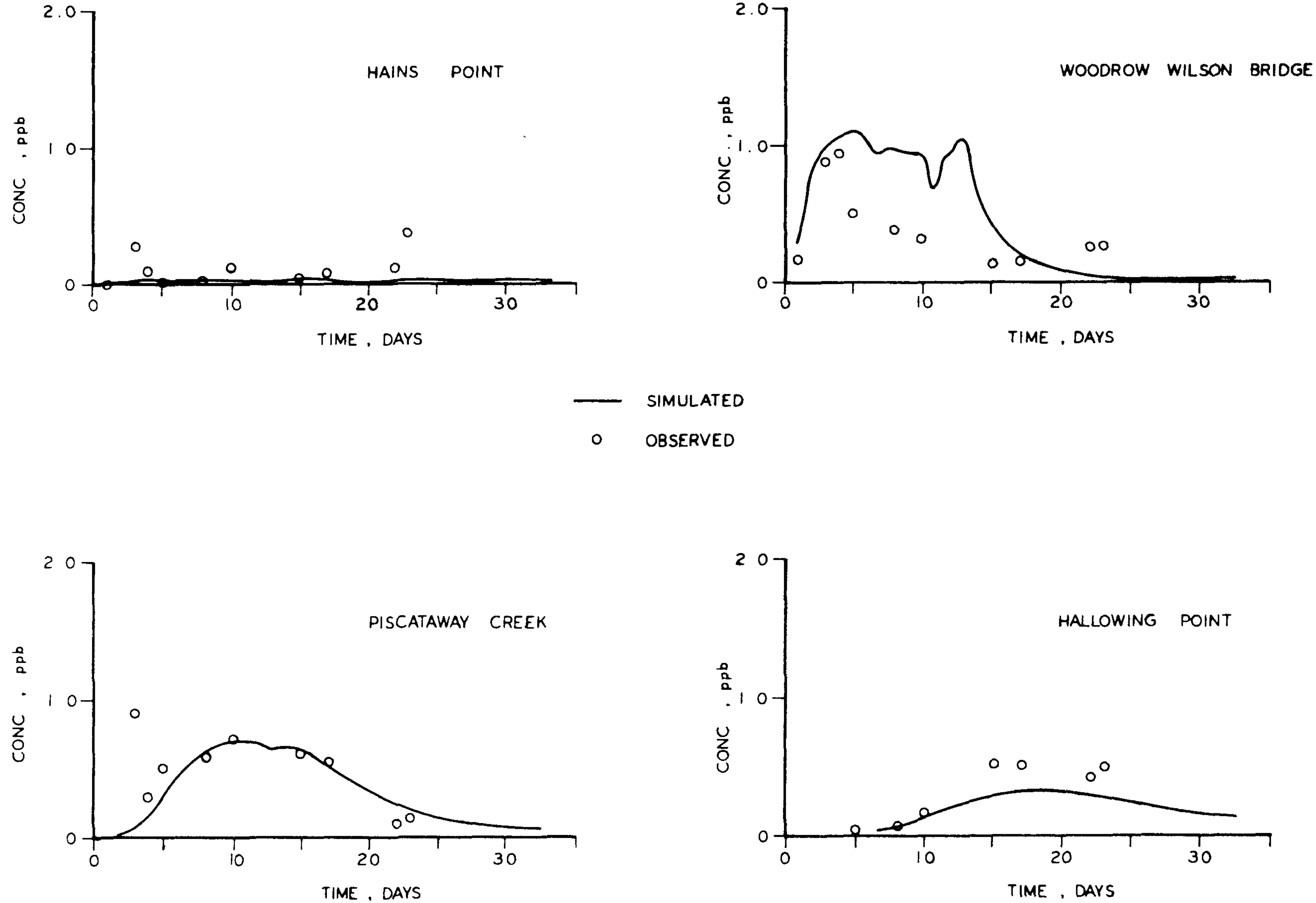



FIGURE V-18

maximum dye concentrations were generally higher than prototype data, they were not characterized by the pronounced "peaking" which occurred with Thomann Model simulations and their spatial position agreed favorably with observed data. The other consistent difference between the observed and simulated profiles was the insufficient downstream dye transport by the model over a given time interval. It is interesting to note that a "real-time" solution permitted the effects of a short term dye slug to be simulated as can be seen in Figure V-15. Considering the difficulty of model verification by a comparison of spatial profiles for specific slack-tide periods, the Dynamic Estuary Model has demonstrated the capability to simulate the hydraulic and quality behavior in the Potomac acceptably utilizing 1969 dye study data. Similar agreement between model and prototype data can be shown when temporal variations are considered. Data of this type (station histories) are presented in Figures V-17 and V-18.

b. Anacostia Dye Study

The physical network of junctions applied to the Anacostia tidal river for the Dynamic Estuary Model is shown in Figure V-1. This network is identical to the one used in the Thomann Model and is comprised of 15 junctions with lengths averaging approximately 1/2 mile.

For all hydraulic simulations during the study period, an average Potomac tide (12.5-hour period) was estimated from data recorded by the U. S. Coast and Geodetic Survey at Piney Point. Some degree of hydrodynamic verification was lacking due to the absence of tidal gaging stations in the Anacostia River. Visual observations of the tidal range near the point of dye release and the model's tidal range predictions appeared to be of similar magnitude; however, it could not be determined whether the simulation of tidal phasing and duration of rise and fall throughout the Anacostia, or even the assumed Manning roughness coefficients were accurate.

The dye study period was divided into four separate hydraulic components as follows:

| Time Period | Average Potomac Flow (cfs) | Average Anacostia Flow (cfs) |
|---|---|---|
| April 20-28 | 30,000 | 180 |
| April 29-May 11 | 15,000 | 83 |
| May 12-18 | 7,800 | 145 |
| May 19-28 | 6,800 | 72 |

The quality program for the Anacostia study was based on a constant dye loading rate of 8.1 lbs/day, a dye loss rate of 0.05/day and a uniform background concentration of 0.10 ppb. Moreover, the dispersion term, $C_4$, was assigned a value of 25.0. The dye profiles observed during various days of the study and corresponding simulated data from the Dynamic Estuary Model are shown in Figures V-19 through V-23. While the general longitudinal dye distribution predicted by the model compared favorably with prototype data, several figures were characterized by insufficient downstream movement of simulated peak concentrations. On one occasion (Figure V-19), the magnitude of the simulated peak was excessive. A further evaluation of the input factors which may have influenced these differences such as network geometry or dye loading rates was made but with no apparent success. It appeared that a lack of tidal data during the study period may have been partially responsible, otherwise a better hydraulic representation would have been obtained. Another possible cause of the differences noted could have been the flow averaging concept used for each hydraulic simulation. This averaging may tend to disregard or minimize the effects of the "flashy" flows that occurred during the early phase of the study.

Improved agreement may have been realized in both models had transect sampling data been collected to correlate mid-channel concentrations with cross-sectional averages. Normally, the differences resulting from this omission would be especially acute near the release point where incomplete mixing could be expected and where most of the model verification difficulties were encountered.

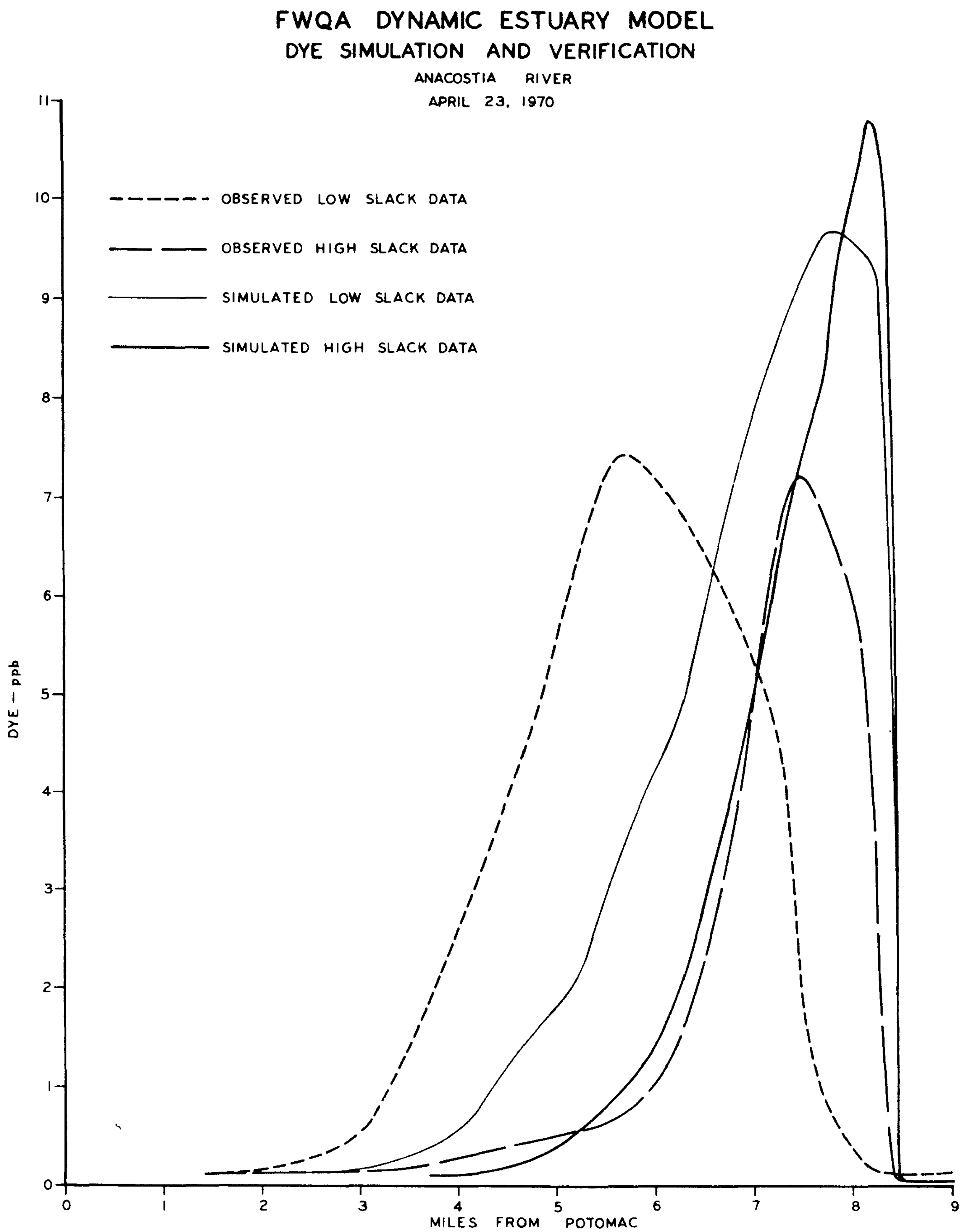

FWQA DYNAMIC ESTUARY MODEL
DYE SIMULATION AND VERIFICATION
ANACOSTIA RIVER
APRIL 23, 1970
OBSERVED LOW SLACK DATA
OBSERVED HIGH SLACK DATA
SIMULATED LOW SLACK DATA
SIMULATED HIGH SLACK DATA
DYE — ppb
MILES FROM POTOMAC
0
1
2
3
4
5
6
7
8
9
10
11

FIGURE V-19

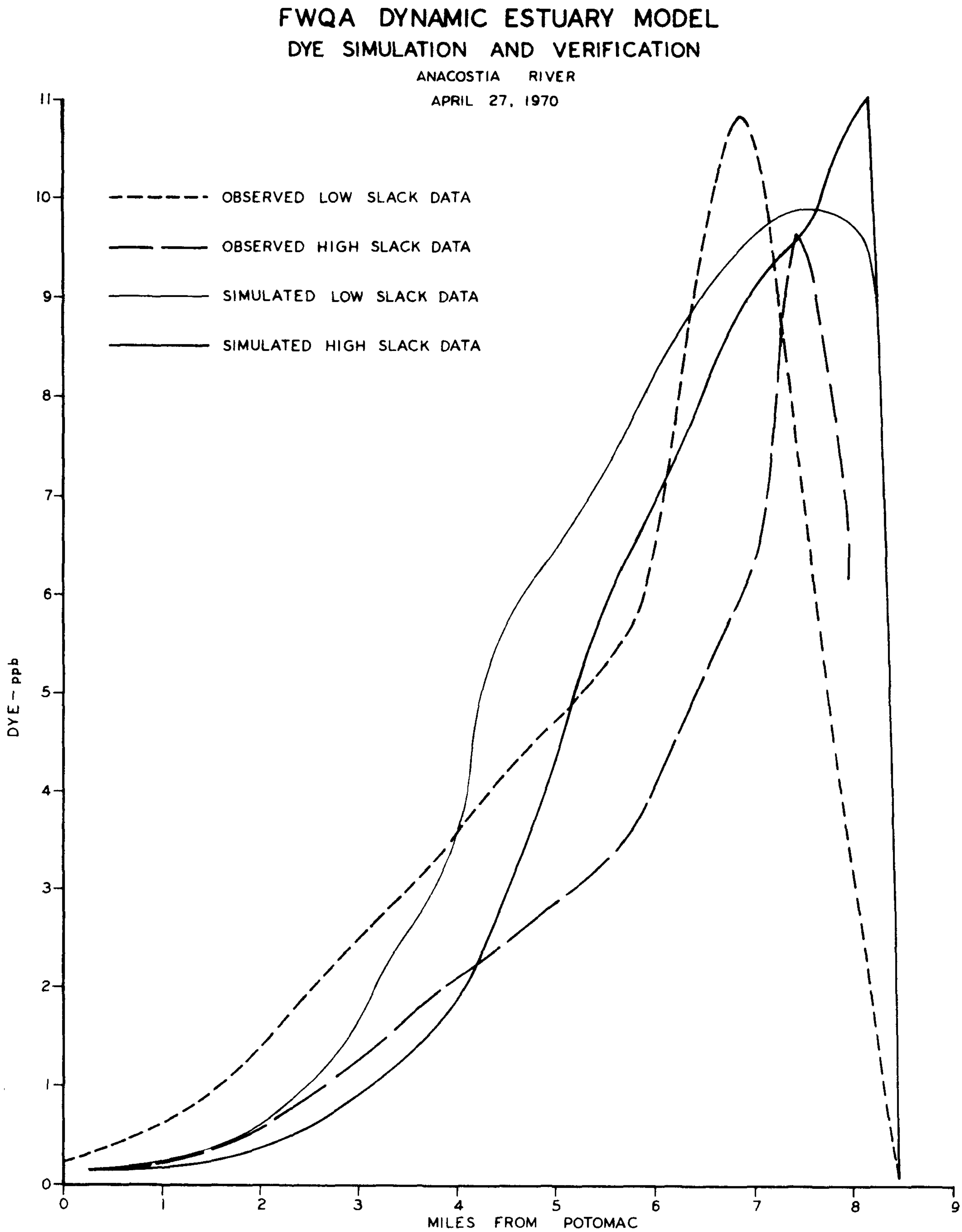

FWQA DYNAMIC ESTUARY MODEL
DYE SIMULATION AND VERIFICATION
ANACOSTIA RIVER
APRIL 27, 1970
OBSERVED LOW SLACK DATA
OBSERVED HIGH SLACK DATA
SIMULATED LOW SLACK DATA
SIMULATED HIGH SLACK DATA
DYE – ppb
MILES FROM POTOMAC
0
1
2
3
4
5
6
7
8
9
10
11

FIGURE V-20

## FWQA DYNAMIC ESTUARY MODEL
### DYE SIMULATION AND VERIFICATION
ANACOSTIA RIVER

APRIL 29, 1970

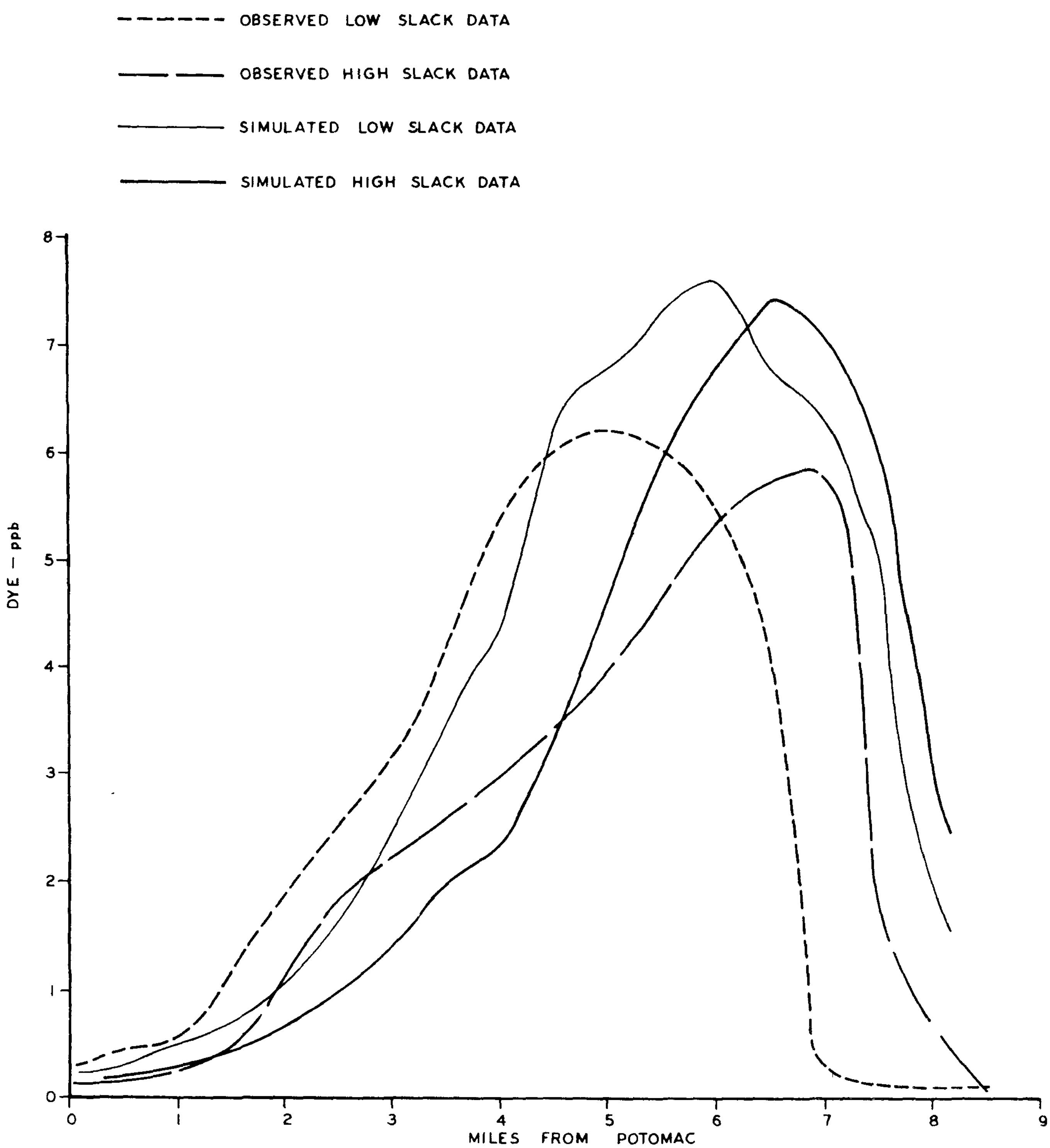



FIGURE V-21

# FWQA DYNAMIC ESTUARY MODEL
## DYE SIMULATION AND VERIFICATION
ANACOSTIA RIVER

MAY 4, 1970

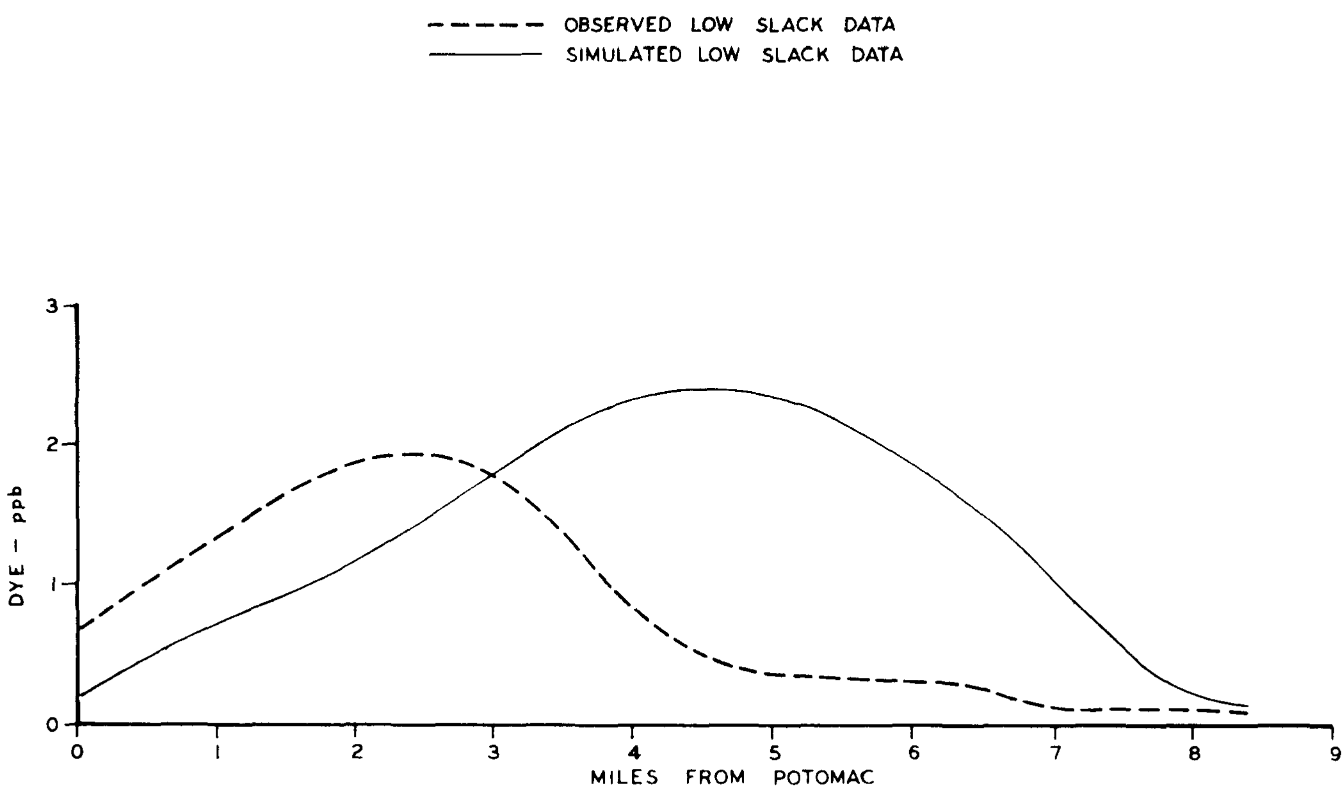



FIGURE V-22

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

ANACOSTIA RIVER

MAY 7, 1970

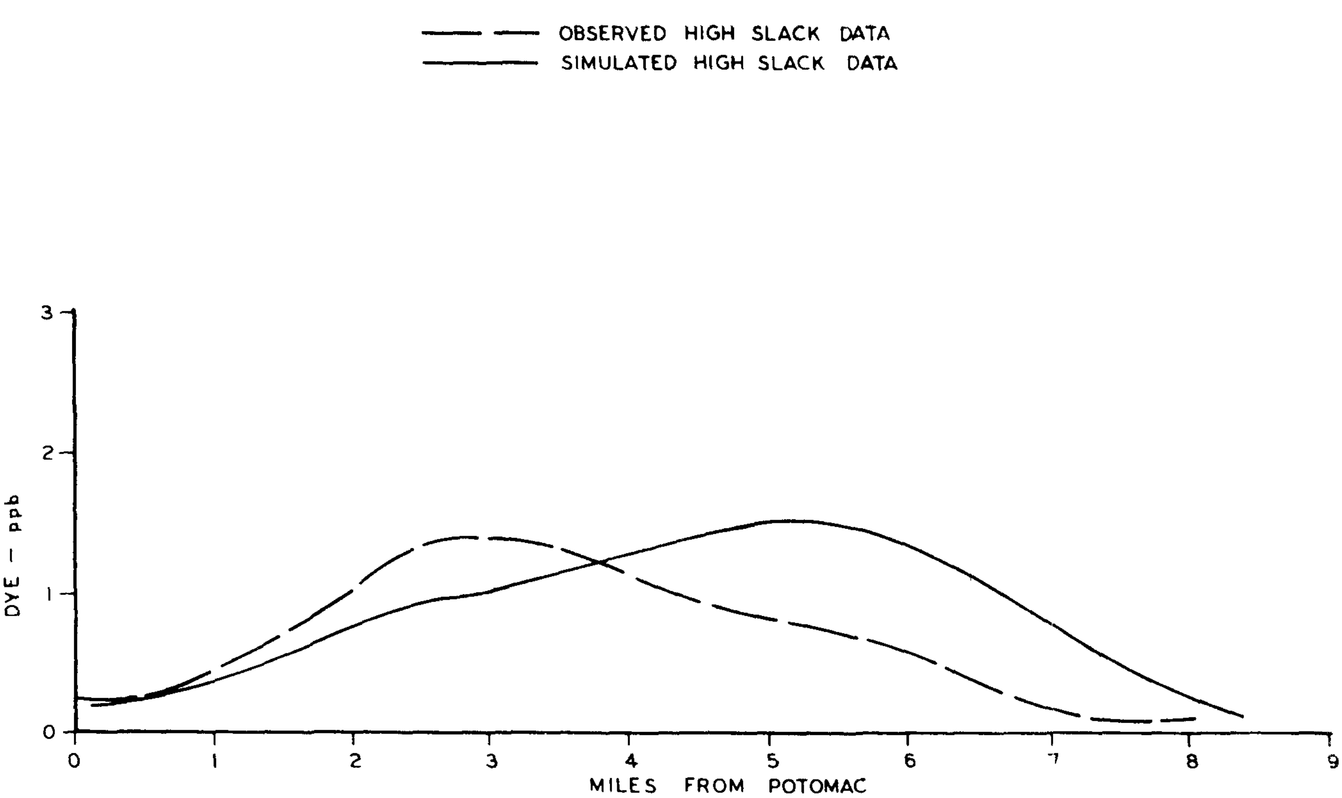



FIGURE V-23

# CHAPTER VI

# OTHER MATHEMATICAL MODEL SIMULATIONS

## A. SIMULATION OF 1969 DYE RELEASE

The 1965 dye release data were incorporated in a series of model runs for verifying both the Thomann and Dynamic Estuary mathematical models under a different hydraulic regime than that which occurred during the November 1969 dye study. The freshwater inflow rates during the 1965 study period (June 10-July 15) averaged about 2,000 cfs, or approximately one-half of the average November 1969 flows. Because of this lower flow, the appropriate dispersion coefficients required to verify the Thomann Model were expected to be significantly different.

### 1. Thomann Model

Figures VI-1 through VI-4 show the observed high- and low-slack water sampling data for various days and the corresponding simulated mean tide data using the Thomann Model. A dispersion coefficient of 2.0 $mi^2$/day was used initially when flows were relatively high, and 1.0 $mi^2$/day for the remainder of the study period when flows were much lower. Although other dispersion coefficients and different spatial variations were investigated for model verification, the above values appeared to yield the closest agreement. It should be noted that these coefficients were considerably higher than those obtained by Hetling and O'Connell [3] using an analog computer solution based on temporal or "station history" verification. Their computed dispersion coefficients varied between 0.2 - 0.6 $mi^2$/day for a similar reach of the upper Potomac Estuary.

# THOMANN MODEL DYE SIMULATION AND VERIFICATION

## 1965 DYE RELEASE

JUNE 14, 1965

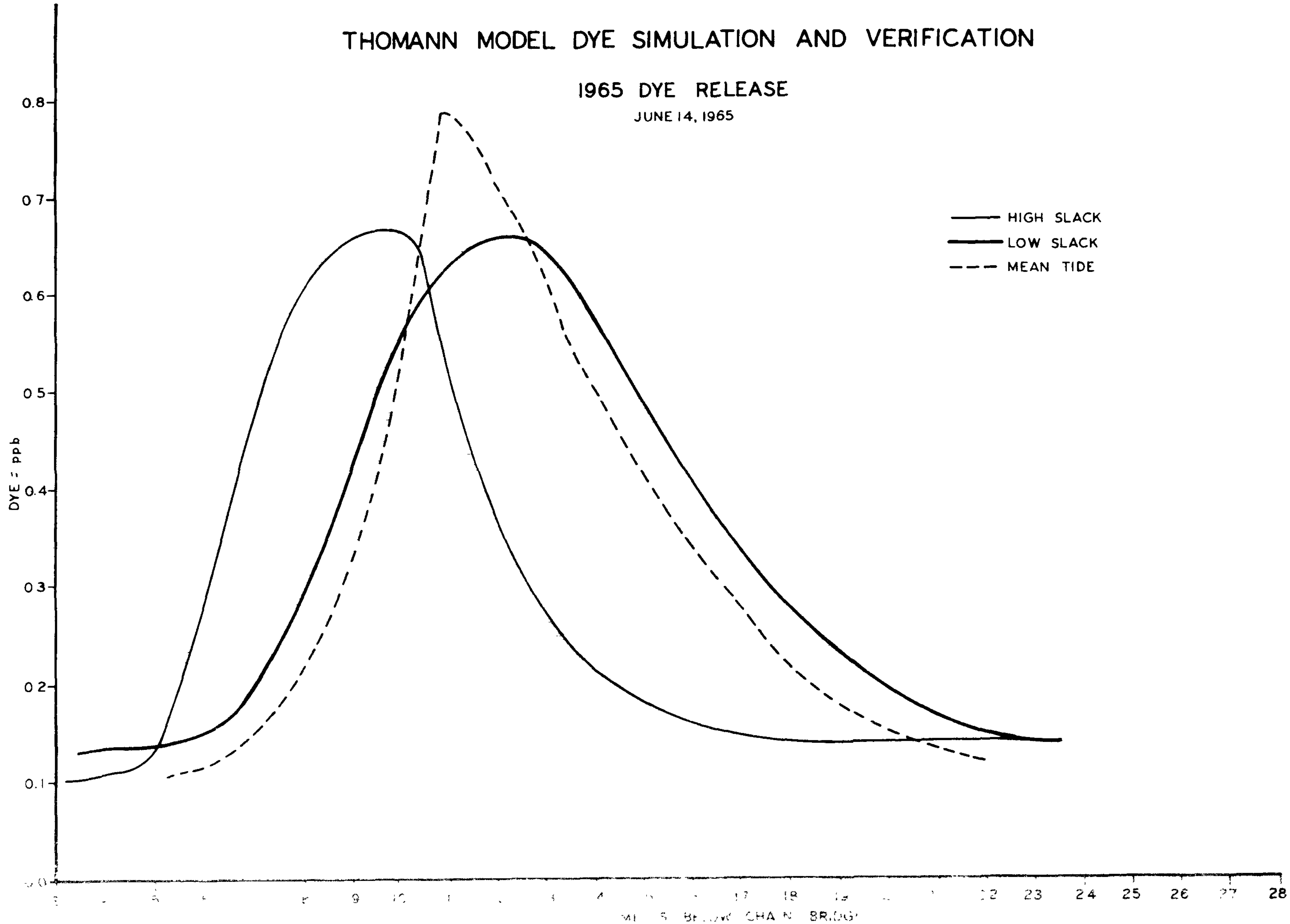



FIGURE VI-1

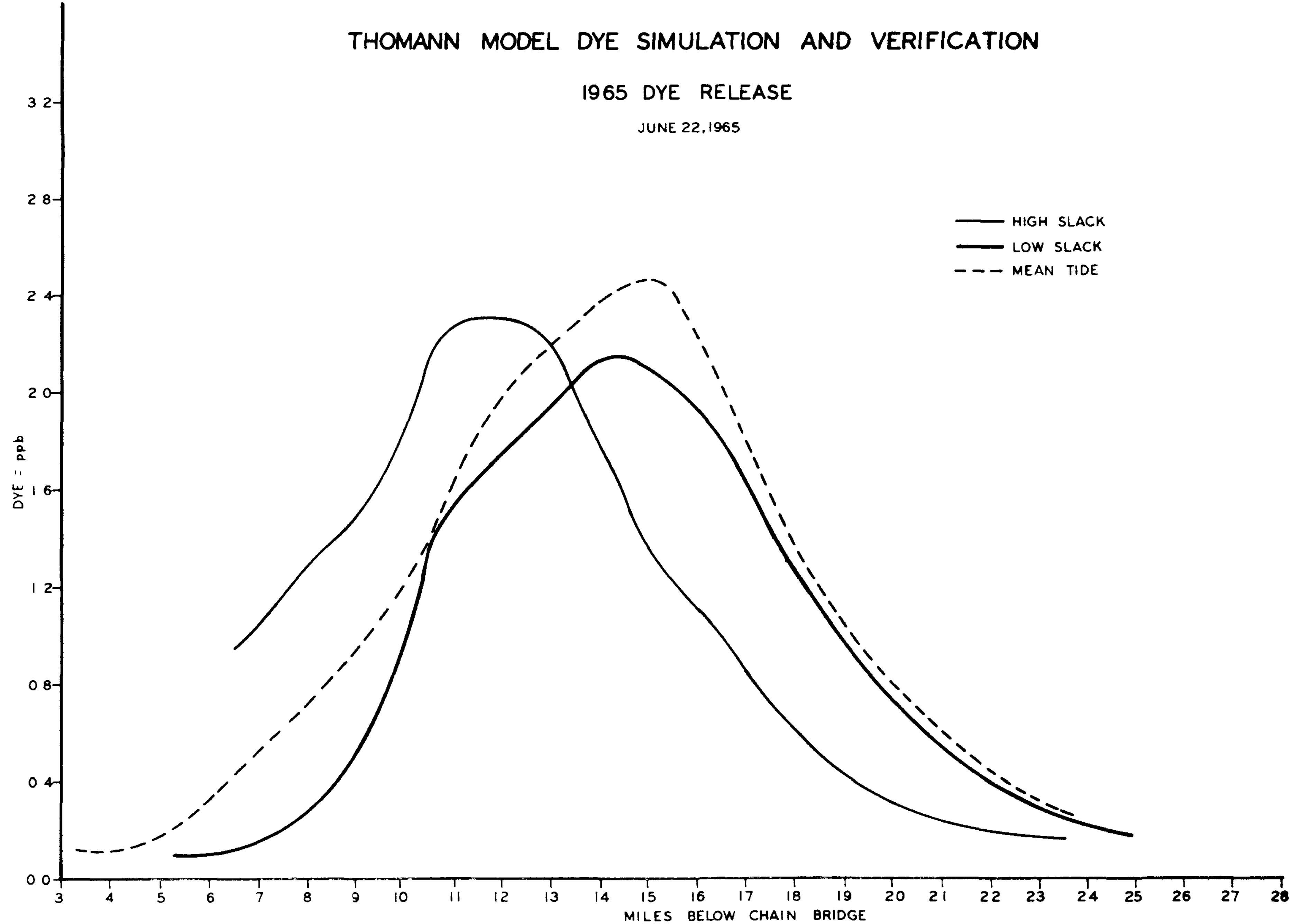

THOMANN MODEL DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JUNE 22, 1965
HIGH SLACK
LOW SLACK
MEAN TIDE
DYE : ppb
0 0
0 4
0 8
1 2
1 6
2 0
2 4
2 8
3 2
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
MILES BELOW CHAIN BRIDGE

FIGURE VI— 2

## THOMANN MODEL DYE SIMULATION AND VERIFICATION

### 1965 DYE RELEASE

JUNE 26, 1965

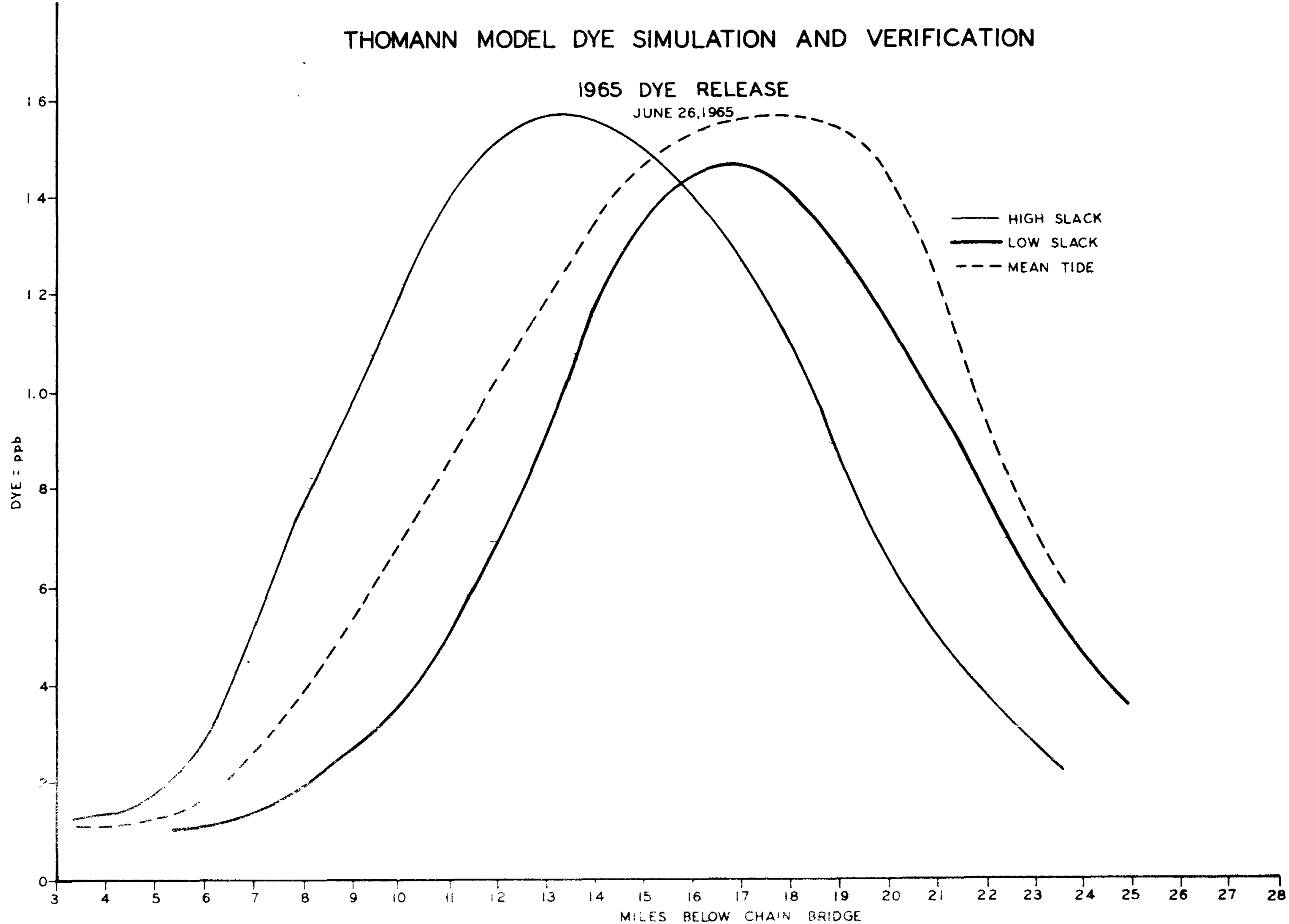



FIGURE VI-3

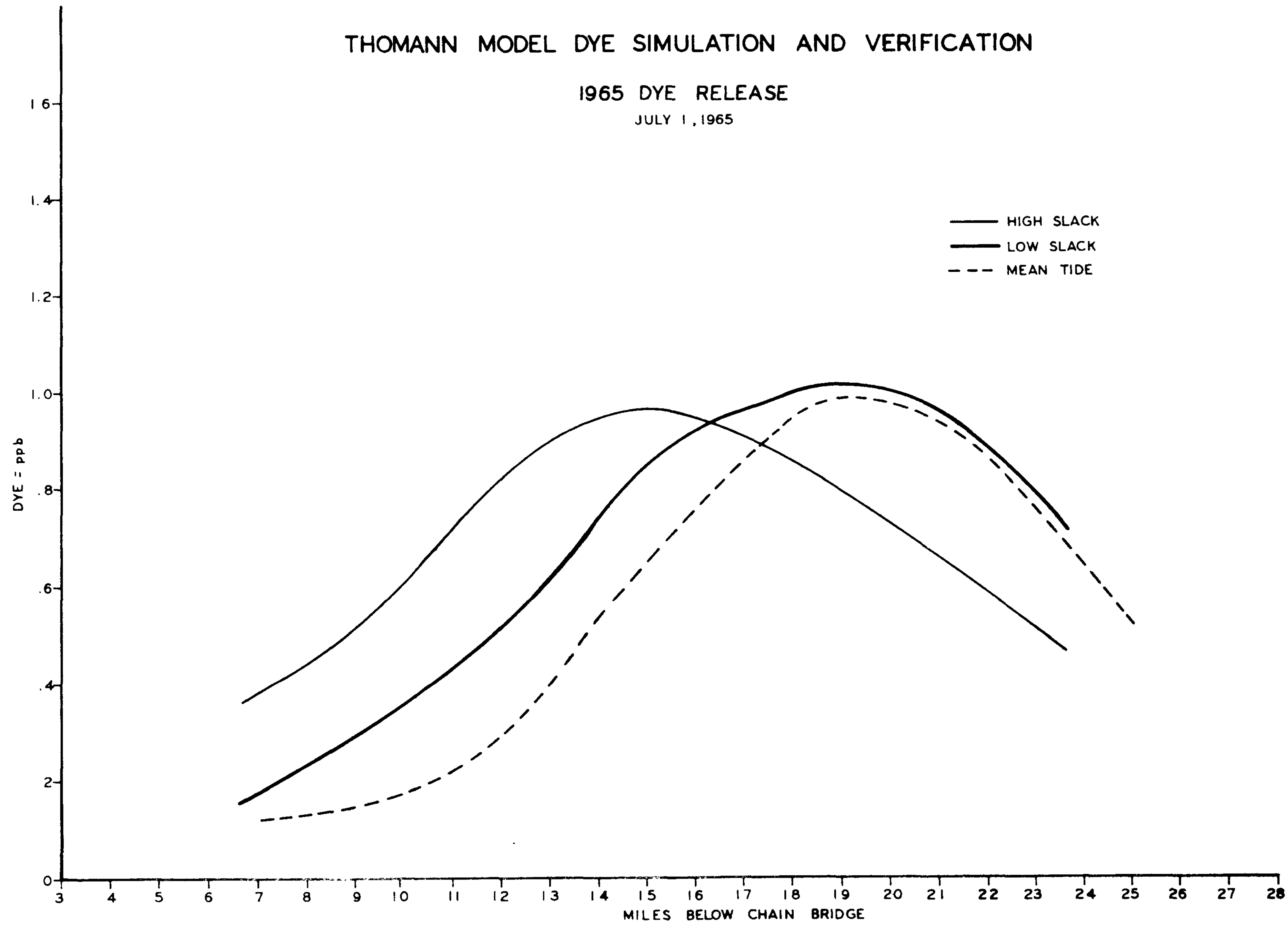

THOMANN MODEL DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JULY 1, 1965
HIGH SLACK
LOW SLACK
MEAN TIDE
DYE = ppb
1 6
1.4
1.2
1.0
.8
.6
.4
2
0
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
MILES BELOW CHAIN BRIDGE

FIGURE VI-4

2. Dynamic Estuary Model

Two separate hydraulic conditions were assumed for the Dynamic Estuary Model when attempting to simulate the 1965 dye study data. Prior to June 23, the freshwater flow was assigned an average value of 2,687 cfs. The second hydraulic condition, which represented the remainder of the study period, was based on a constant flow of 1,451 cfs. In general, a steadily declining flow was experienced during this dye study.

The simulated 1965 dye profiles (high- and low-slack water) that resulted from using the Dynamic Estuary Model along with observed data are shown in Figures VI-5 through VI-8 for several days of the study period. An examination of these figures showed relatively close agreement in the spatial position, shape, and peak dye concentrations between the prototype and model data. However, in order for the observed and simulated dye mass characteristics to compare favorably, it was necessary to treat the dye as a conservative substance since applying a decay rate of either 0.034/day or 0.02/day in the model reduced the dye concentrations, and thus the mass, beyond an acceptable level. As will be pointed out in a subsequent chapter, the effects of decay rate are quite significant. The reason that this problem occurred in the mass balancing of prototype and model data cannot be explained except that the indeterminate fluorescent contribution from algae may have been responsible.

## FWQA DYNAMIC ESTUARY MODEL
### DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JUNE 14, 1965

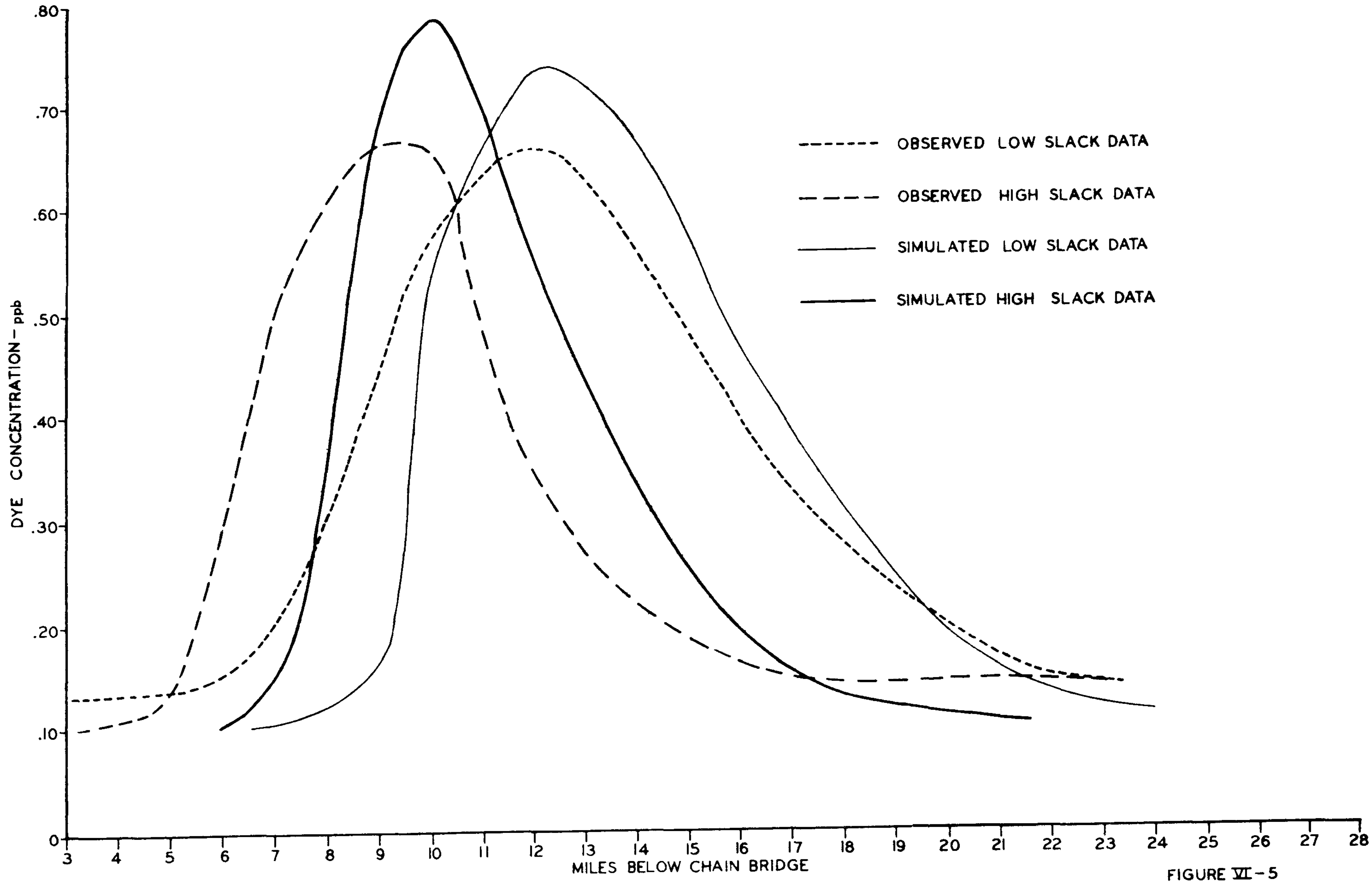



FIGURE VI-5

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

1965 DYE RELEASE
JUNE 26, 1965

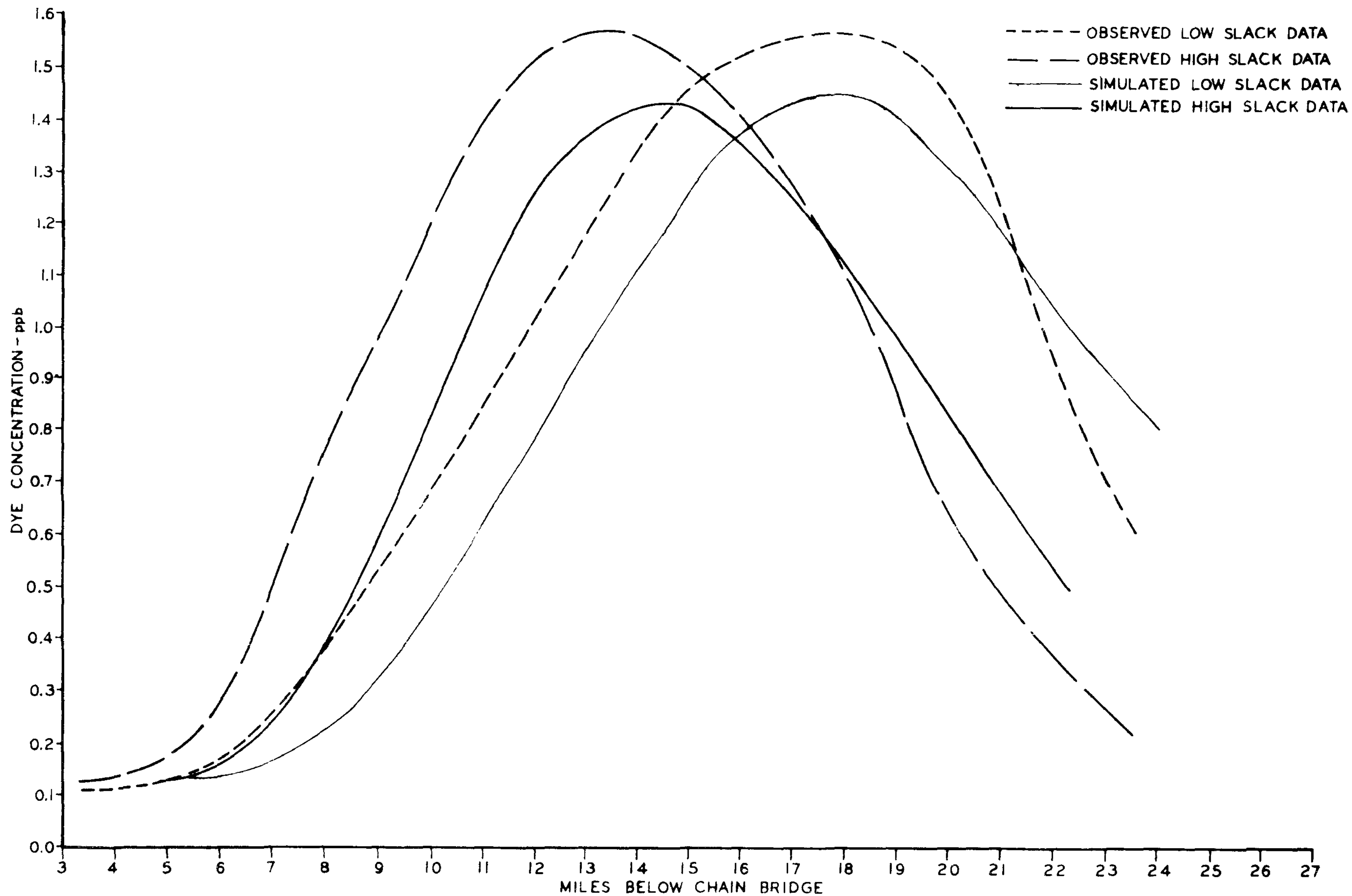



FIGURE VI-6

# FWQA DYNAMIC ESTUARY MODEL

## DYE SIMULATION AND VERIFICATION

1965 DYE RELEASE

JULY 1, 1965

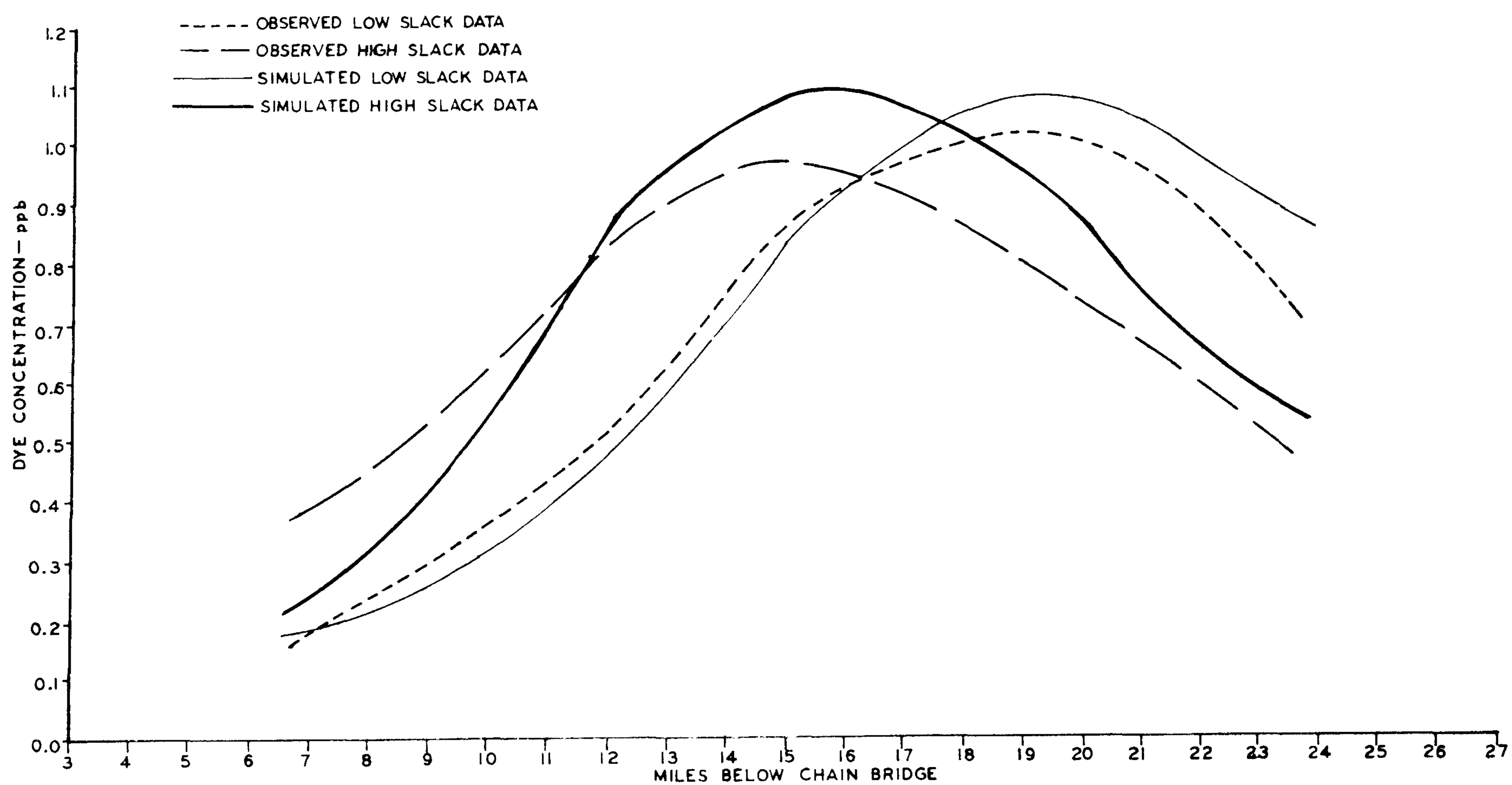
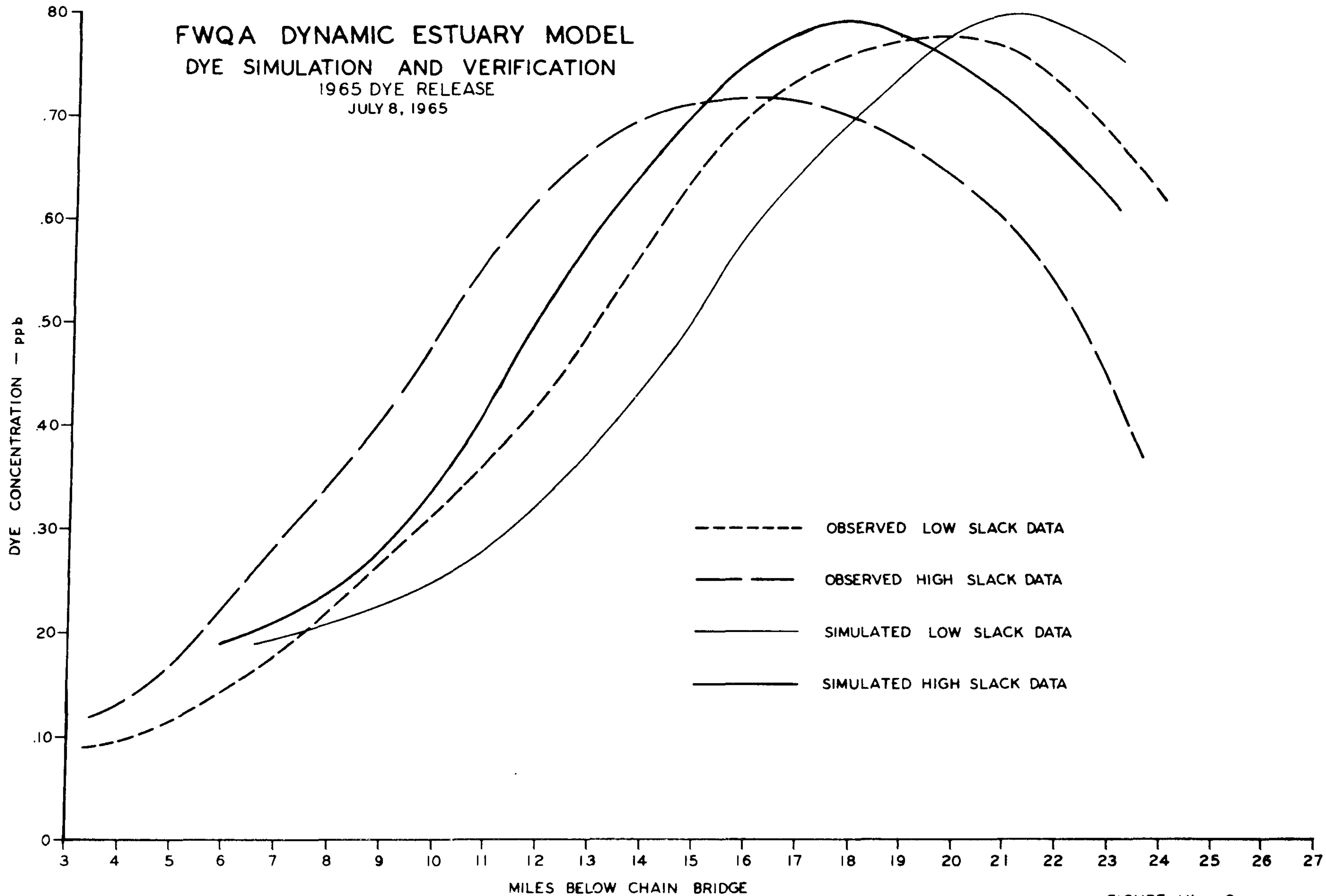



FIGURE VI-7



FWQA DYNAMIC ESTUARY MODEL
DYE SIMULATION AND VERIFICATION
1965 DYE RELEASE
JULY 8, 1965
80
.70
.60
.50
.40
.30
20
.10
0
DYE CONCENTRATION — ppb
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
MILES BELOW CHAIN BRIDGE
OBSERVED LOW SLACK DATA
OBSERVED HIGH SLACK DATA
SIMULATED LOW SLACK DATA
SIMULATED HIGH SLACK DATA

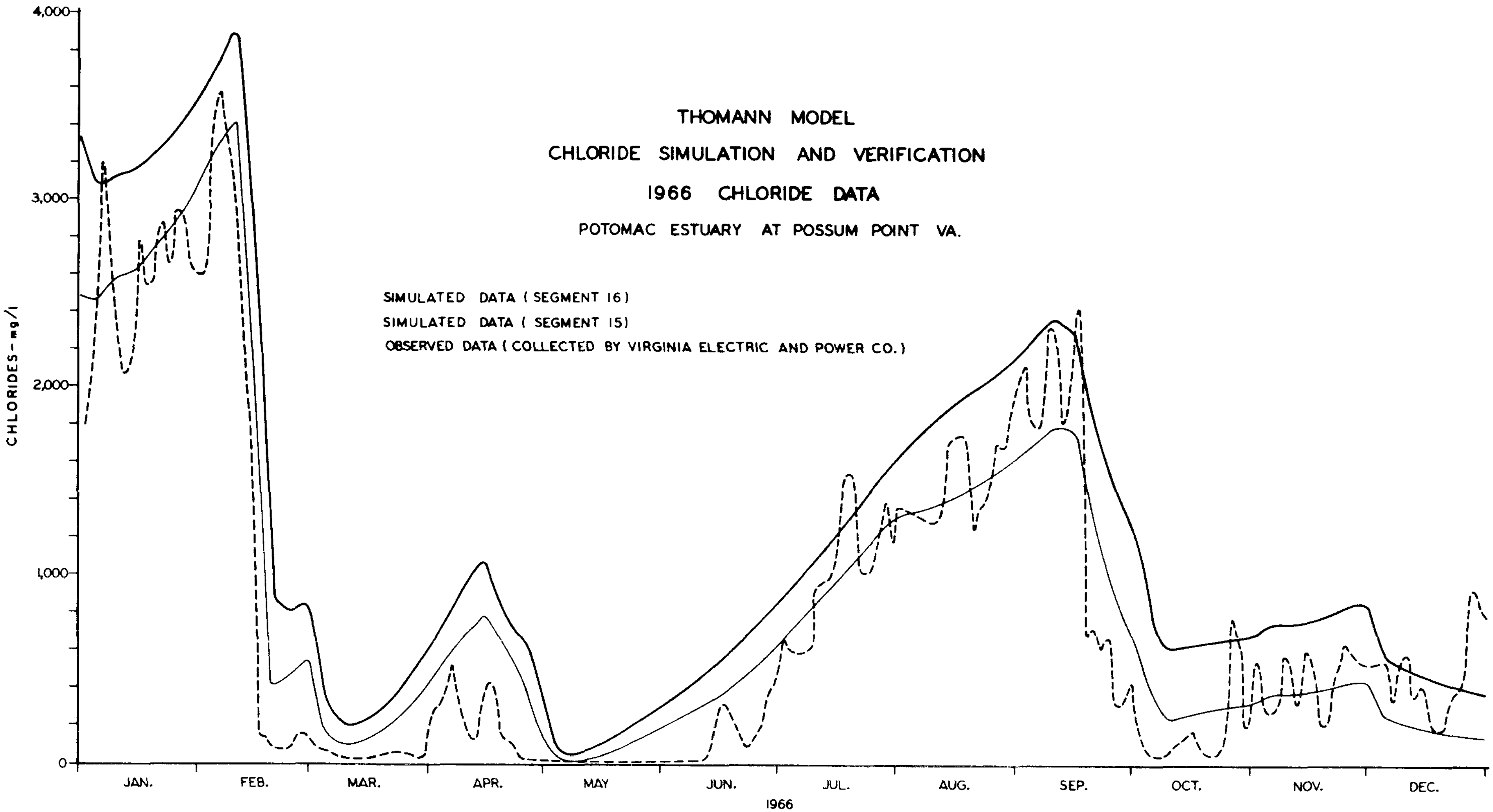

FIGURE VI — 8

## B. CHLORIDE SIMULATIONS - 1966 AND 1969

### 1. Thomann Model

Further simulation and verification studies with the Thomann Model were made using 1966 and 1969 chloride data from the Potomac Estuary. It was believed that chloride data would provide a sound basis for estimating dispersion characteristics throughout the entire estuary rather than just the upper portion for which dye data was available. Moreover, the effects of density gradients created by varying chloride concentrations on dispersion rates could be evaluated.

The most complete temporal record of 1966 chloride concentrations in the Potomac was provided by the Virginia Electric and Power Company generating plant at Possum Point. These data along with the simulated chloride profiles at two representative model segments are shown in Figure VI-9. Observed and simulated profiles show reasonable agreement except for the almost continuous cyclic variation in the observed data. Two sets of dispersion coefficients were used in the Thomann Model for the 1966 chloride simulations. One set ranging from 2.0 - 20.0 $mi^2$/day was selected for the period January-May when freshwater inflows were usually between 11,000 and 14,000 cfs. The other set which ranged from 1.5 - 14.0 $mi^2$/day was used for the remainder of the year for 1,000 - 7,000 cfs inflows. The high range, of course, applied to the seaward portion of the estuary where maximum density differences could be expected.



THOMANN MODEL
CHLORIDE SIMULATION AND VERIFICATION
1966 CHLORIDE DATA
POTOMAC ESTUARY AT POSSUM POINT VA.
SIMULATED DATA ( SEGMENT 16 )
SIMULATED DATA ( SEGMENT 15 )
OBSERVED DATA ( COLLECTED BY VIRGINIA ELECTRIC AND POWER CO. )
CHLORIDES - mg/l
4,000
3,000
2,000
1,000
0
JAN.
FEB.
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.
1966


FIGURE VI-9

Chloride concentrations at the upper boundary (Chain Bridge) were determined from D. C. Department of Sanitary Engineering sampling data. Seaward boundary values were correlated to U. S. Coast and Geodetic Survey data collected at Solomons, Maryland. Supplemental sampling data were obtained from a Potomac nutrient study conducted by the Chesapeake Bay Institute. The concentration of chlorides in wastewater discharges was assumed to be 40 mg/l.

A comparison of simulated and observed profiles showing 1969 chloride distributions is given in Figures VI-10 and VI-11 for sampling stations in the middle and lower reaches of the Potomac Estuary. The data as presented in these figures indicate relatively close agreement between model predictions and observed chloride profiles, again except for the day-to-day fluctuations in the observed data. Various sets of dispersion coefficients were tried in verifying the 1969 chloride data and the best agreement was obtained by using one set of coefficients ranging from 2.0 - 16.0 $mi^2$/day. It should be noted that use of a single set of coefficients departs from previous Thomann Model simulation studies discussed in this report wherein dispersion was found to be directly related to freshwater flow rates. While flows varied greatly during 1969, attempts to refine the dispersion coefficients to reflect these flow changes did not prove successful.

THOMANN MODEL

CHLORIDE SIMULATION AND VERIFICATION

1969 CHLORIDE DATA

POTOMAC ESTUARY AT NANJEMOY CREEK

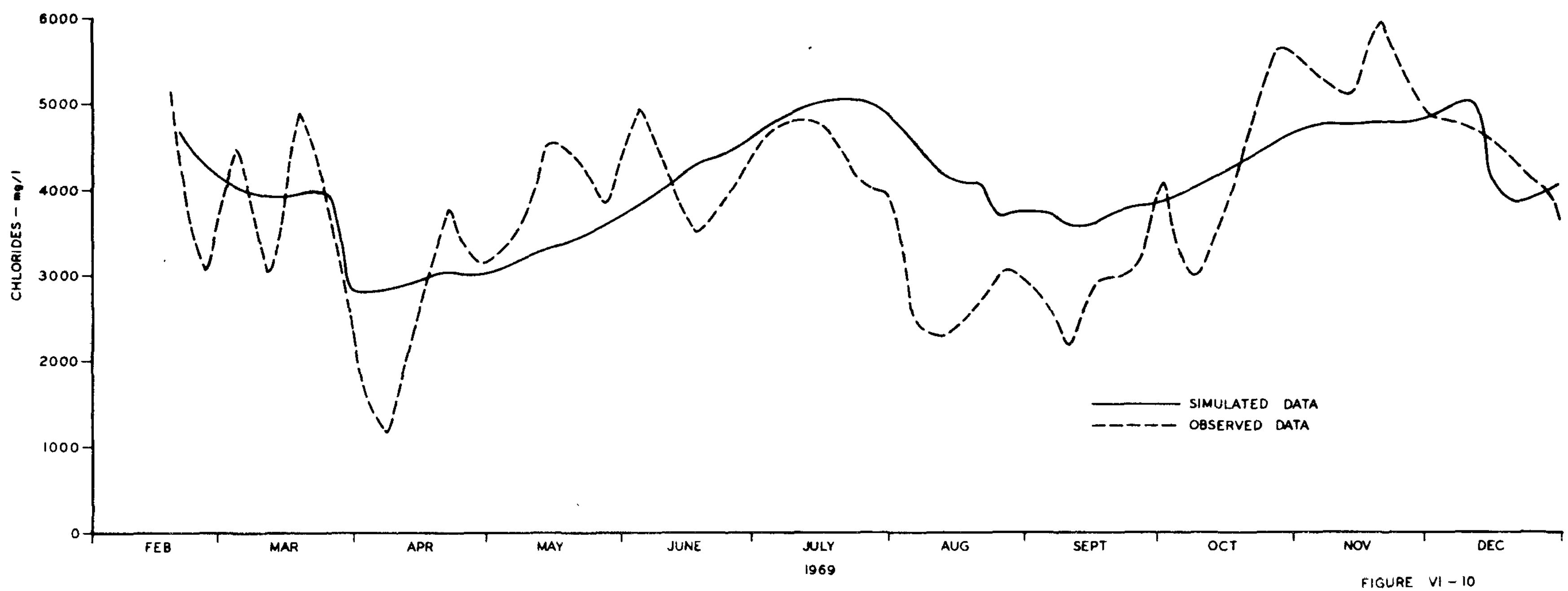



FIGURE VI – 10

## THOMANN MODEL
### CHLORIDE SIMULATION AND VERIFICATION
1969 CHLORIDE DATA

POTOMAC ESTUARY AT WICOMICO RIVER

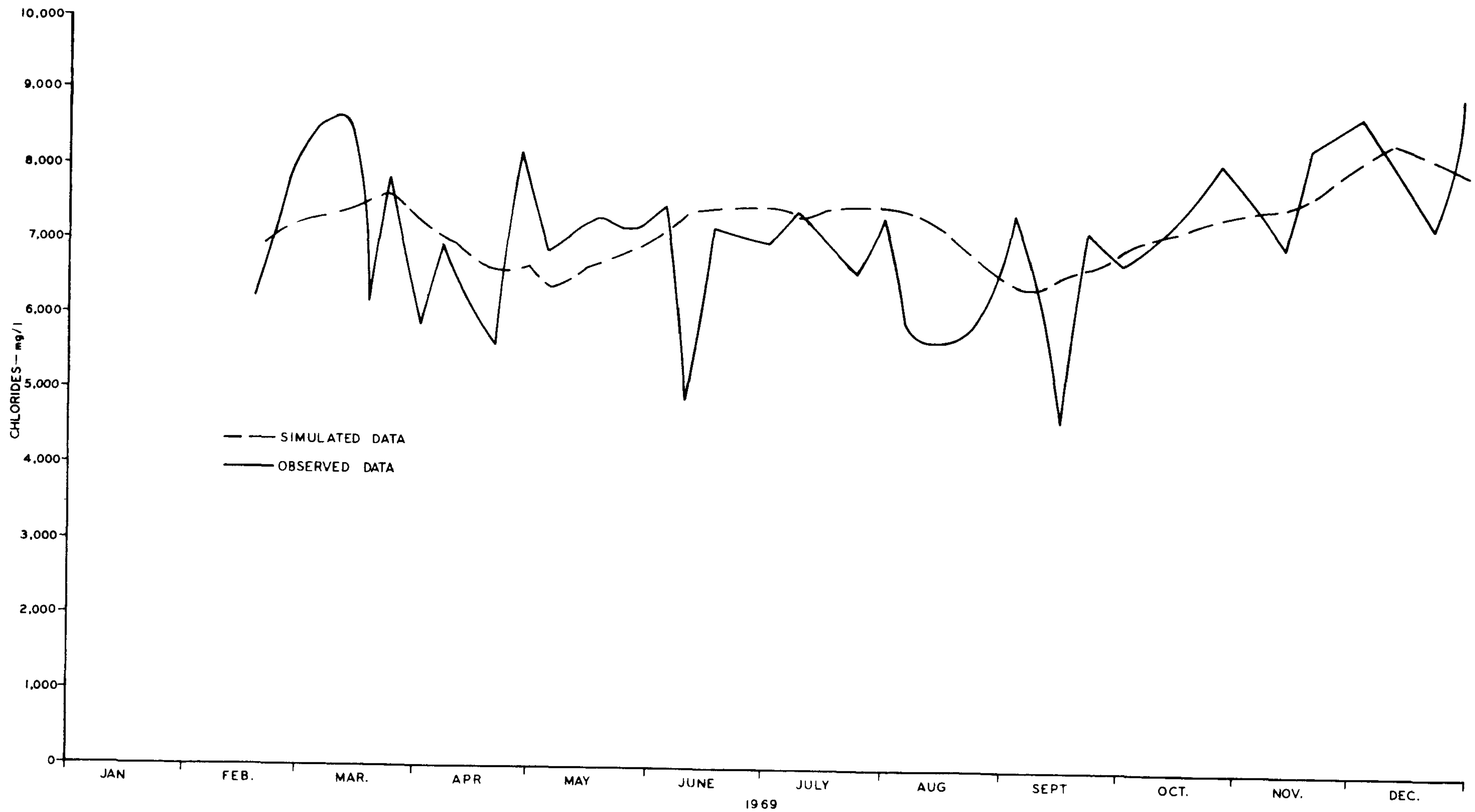



FIGURE VI—11

## C. SIMULATION OF 1965 CHLORIDES

### 1. Dynamic Estuary Model

To demonstrate the Dynamic Estuary Model's capability of simulating changing salinity conditions in the Potomac Estuary, an historical period (July-December 1965) was selected for which sufficient data were available to establish the salinity distribution throughout the system at two different points in time and for which flow rates were relatively uniform. The mean Potomac River flow over Great Falls remained near 1,300 cfs during this 5-month period with the mean monthly flows varying between 1,018 and 1,585 cfs. Data were available to establish the salinity profile in the main stem of the Potomac near the start of the period (July 7-8, 1965) and also near the end (December 1-2, 1965). These data were converted to chloride concentrations and were then utilized to establish visual "best fit" profiles for these two points in time as illustrated in Figure VI-12. No attempt was made to relate any specific data point to the tidal phase at the time of sampling, e.g., high- or low-slack water conditions; hence, the concentrations were assumed to be representative of the mean concentration over a full tidal cycle.

The profile for July 7-8, 1965, was specified as the initial profile in the model. For this simulation, the network extended to Piney Point, near River Mile 99. The specified chloride concentration at the seaward boundary was changed during the simulation to correspond to the change noted in the prototype during the same period, i.e., the concentration

## FWQA DYNAMIC ESTUARY MODEL
## CHLORIDE SIMULATION AND VERIFICATION
### POTOMAC ESTUARY
### JULY — DECEMBER, 1965

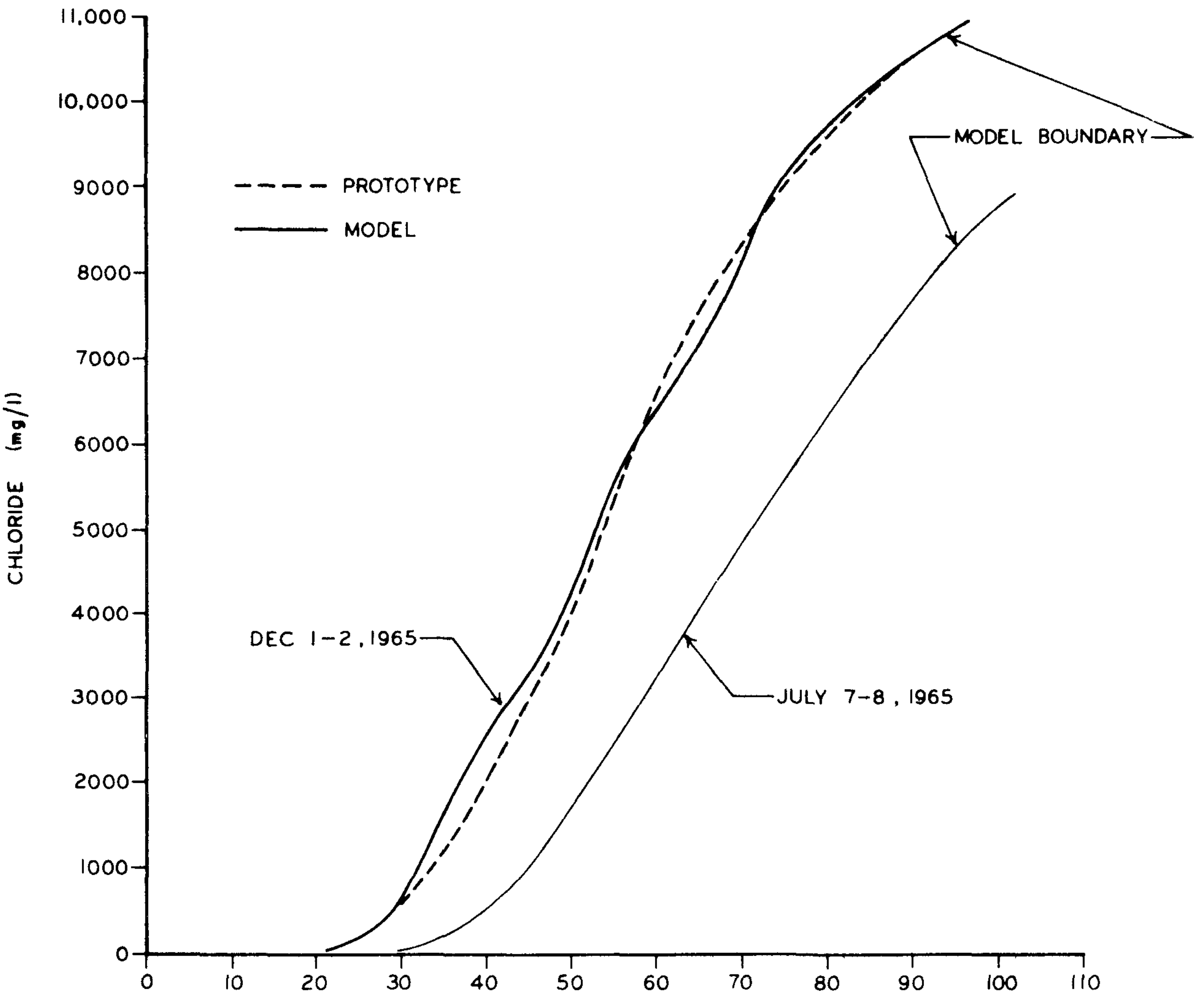



FIGURE VI - 12

was increased from 8,400 mg/l to 10,930 mg/l in increments of 55 mg/l every 3 days. A uniform flow of 1,300 cfs in the Potomac River was maintained in both the hydraulic and quality simulations.

The chloride profile predicted by use of the model after the 147-day simulation period is illustrated in Figure VI-12 along with that measured in the prototype. As can be seen, the upstream movement of the "salt wedge" and the spatial chloride distribution in the Potomac Estuary were successfully simulated for this 5-month condition.

In the course of model verification, certain unexpected problems arose which were related to the basic transport mechanisms, advection, and dispersion. These problems were evidently the result of simulating a constituent having an extremely high concentration gradient. For example, the standard one-quarter point method, i.e., the assigning of an advective concentration equal to that at one-quarter of the channel length measured in the direction of decreasing gradient, did not prove adequate. Although this solution technique for advective transport is acceptable in terms of numerical mixing, accuracy, and stability when simulating dye or other constituents with a small concentration gradient, the one-third point method yielded the best results with chlorides. A discussion of the Dynamic Estuary Model's sensitivity to the advective transport solution is included in Chapter VII.

The chloride simulation presented in Figure VI-12 was based on $C_4$ values of 15.0 (above River Mile 55), 80.0 (River Mile 55 to River Mile 70) and 250.0 (River Mile 70 to River Mile 99). Unlike previous simulations where the rate of dispersion was considered constant throughout the system, it appeared that a strong relationship existed between dispersion rates and increased salinity gradients as suggested by Harleman [7]. A discussion of this aspect is also presented in Chapter VII.

It should be noted that an improved representation of the chloride distribution with less difficulty in defining the transport components of the model, including the transfer of chlorides across the seaward boundary, might have been realized had the model network been more refined in the lower portions of the Potomac Estuary. Almost all channels in this area were much wider than they were long, a distortion which could conceivably influence the chloride predictions obtained using the Dynamic Estuary Model.

# CHAPTER VII

## COMPARATIVE SENSITIVITY EVALUATIONS

## THOMANN AND DYNAMIC ESTUARY MODELS

### A. DECAY RATE OF POLLUTANT

The purpose of investigating the role of decay rate during mathematical modeling studies in the Potomac was essentially twofold: (1) to ascertain the effects of decay on the simulated distribution (steady state) of a pollutant by using both the Thomann and Dynamic Estuary Models and (2) to compare profiles from the two models for similar loading rates and freshwater flows for determining whether the predicted results agree, and what effect, if any, does decay rate exert on this agreement.

Figures VII-1 and VII-2 present steady-state simulated profiles from the Dynamic Estuary and Thomann Models, respectively, for decay rates varying from 0.0 to 0.4/day (base e), for a constant loading of 100,000 lbs/day, and for a flow of 4,430 cfs. As can be seen in these figures, each model's predictions are highly sensitive to the magnitude of the decay rate and each behaves similarly, i.e., lower peak concentrations and less mass transport, particularly downstream, as the decay rate increases. The major change in profiles occurs between decay rates of 0.0 (conservative) and 0.1/day. A further increase diminishes the effects of the decay rate in both models.

By comparing Figures VII-1 and VII-2, it is clearly evident that many similarities existed in the predictions from both models. Of particular importance was the close agreement obtained in peak magnitudes

# EFFECTS OF DECAY RATES
## DYNAMIC ESTUARY MODEL

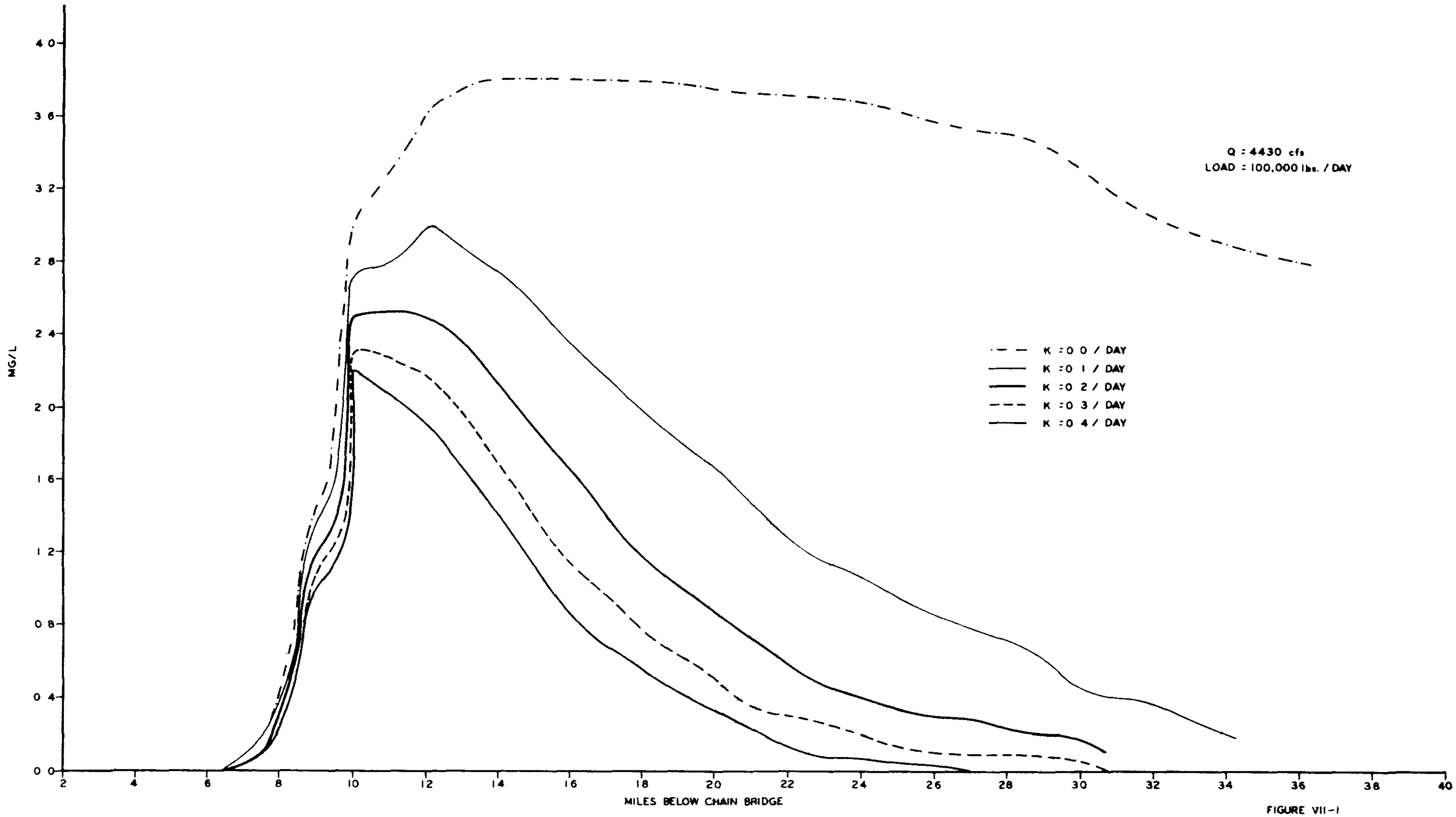



FIGURE VII-1

# EFFECTS OF DECAY RATES
## THOMANN MODEL

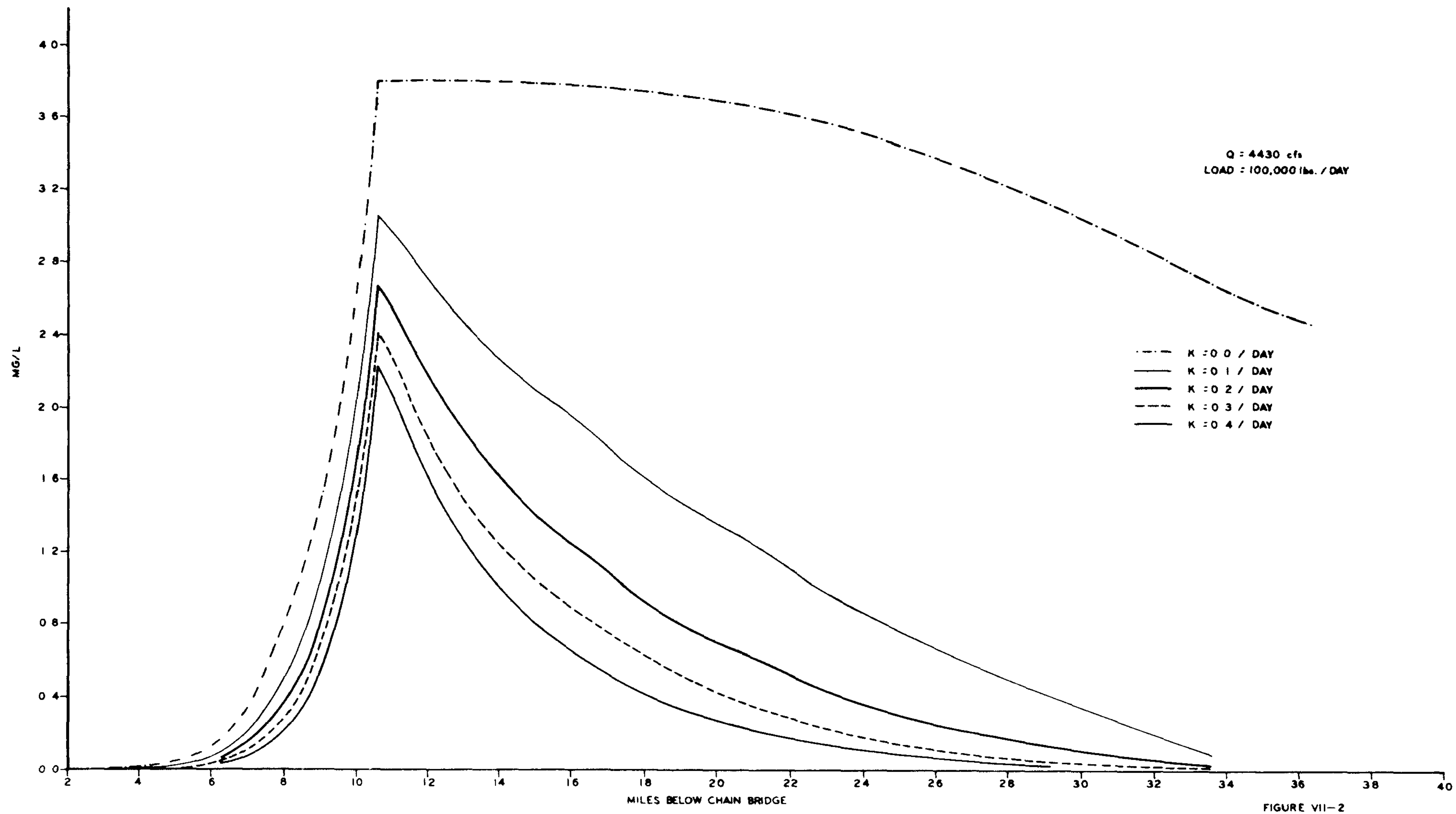



FIGURE VII-2

for each of the decay rates investigated. Moreover, the general shape and position of the profiles did not differ appreciably over this complete range in decay rates, indicating that either model can be used to simulate a given constituent regardless of its decay rate. As was noted previously when simulating dye data, the major difference between the two models' predictions was the pronounced peaking with the Thomann Model whereas the DEM "smoothed" the gradients considerably in the area of maximum concentration.

B. SEGMENT LENGTH

1. Thomann Model

A certain degree of refinement in the segmentation and the associated physical data of an estuary is necessary; however, the CTSL studies in the Potomac using the Thomann Model suggest that overrefinement of the geometry may be a wasted effort. Figures VII-3, VII-4, and VII-5 show simulated 1969 dye data for two separate networks that were applied to the Potomac Estuary. According to these figures, there is relatively low model sensitivity to the length of segments. The original 28-segment system, from which 15 segments were used for this analysis, produced basically the same profiles as the expanded system for 3 different days during the dye study period. The only differences noted were (1) slightly higher peak concentrations, and (2) slight downstream displacement of entire profile. The foregoing results remain true for decay rates of either 0.03 or 0.3 per day.

The effects of "induced dispersion" due to averaging concentrations throughout the larger volumes and longer distances in a coarse network appeared to be minimal.

2. Dynamic Estuary Model

A detailed investigation was not undertaken to determine the sensitivity of the Dynamic Estuary Model to network detail. In fact, the 114-node network used for all DEM simulations throughout this report was initially laid out for the Thomann Model. In order to avoid the time-consuming task of developing the additional data required for a new network, the original segmentation, except for embayments, was used without basic change in the DEM. Subsequent simulations have indicated that this degree of refinement was adequate to reproduce the hydrodynamic and quality behavior in the prototype. A single run based upon a 28-node network, also specifically designed for the Thomann Model, showed that a network with this coarse detail could not accurately simulate tidal movement in the Potomac Estuary.

## EFFECTS OF SEGMENTATION
### THOMANN MODEL DYE SIMULATIONS
NOVEMBER 6,1969

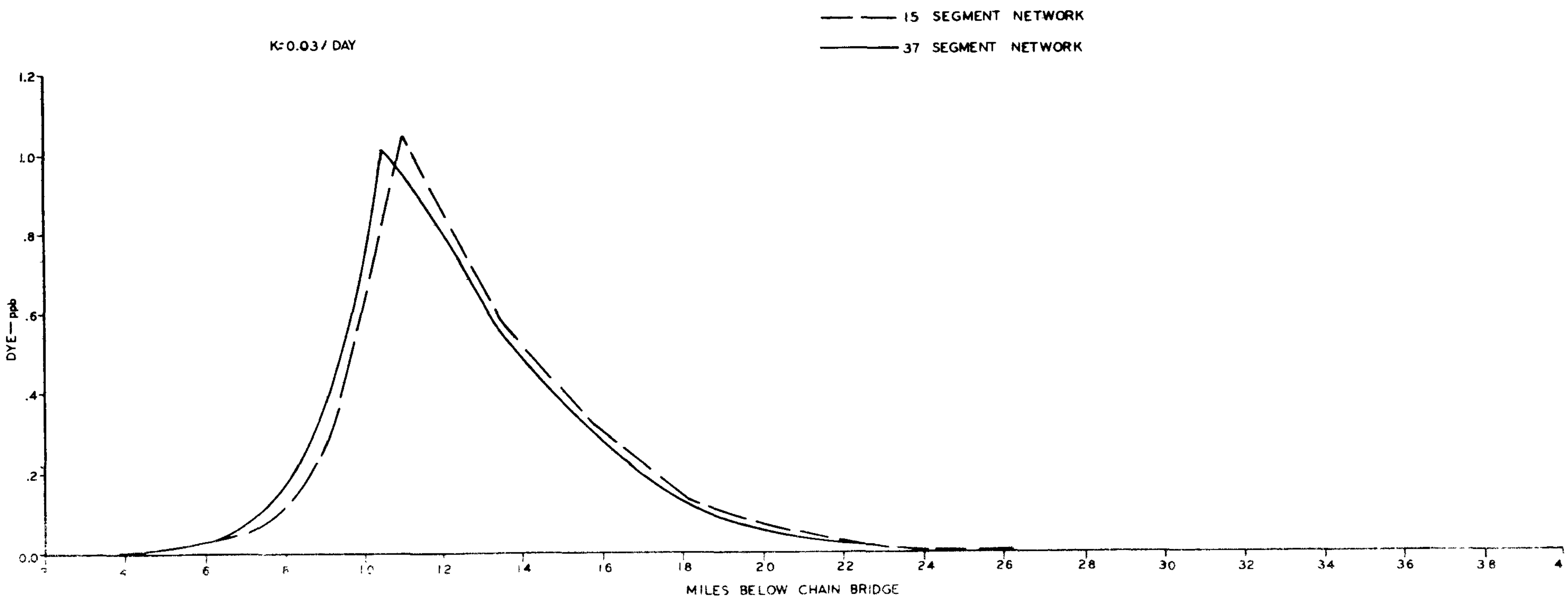



FIGURE VII-3

## EFFECTS OF SEGMENTATION

THOMANN MODEL DYE SIMULATIONS
NOVEMBER 12, 1969

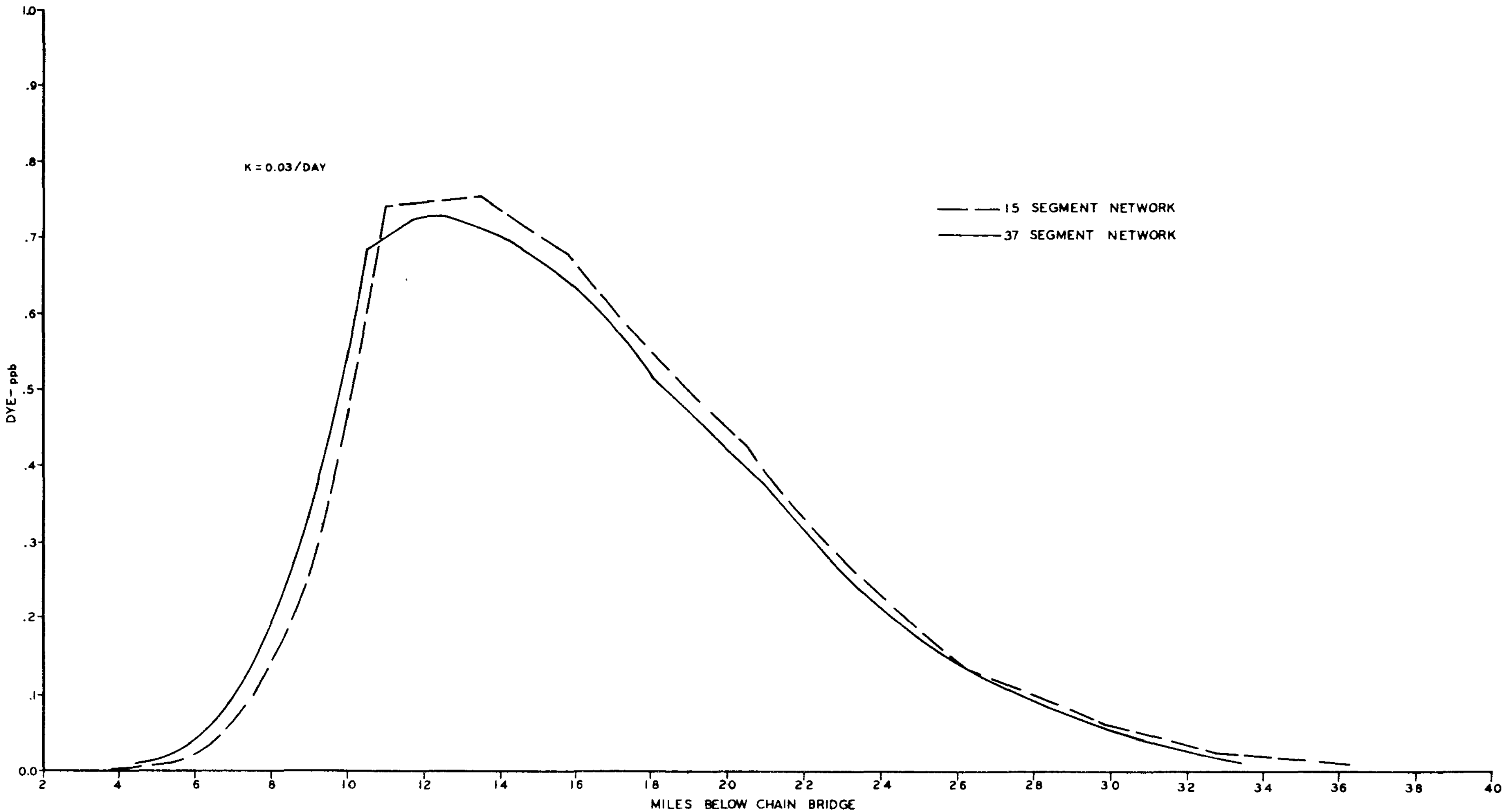
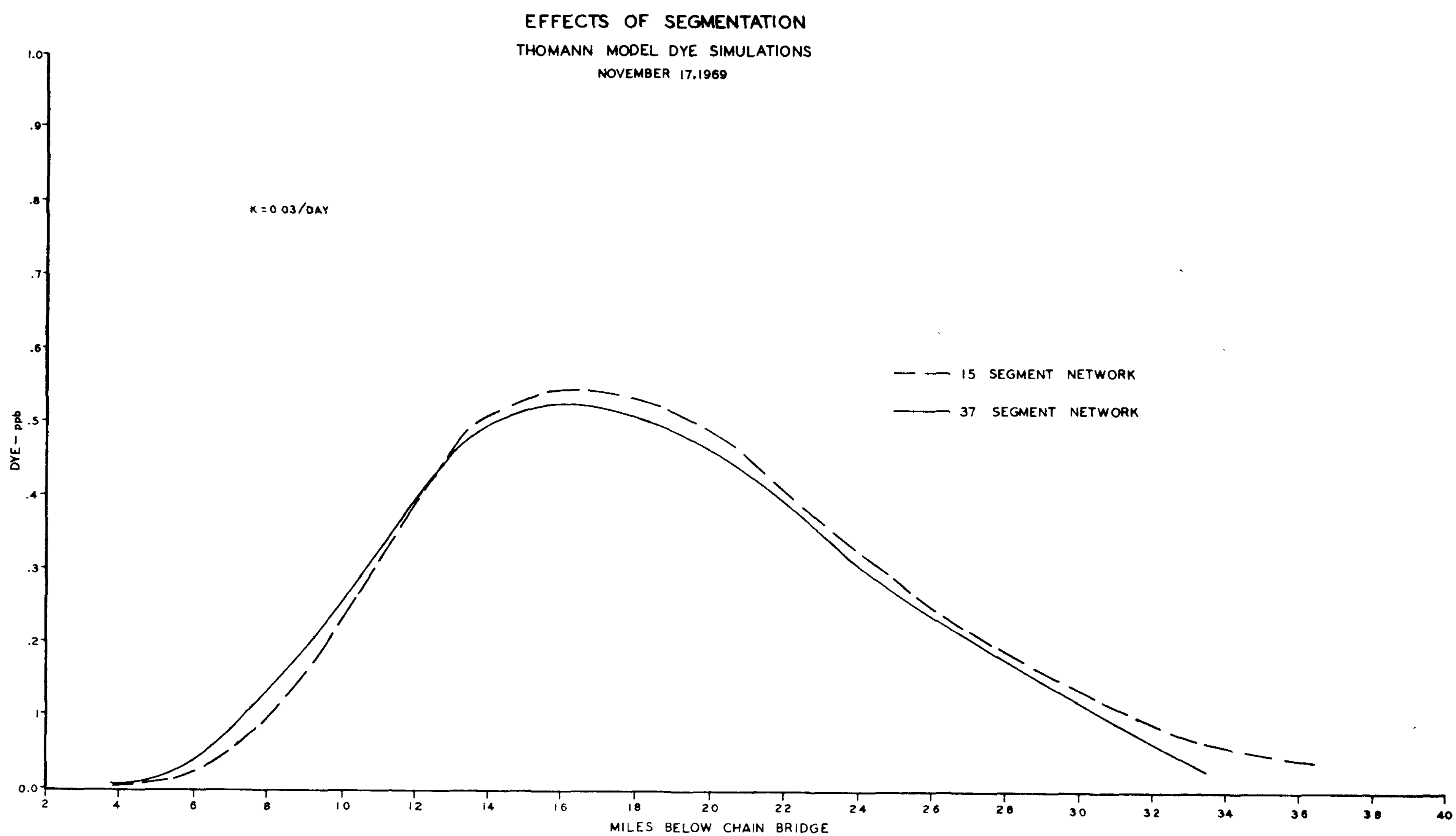



FIGURE VII – 4



EFFECTS OF SEGMENTATION
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 17,1969
K = 0 03/DAY
15 SEGMENT NETWORK
37 SEGMENT NETWORK
DYE – ppb
MILES BELOW CHAIN BRIDGE


FIGURE VII–5

## C. DISPERSION COEFFICIENT

### 1. Thomann Model

#### a. Point Discharges

Of the various input parameters investigated, the Thomann Model appeared to be most sensitive to the dispersion coefficient (K), especially when simulating constituents having low decay rates. The importance of this term is evident from an examination of Figure VII-6, VII-7, and VII-8 wherein simulated 1969 dye profiles are shown for K values ranging from 0.5 $mi^2$/day to 10.0 $mi^2$/day for all segments. The higher dispersion coefficients indicated greater upstream and downstream dye movement. Moreover, higher coefficients greatly decreased concentration peaks to compensate for the additional mass of dye at the leading and trailing edges. On November 17 (Figure VII-8), for example, dye peaks of 0.8 ppb, 0.7 ppb, 0.5 ppb, and 0.4 ppb were predicted for dispersion coefficients of 0.5, 2.0, 5.0, and 10.0 respectively. The remaining 2 days of the study for which data were plotted indicated similar results.

The spatial position of peak concentrations was also affected by the dispersion coefficient. As can be seen in Figures VII-7 and VII-8, increased dispersion coefficients resulted in a lower rate of downstream movement of the concentration peak.

The range in dispersion coefficients selected for this sensitivity analysis may have been extreme, but it nevertheless showed that a relatively accurate estimate of the dispersion coefficient was required for the Thomann Model either by conducting a dye study or by using some

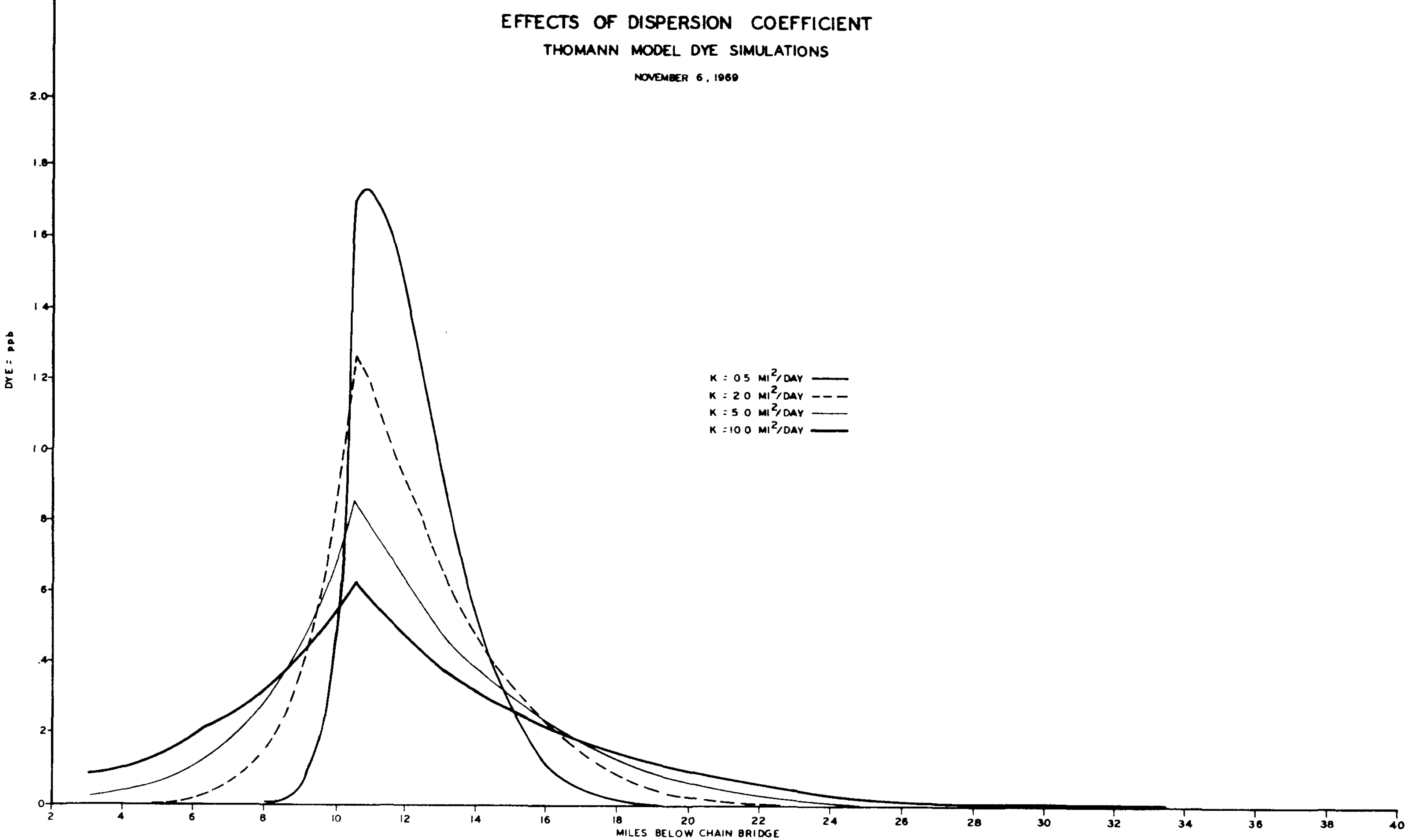

EFFECTS OF DISPERSION COEFFICIENT
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 6, 1969
K = 0.5 MI²/DAY
K = 2.0 MI²/DAY
K = 5.0 MI²/DAY
K = 10.0 MI²/DAY
DYE : ppb
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
MILES BELOW CHAIN BRIDGE

FIGURE VII—6

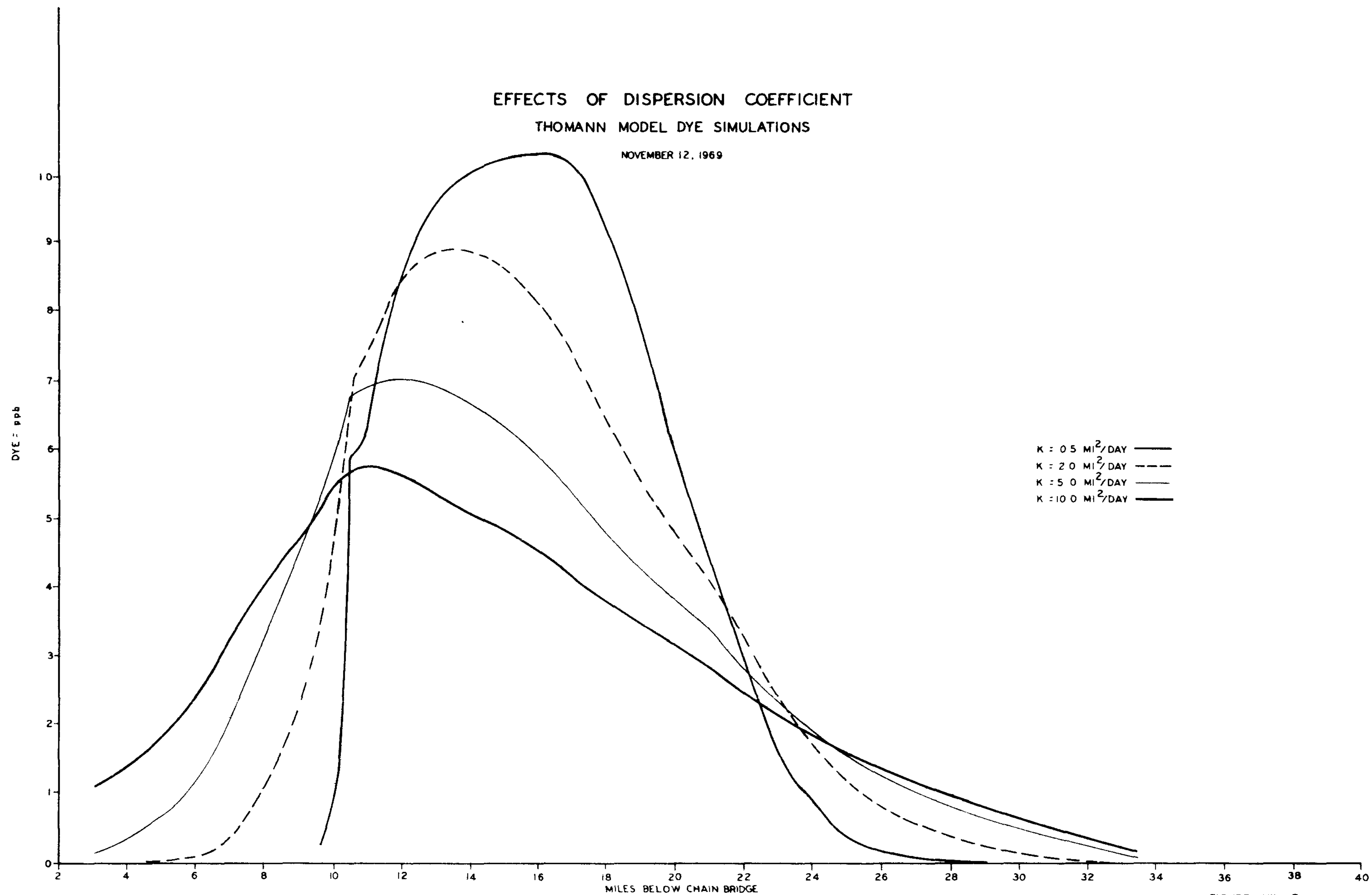

EFFECTS OF DISPERSION COEFFICIENT
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 12, 1969
K = 0.5 MI²/DAY
K = 2.0 MI²/DAY
K = 5.0 MI²/DAY
K = 10.0 MI²/DAY
DYE : ppb
MILES BELOW CHAIN BRIDGE

FIGURE VII – 7

## EFFECTS OF DISPERSION COEFFICIENT

THOMANN MODEL DYE SIMULATIONS

NOVEMBER 17, 1969

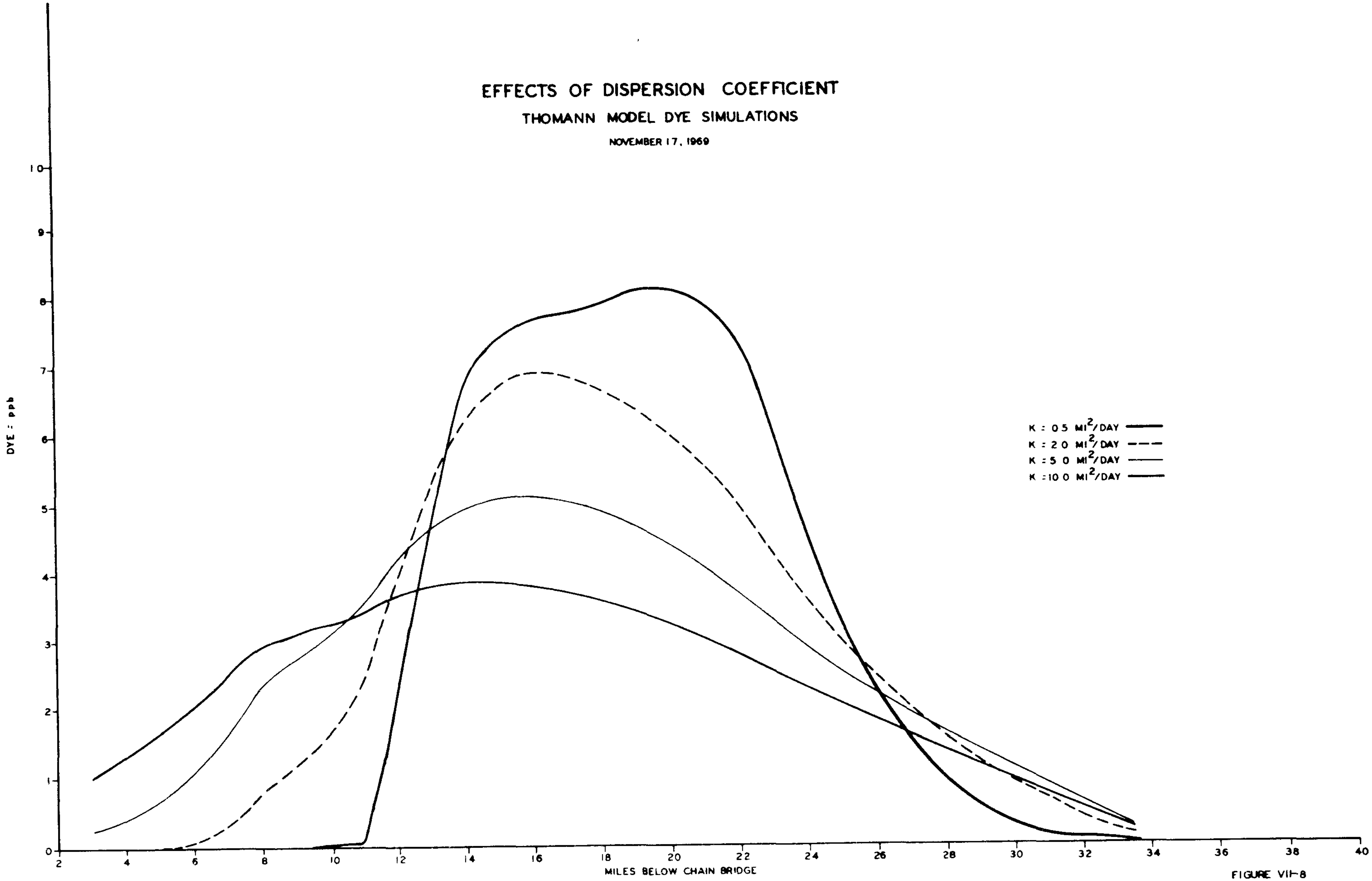



FIGURE VII-8

natural tracer. The relationship of dispersion coefficient to fresh-water inflow, salinity, and possibly the physical characteristics of the system should also be defined prior to extensive model use.

For nonconservative constituents such as BOD, the effects of decay somewhat overcome the influence of dispersion coefficient in the Thomann Model.

b. Chloride Distributions

The effects of using three different sets of dispersion coefficients in the Thomann Model to simulate the annual (1969) chloride distribution at Nanjemoy Creek are shown in Figure VII-9. Increasing the previously verified dispersion coefficients of 2.0 to 16.0 $mi^2$/day by an order of magnitude resulted in a profound change in chloride concentrations. Instead of the model predicting chloride concentrations between 3,000 and 5,000 mg/l, which were comparable to observed values, the chloride levels were generally in the range of 7,000 to 9,000 mg/l. Similar differences could be expected at most other locations along the Potomac Estuary.

The third profile shown in Figure VII-9, based on a constant dispersion coefficient of 2.0 $mi^2$/day, indicates the considerable effect that changing chloride gradients exert on Thomann Model simulation studies. Under this assumption, a minimal amount of chlorides (< 500 mg/l) were transported up the Potomac Estuary from Chesapeake Bay. It can be concluded that the Thomann Model's sensitivity to dispersion is at least equally as great for simulating chlorides as it is for point-source discharges.

The relationship of dispersion coefficient and chloride concentrations established from Thomann Model simulations and actual data collected in 1969 during a relatively steady-state flow period (3,000 cfs-5,000 cfs) can be seen in Figure VII-10.

## EFFECTS OF DISPERSION COEFFICIENT
## THOMANN MODEL CHLORIDE SIMULATIONS
### POTOMAC ESTUARY AT NANJEMOY CREEK

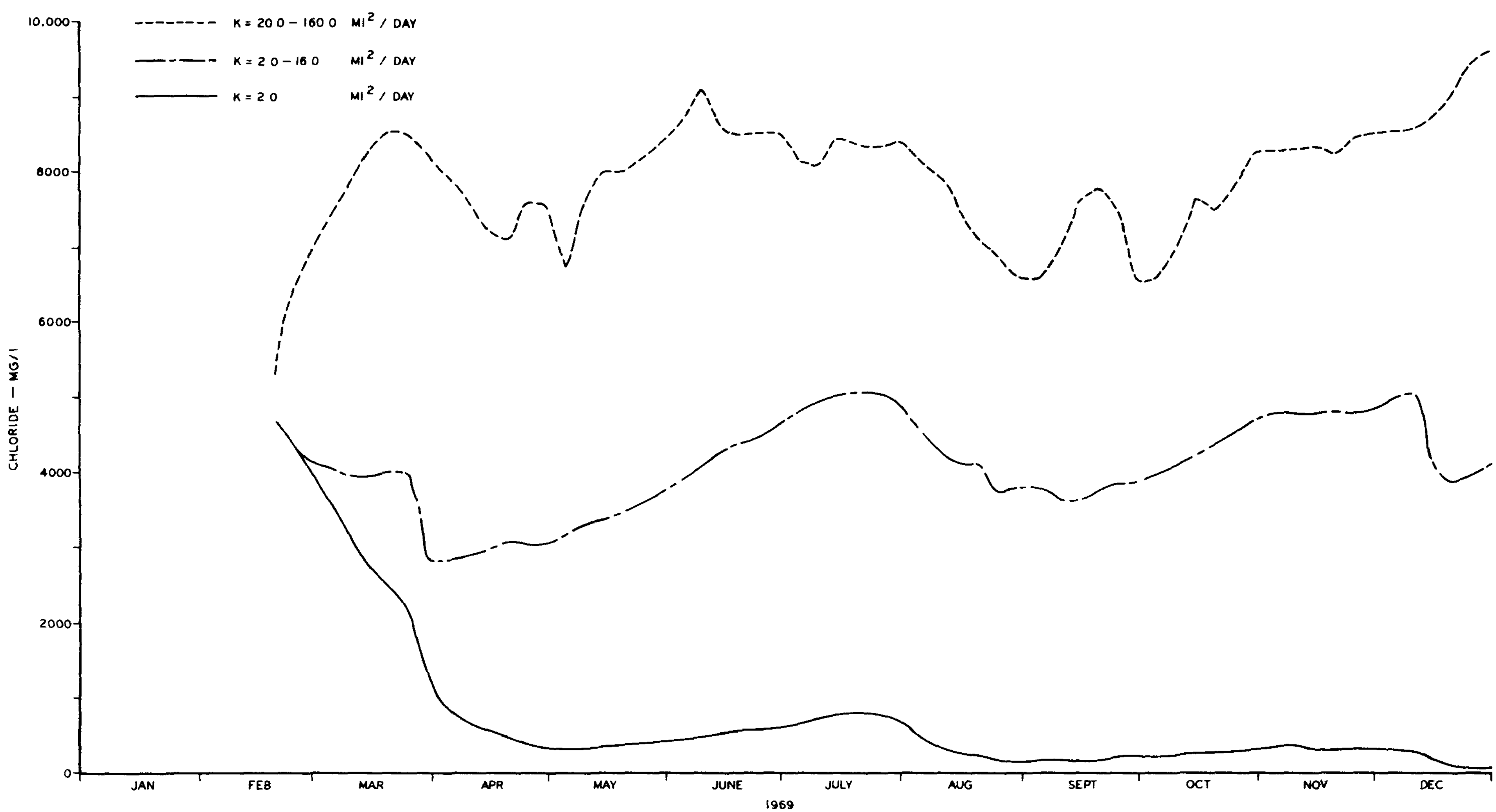



FIGURE VII – 9

## RELATIONSHIP OF DISPERSION COEFFICIENT TO CHLORIDES

**BASED UPON 1969 (3000 — 5000 cfs) DATA**

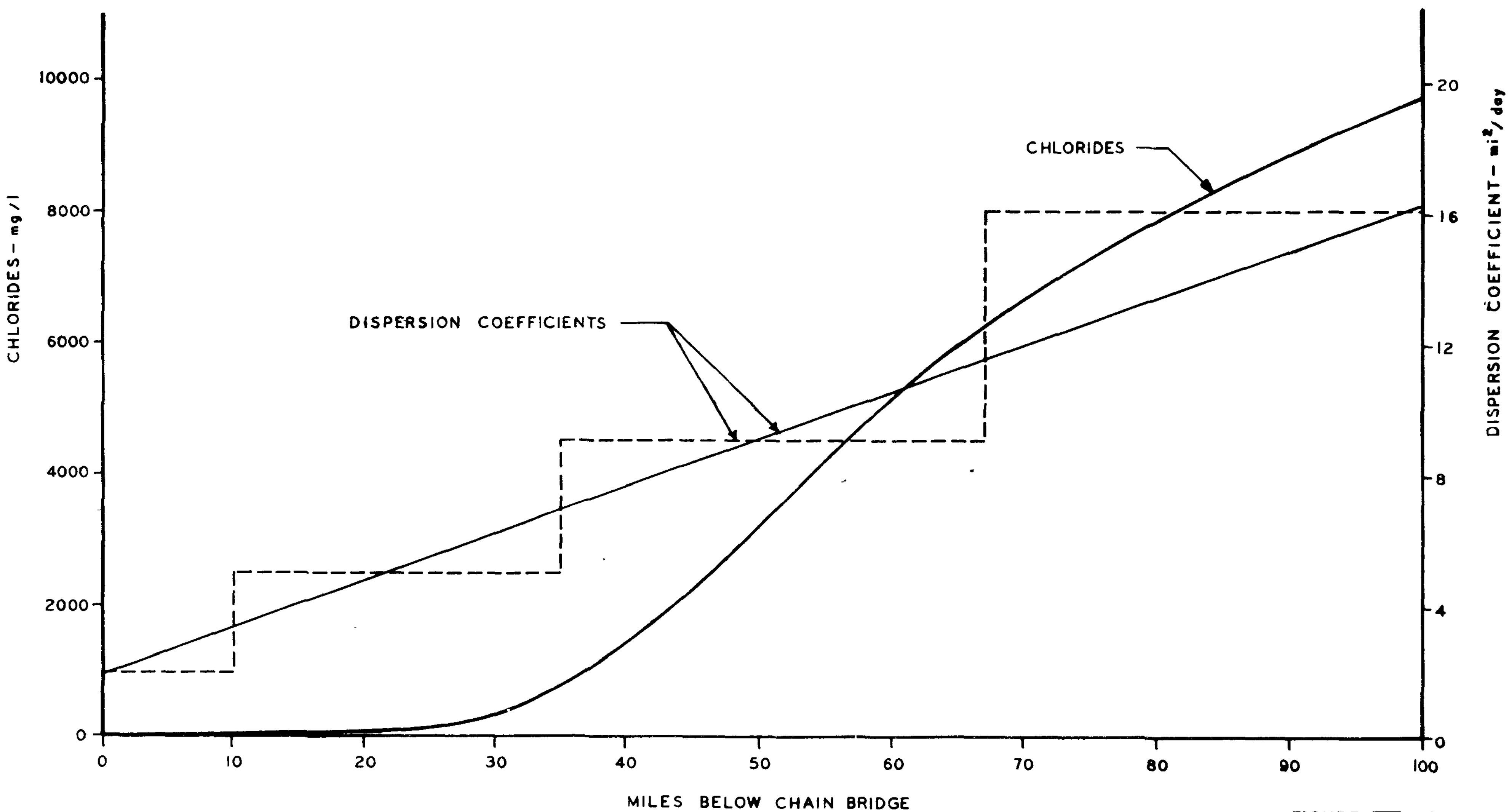



FIGURE VII - 10

## 2. Dynamic Estuary Model

Studies with the Dynamic Estuary Model in the Potomac Estuary indicate that the quality solution is relatively insensitive to the dispersion constant ($C_4$) when considering point discharges in the freshwater portion of the system. On the other hand, the simulation of salinity intrusion with this model indicated a significantly greater sensitivity to the dispersion term. The difficulty encountered with proper assignment of the dispersion term in high salinity areas is due in part to representing a vertically stratified system with a one-dimensional model.

### a. Point Discharges

The effect of the dispersion constant, $C_4$, on the steady-state distribution resulting from a point discharge of 100,000 lbs/day at Blue Plains is indicated in Figure VII-11. These studies were conducted with a 4,430 cfs freshwater inflow and mean tidal conditions. As would be expected, increasing the dispersion constant generally lowers the peak concentration and reduces the concentration gradient somewhat. These comparisons indicate that the predicted distribution resulting from a point discharge is relatively insensitive to the dispersion term in the Dynamic Estuary Model. Because this model simulates advective transfers and mixing resulting from tidal action, there is significantly less dependence on a dispersion term than that shown with the Thomann Model.

## EFFECTS OF DISPERSION CONSTANT ($C_4$)
### ON DYNAMIC ESTUARY MODEL SIMULATIONS
### FOR A POINT DISCHARGE

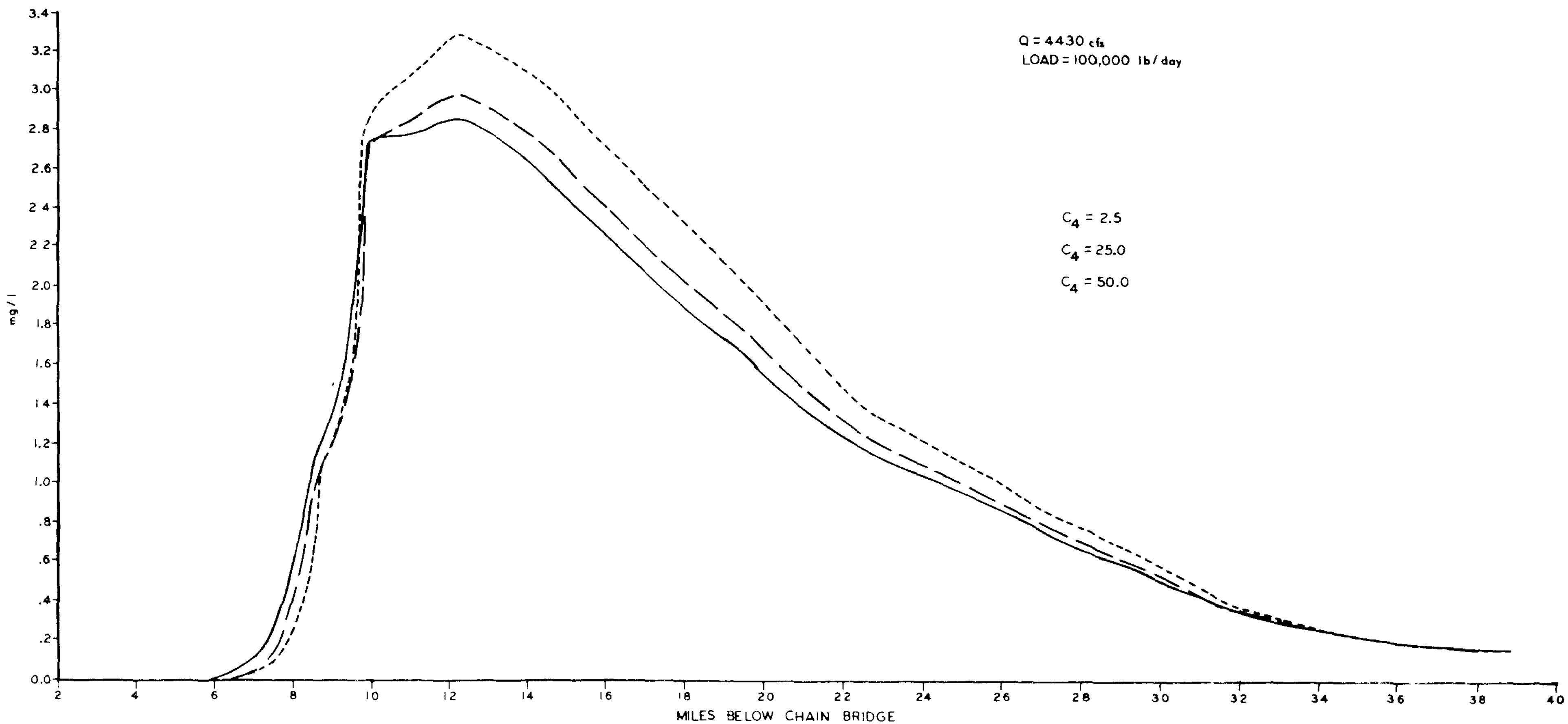



FIGURE VII-11

b. Chloride Distributions

As a second test of the significance of the dispersion term $C_4$ in the Dynamic Estuary Model, an attempt was made, as discussed in the preceding chapter, to simulate changing salinity conditions in the Potomac Estuary during the July 1965 to December 1965 period.

The profiles representing prototype conditions for July 7-8, 1965, and December 1-2, 1965, are shown in Figure VII-12. The initial simulation was completed with the dispersion constant $C_4$ equal to 2.5 for the entire system (labeled model prediction number 1 in Figure VII-12). A second simulation with $C_4$ increased to 25.0 (model prediction number 2 in Figure VII-12) resulted in only a slightly better agreement. From these two simulations, it was apparent that the model was significantly misrepresenting the rate of chloride incursion as well as the chloride distribution through the system. The discrepancies could be attributable to any of several causes, including:

1) Network layout - a brief discussion of the effect of network layout on model predictions is presented in other sections of this report. No further attempt to determine the effect of the network layout on chloride intrusion was made. It remains as a possible significant cause of the poor simulation agreements.
2) Prototype data - insufficient and/or inadequate data to establish prototype behavior can present appreciable problems in model verification. For this comparison, however, the data

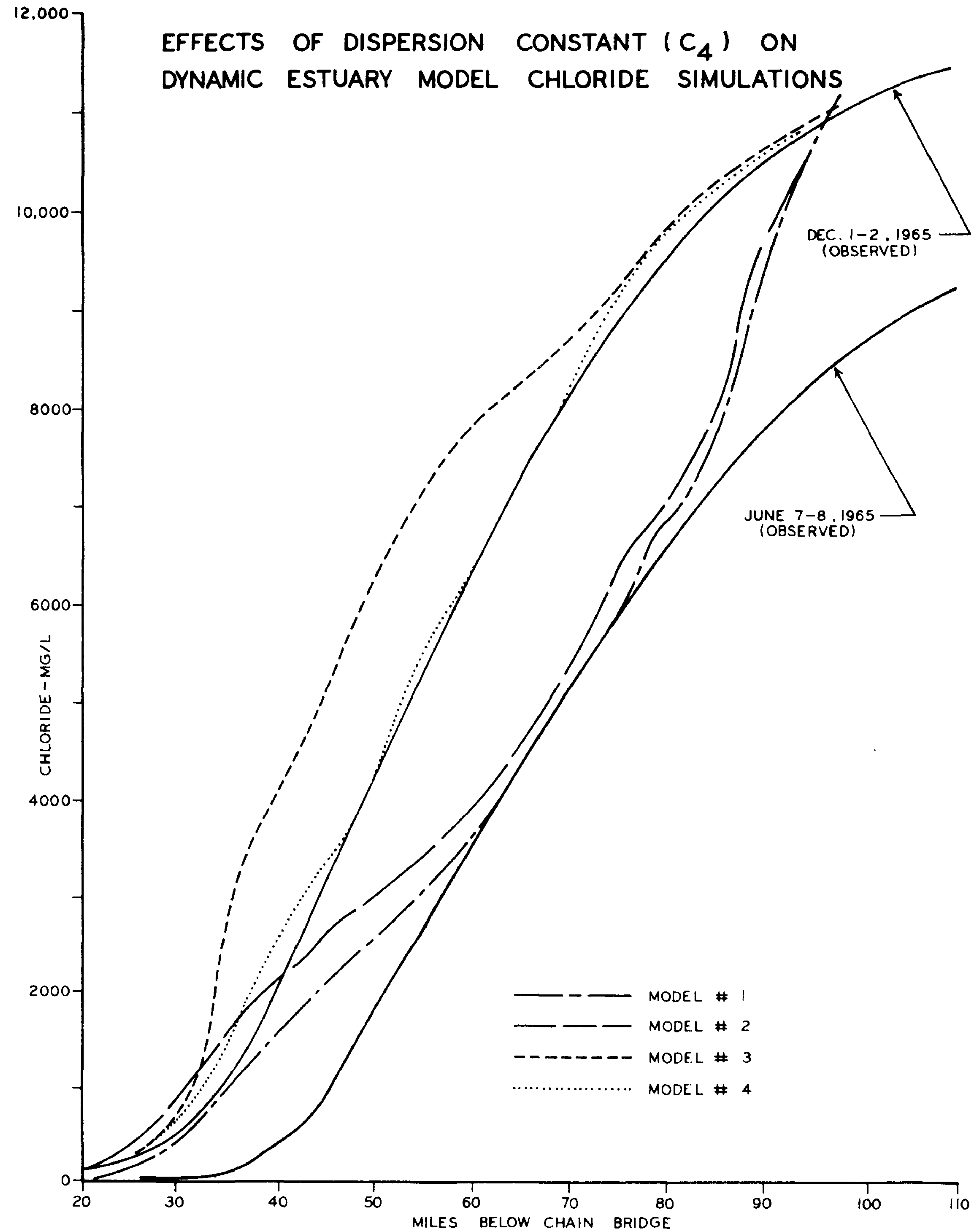



FIGURE VII-12

were considered sufficient to adequately define the profiles and to dismiss the prototype data as a major cause of the discrepancies.

3) Advective transport techniques - the techniques utilized for advective transport within the quality model can significantly affect the rate of movement and the profile of any quality constituent but particularly one which has steep concentration gradients such as salinity. This "numerical mixing" phenomenon is discussed in detail in the DEM Documentation Report [8].

4) Dispersion - although previous applications [8] of the Dynamic Estuary Model indicated that transport due to dispersion was relatively insignificant when compared to advective transport, recent studies by Harleman [7] demonstrated that the dispersion term can be very important in those portions of an estuary with vertical or longitudinal concentration gradients. For this reason the sensitivity of the dispersion term on model predictions was further investigated.

The studies by Harleman [7] indicate that dispersion in areas with perceptible salinity gradients is many times greater than dispersion in areas with uniform salinity. To evaluate the significance of this phenomenon in the Dynamic Estuary Model, it was necessary to incorporate the ability to vary the constant $C_4$ with distance from the seaward boundary. For this study, the estuary was divided into three zones with a different constant for each. The $C_4$ constant was assigned a relatively low value in both the upstream and middle reaches but was increased substantially in the seaward reach. In one simulation (labeled model number 3 in Figure VII-12) $C_4$ was assigned a value of 2.5 in the upper 40 miles of the estuary, 25.0 in the next 20 miles, and a value of 250.0 between River Miles 60 to 96 (the seaward boundary for the model). This simulation demonstrated the marked effect of increasing the dispersion term. The final simulation presented (model number 4 in Figure VII-12) was a result of utilizing a $C_4$ value of 15.0 in the upper 55 miles of the estuary, 80.0 in the next 15 miles, and 250.0 in the downstream 29 miles (River Miles 70-99). Further refinement and adjustment of these dispersion terms undoubtedly would have resulted in even more favorable agreement between model and prototype behavior. However, because of uncertainties in the prototype data base, the uncertainty of the model network effect and other factors, further refinement in this one aspect of the model did not appear warranted. The conclusion reached from this study was that a significant transfer of chloride across the seaward boundary above and beyond that entering the model via the advective transport mechanism is necessary to adequately simulate chloride distributions in the Potomac. This was demonstrated in this study by substantially increasing the dispersion term in the downstream portions of the estuary. Thus the dispersion term appears to be the important factor in predicting the distribution and rate of transfer of a water quality constituent having the ocean as its major source such as chlorides. It should be kept in mind that no specific study was conducted to determine the effect of the network layout on the rate of advective transfer across the seaward boundary. Whether or not this is a significant factor in the case of the Potomac system has yet to be demonstrated.

It is also possible that the dispersion constants determined in this analysis are applicable only for the flow and tidal conditions existing at the time. No specific analysis was conducted to determine whether these constants are appropriate for other freshwater flow conditions.

D. ADVECTIVE TRANSPORT

1. Thomann Model

As mentioned previously, the advective proportionality factor ($\alpha$) should theoretically range between 0.5 and 1.0 depending on the relative importance of dispersion and advection for a given estuary. In the Thomann Model, it is computed as a function of the eddy exchange coefficient and flow. Simulated dye profiles based upon $\alpha$ values of 0.5, 0.75, and 1.0 for all model segments with other variables held constant are shown in Figures VII-13 and VII-14. As can be seen in both of these figures, the three profiles almost coincide indicating that the model is quite insensitive to $\alpha$. Decreasing $\alpha$ results in slightly higher peak concentrations accompanied by less upstream movement. The configuration of the profile's leading edge is unaffected.

In addition to dye simulations, the effects of $\alpha$ on chloride modeling was also investigated. The considerably higher concentration gradient found in the longitudinal chloride distribution did not appear to increase the Thomann Model's sensitivity to the advective component of mass transport as was noted with the dispersion component for similar conditions.

Based upon the above discussion, it would seem that the advective transport mechanism plays an insignificant role in the Thomann Model.

EFFECTS OF ADVECTION FACTOR ($\alpha$)
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 6, 1969

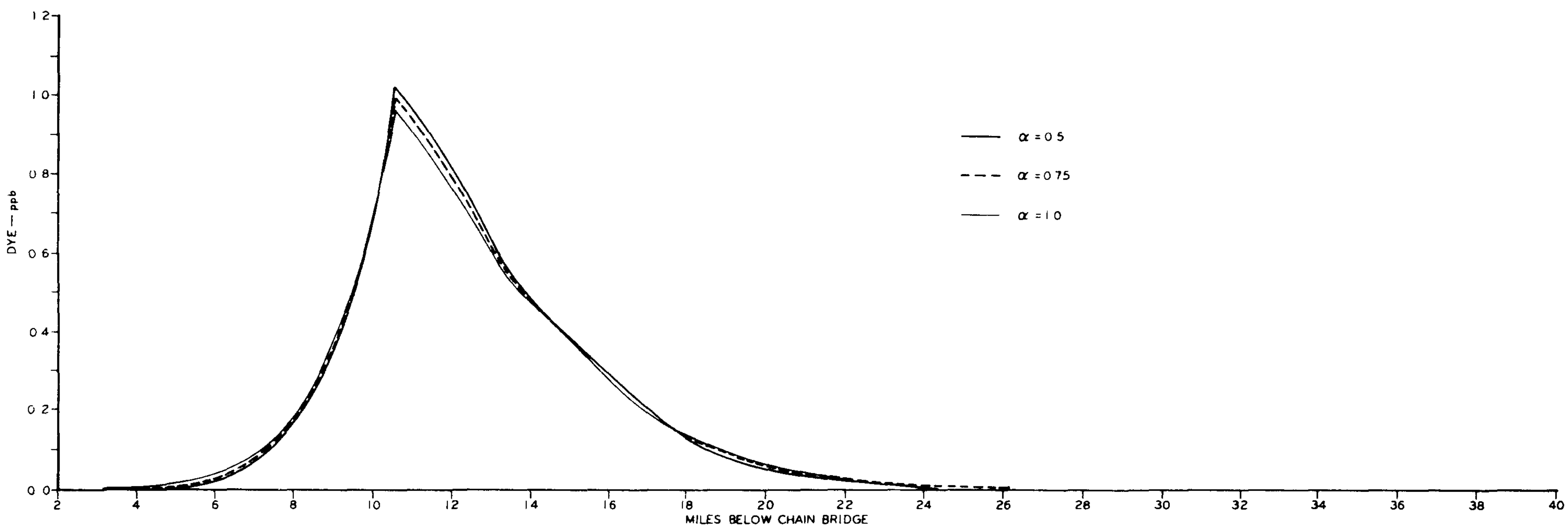



FIGURE VII-13

EFFECTS OF ADVECTION FACTOR (α)
THOMANN MODEL DYE SIMULATIONS
NOVEMBER 12, 1969

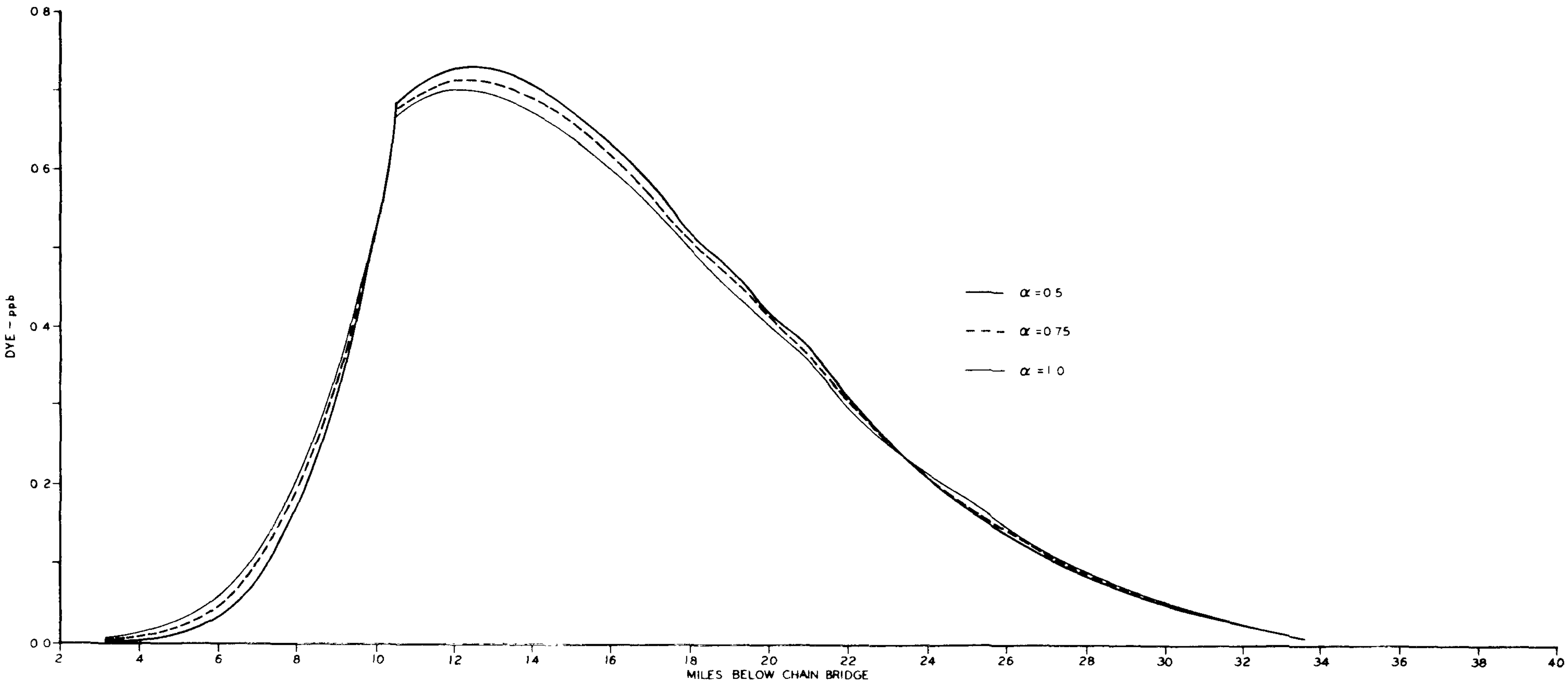



FIGURE VII – 14

2. Dynamic Estuary Model

The effectiveness of the method utilized for advective transport determination in the Dynamic Estuary Model was demonstrated by simulating a somewhat shorter historical salinity incursion period than that utilized to demonstrate the effect of the dispersion term. For this analysis, the chloride conditions in the Potomac during the period October 19 through December 2, 1965, were used as a basis for comparing two different solution techniques. The effect of changing the concentration in the advected water from that computed at a channel's quarter point to that computed at the upstream third point is illustrated in Figure VII-15. As can be noted, the quarter-point method significantly increases the predicted upstream incursion and tends to flatten the gradient more than the third-point method. While the third-point method produces the more favorable comparison with prototype behavior, it should not be interpreted as the "best" the model can do since the comparisons could have been improved by use of appropriate dispersion constants throughout the estuary (as discussed in a previous section). The curves are included only to illustrate the effect of the advective solution technique. It is apparent that the model predictions are sensitive to the method used for advective transport; however, the effect is more pronounced for water quality constituents with substantial concentration gradients such as chloride. For other water quality constituents with less significant gradients, the predictions are much less sensitive to the solution technique used.

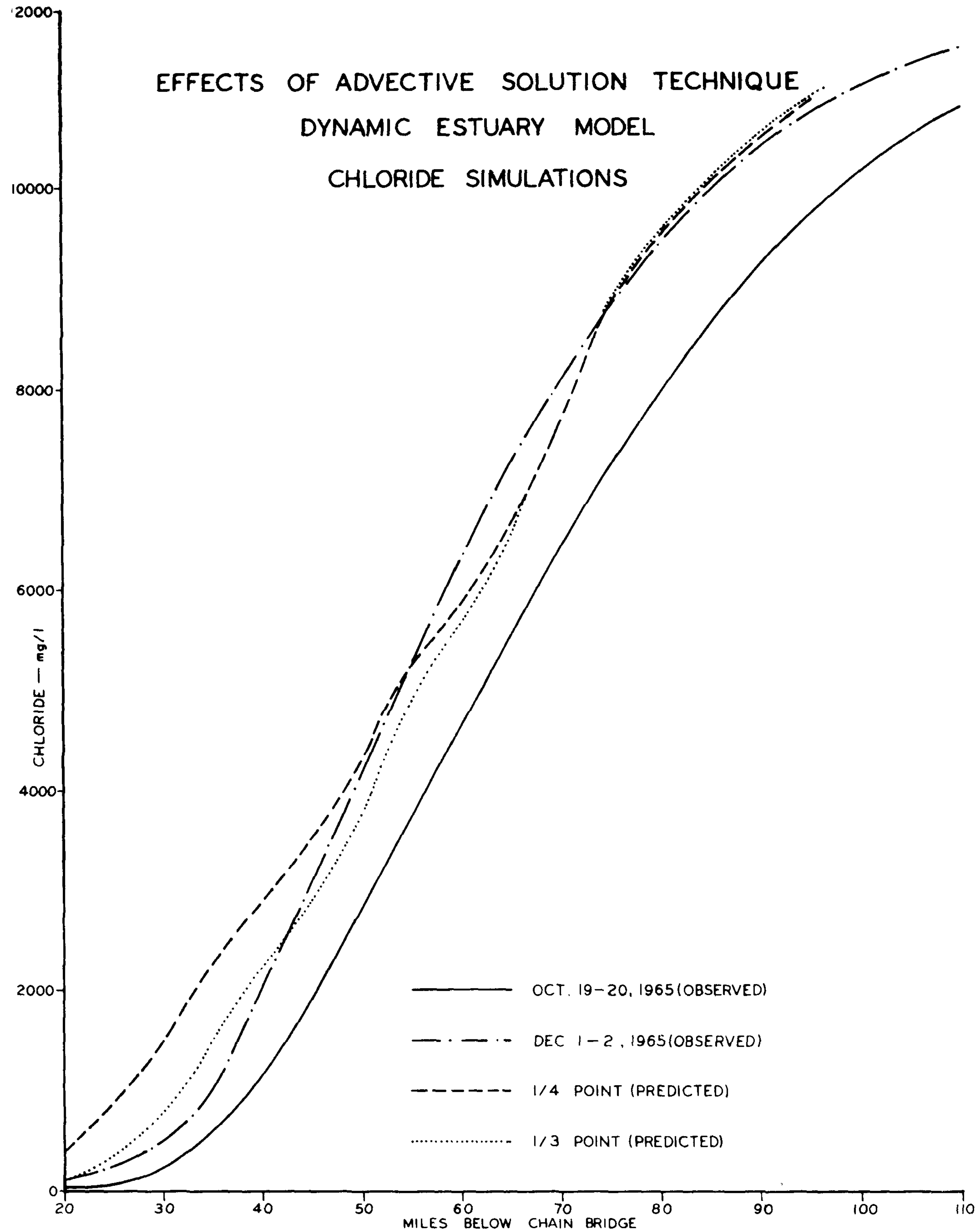



FIGURE VII-15

E. RIVER FLOW AND DISPERSION COEFFICIENTS (THOMANN MODEL)

To increase the predictive reliability of the Thomann Model in the upper Potomac Estuary, the effect of freshwater inflows on dispersion coefficients was investigated. The simulation of November 1969 and June 1965 dye study data indicated that a direct relationship existed whenever flows were between 1,400 and 4,000 cfs. The increased inflows which occurred during the study periods required higher dispersion coefficients in order to obtain a satisfactory agreement between prototype and model data. Moreover, a study in the Delaware Estuary by Paulson [9] also indicated that dispersion increased directly with flow. This relationship may be partly due to the dissipation of the larger energy levels associated with greater flows.

The approach adopted for this analysis was a comparison of simulated data from the tidal and nontidal models for the upper 30 miles of the Potomac Estuary. The data generated by the "real-time" tidal model was used as a basis for determining when the most favorable predictions, hence most applicable dispersion coefficients, occurred with the Thomann Model. Four separate flow conditions, ranging from 930 cfs to 20,000 cfs, were investigated. For each inflow, an arbitrary loading at Blue Plains of 100,000 lbs/day with a decay rate of 0.1/day (base e) was assumed. Initial and boundary concentrations were set to zero in both models and simulations continued in time until steady-state conditions were observed.

The dispersion coefficients yielding the best data with the Thomann Model are plotted as a function of flow in Figure VII-16.

## DISPERSION COEFFICIENT VS. FLOW
### THOMANN MODEL
### UPPER POTOMAC ESTUARY

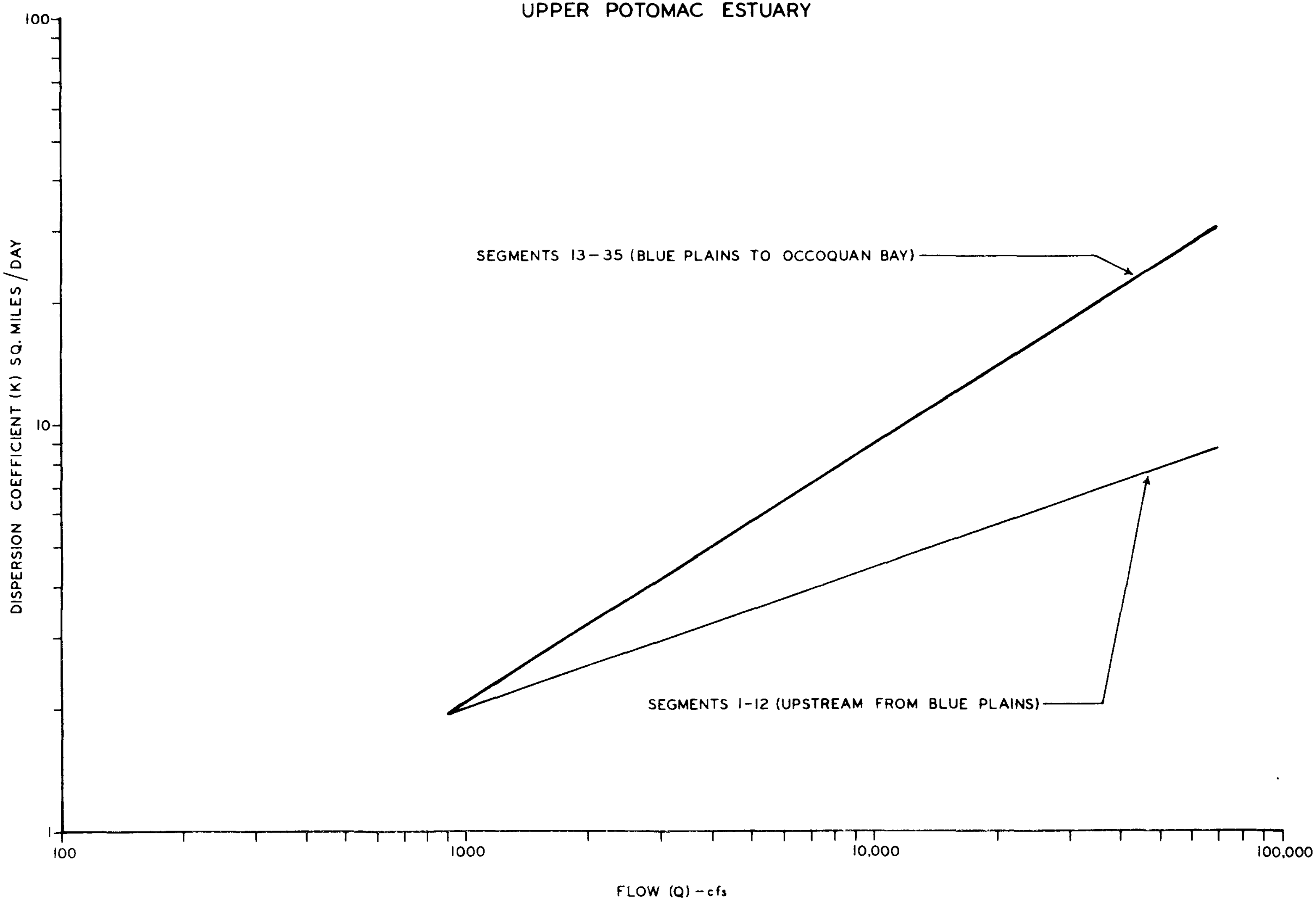



FIGURE VII – 16

As can be seen in Figure VII-16, there were two different K versus Q relationships--one applied to the model segments upstream from the discharge point and the other to the segments between the discharge point and the Occoquan Bay. The effects of flow on the dispersion coefficient were more pronounced in the downstream direction but nevertheless a direct relationship between the two existed upstream as well. For the higher flow conditions, it appeared that the increased downstream advective movement overshadowed the effects of upstream dispersion resulting from the higher coefficients.

F. MANNING COEFFICIENT AND TIDAL EFFECTS (DYNAMIC ESTUARY MODEL)

Studies were made with the Dynamic Estuary Model to ascertain the effects of Manning's roughness coefficient (n) on the steady-state hydraulic solution and its subsequent effects on the quality program. Moreover, two different tidal conditions (mean annual and mean spring tide) were simulated hydraulically to determine the sensitivity of tidal input on quality predictions.

The following table contains various sets of Manning coefficients for the main Potomac and the corresponding dynamic steady-state tides predicted at Washington. For purposes of comparison, the mean tide which was used for this investigation had an average range at Washington of 2.9 feet and phasing differences referenced to Piney Point of 6.4 hours and 7.1 hours for high and low water, respectively. At Piney Point, the average tidal range was 1.4 feet.

Table VII-1

Effects of Manning Coefficients on Tides

| "n" (decreasing downstream) | Tidal Range (ft.) | High and Low Lag Times (hrs.) |
|---|---|---|
| .023 - .020 - .016 | 2.60 | 5.80 - 7.00 |
| .020 - .019 | 2.23 | 6.05 - 7.10 |
| .025 - .020 - .017 | 2.48 | 5.80 - 7.00 |
| .025 - .022 - .020 | 2.13 | 6.10 - 7.15 |
| .020 - .017 - .015 | 2.73 | 5.85 - 7.00 |
| .020 - .017 - .014 | 2.85 | 5.90 - 7.00 |

It is evident from the above data that tidal range was more sensitive to channel roughness than tidal phase. The greater roughness values slowed the tidal movement and thereby produced greater lag times and lower ranges. The best agreement was obtained with "n" ranging from .020 to .014. While the hydraulics were relatively sensitive to Manning coefficients, quality program output based upon two different sets of coefficients indicated that simulated concentrations were essentially unchanged. An attempt to overrefine Manning coefficients does not appear warranted from the standpoint of required predictive capability.

In addition to the use of mean tidal figures previously discussed, numerous simulation studies were made for the Potomac using the mean spring tidal figures. This particular tide has a range of 1.6 feet at Piney Point and 3.3 feet at Washington. The most favorable simulation of the spring tide again occurred with Manning coefficients varying from .020 to .014. The predicted quality data in the upper Potomac Estuary resulting from the use of mean spring tidal figures did not differ appreciably from a mean annual tide hydraulic condition. Maximum concentration differences were less than 10 percent.

# CHAPTER VIII

# ENGINEERING CONSIDERATIONS

## A. DISPERSION AND ADVECTION

The mathematical model simulation studies discussed in this report indicated that dispersion coefficients were particularly significant when a "tidal-averaging" concept was used. Since lateral differences in tidal velocities are the predominant driving force in physical dispersion, a nontidal system must include a gross term approximating the total effect of various individual dispersion components.

The dispersion coefficient employed in the Thomann Model was hard to evaluate. Two large scale dye studies were conducted in the upper Potomac Estuary in an attempt to characterize dispersion, but the results appear to contain discrepancies. The 1969 dye study yielded dispersion coefficients of 2.0 and 3.0 $mi^2$/day for 1,900 cfs and 3.0 and 5.0 $mi^2$/day for 4,000 cfs. For a similar reach of the Potomac, values of 2.0 $mi^2$/day (3,200 cfs) and 1.0 $mi^2$/day (1,600 cfs) provided the best agreement between observed and simulated 1965 dye study data. While it can be concluded that dispersion coefficients in the Thomann Model for a point-source discharge appeared to be directly related to freshwater inflow rates, the probable magnitudes to be assigned for predictive studies using fairly conservative constituents are difficult to determine. It should be noted that the aforementioned dye studies produced only approximate values of dispersion which have limited application. When constituents exhibiting significant degradability are simulated, i.e., $K > 0.1$/day, the effects of dispersion in the nontidal modeling approach will be decreased because the natural decay process dominates the effects of transport and primarily governs the constituent distribution.

Simulation of chloride data also created problems because dispersion coefficients appear to be greatly influenced by salinity gradients. The 1966 and 1969 chloride simulations, as presented in Chapter VI, again indicated wide variation in dispersion coefficients both spatially and temporally. From the dispersion standpoint, the 1966 chloride simulations yielded results comparable to those of the dye studies, i.e., dispersion coefficients were found to be directly proportional to freshwater inflow. However, the 1969 chloride simulations showed a different relationship. In order to realize basic agreement between simulated profiles and observed data, dispersion coefficients were held constant for the entire year of simulation regardless of freshwater inflow rates. Not only did this approach differ with the direct K versus Q relationship developed in Chapter VII for a point discharge but with the logical definition of dispersion as applied to chloride intrusion as well. It would appear that the true dispersion coefficients for a tracer discharged into the upper reaches of the Potomac Estuary and dispersing primarily in a downstream direction are directly proportional to inflow rates because advection and diffusion forces have accumulative effects. Dispersion coefficients for chlorides and other constituents dispersing upstream should then be inversely proportional to flow; although this was not reflected in the Thomann Model simulations presented in this report. Since chloride intrusion is in an upstream direction and the forces of advection and diffusion oppose each other, it is reasonable to assume that during low-flow periods, maximum intrusion would result. To duplicate similar performance in the model, high dispersion coefficients were necessary to simulate the downstream movement of the chloride wedge.

Discrepancies in the interrelationship between dispersion, advection and flow on the hydrodynamic behavior and the relative insensitivity of the advective proportionality factor suggest that tidal and nontidal advection is deemphasized in the Thomann Model. The method by which this model handles incoming flows may be responsible for deficiencies in the basic transport mechanisms of dispersion and advection. A given flow sequence, for example, is assumed to occur instantaneously throughout the system, indicating that the hydraulics are strictly a function of velocity (Q/A) and not volume displacement. It can be concluded that continual refinement of the dispersion coefficient and a sound understanding of how it is affected by various factors within a given system are mandatory when applying the Thomann Model to any great extent.

The simulations for a point-source discharge conducted using the Dynamic Estuary Model indicated that a much more accurate representation of advection and dispersion can be expected. The insensitivity of this model to the dispersion component and the relative importance of tidal and advective forces were indications that the DEM more realistically approximates the hydrodynamic behavior of the prototype.

In the case of chlorides or other constituents entering the Potomac Estuary from the Chesapeake Bay, caution must be exercised when assigning the dispersion term $C_4$ in areas with large concentration gradients. The chloride simulations performed with the DEM showed that dispersion can be directly related to the concentration gradient and furthermore that the advective concentration is quite important. Whether this can be attributed to the coarse network used or some other peculiarity in the solution technique has not been adequately determined. Since this model employs a "real-time" system, it is essential that the total quantity of constituent crossing the seaward boundary over a complete tidal cycle be accurately represented, even if this is done by drastically increasing dispersion.

## B. MODEL COMPARISON

As discussed in previous sections of this report, the primary disadvantage of the Thomann Model, or any other nontidal model, is the difficulty in selection of appropriate dispersion coefficients. Costly dye studies and field data collection can provide an approximation of this coefficient but the accuracy necessary for various predictive water quality studies will probably remain to be developed. Other important disadvantages of the Thomann Model are its inability to (1) branch in a lateral direction, (2) link more than two constituents, and (3) simulate the effects of tides on the distribution of a constituent.

The major advantages of the Thomann Model over the FWQA Dynamic Estuary Model as presently programmed are (1) less stringent input requirements, (2) its ability through Namelist I/O option to change input variables, such as flow on a daily basis, and thereby readily simulate an entire year's or season's characteristics, and (3) the capability of running several different data decks "back-to-back" without having to resubmit the whole program. In light of the above, one can investigate many more alternatives in much less time with the Thomann Model which is important when time is critical.

Except as noted earlier, the Dynamic Estuary Model does not appear to be very sensitive to the dispersion coefficient since tidal effects are included. Furthermore, the short time step which can be used in the real-time quality solution enables this model to make a better prediction for constituents having a relatively fast reaction rate. Nitrification analysis, for example, may be better investigated with the Dynamic Estuary Model. Recent refinement in the quality program has added several additional source and sink terms in DO budget analyses. The effects of algal photosynthesis and respiration based upon conversion of inorganic nitrogen to chlorophyll a, nitrogenous oxygen demand, benthic oxygen demand, and modifications to the reaeration term have been programmed into the model and should definitely increase its capability in predicting DO concentrations in eutrophic estuarine waters. Another recent innovation was the expansion of the first-order reaction system to any order system. This was the outcome of preliminary phosphate simulation data analysis which indicated that a second-order reaction was more applicable. A report currently being prepared by CTSL [10] describes such nutrient and DO simulation studies. Source and sink terms in the DO budget have not been delineated to this extent in the Thomann Model nor can chlorophyll levels be simulated by linkage with the nitrogen cycle.

When initially applying the Dynamic Estuary Model to a given system, reasonable care is required in simulating the hydraulics to avoid major errors in the quality predictions. The values assumed for Manning roughness coefficients are particularly important since they influence both the tidal range and phasing. An optimum set of coefficients with verification based upon USC&GS tidal data should be determined by trial and error procedures prior to any quality simulations. Another factor warranting consideration in the hydraulic model is the time step used for the solution. In order to minimize hydrodynamic instability, a stability criterion which relates channel length, wave celerity, and tidal velocity to the time step, must be satisfied. Once the stability criterion is met, selecting shorter time intervals would not improve the hydraulic predictions significantly.

A discussion of both models' sensitivity to the physical network detail was previously presented. The Thomann Model, possibly because of its averaging effect over long time periods, does not appear to be very sensitive to degree of segmentation. For the Potomac Estuary, segment lengths of 1 to 3 miles were adequate. The Dynamic Estuary Model appears to be considerably more sensitive to the refinement of the network based upon limited data pertaining to the two networks originally developed for the Thomann Model. However, it should be recognized that input requirements and computer time and output increase in proportion to the number of channels and junctions selected. Time and resource restraints must be weighed against accuracy of data required before an evaluation of the required network can be made.

Practically all of the prototype dye data were reasonably simulated with the Thomann and Dynamic Estuary Models. With sufficient manipulation of dispersion coefficients, it was possible to make reasonable simulations of the 1966 and 1969 Potomac Estuary chloride distributions using the Thomann Model and of a 5-month transient chloride condition (1965) using the DEM. From an engineering viewpoint, it is preferable to refine the hydrodynamics of a system by utilizing a real-time solution (such as the Dynamic Estuary Model) rather than to represent a gross tidal mixing phenomenon with an empirically derived dispersion coefficient applicable only over a narrow range of prototype conditions. This is particularly significant when attempting to predict water quality behavior for future conditions significantly different from any experienced historically and for which the validity of the dispersion coefficients is uncertain. From a practical standpoint, however, the Thomann Model does offer expediency with minimum effort.

# APPENDIX

## A. POTOMAC DYE STUDY - 1969

### 1. Release Conditions

A 6-percent solution of Rhodamine WT dye was discharged continuously into the upper Potomac Estuary from November 2-14, 1969, via the District of Columbia's Blue Plains Sewage Treatment Plant outfall. This outfall extends to the main shipping channel approximately 900 feet from the eastern shore at a point 10.4 miles downstream from Chain Bridge. The dye solution was discharged into the elutriation washwater discharge sump which drains directly to the outfall. Initially, dye was pumped at a rate of 120 ml/min but a pump failure occurred during the second day of the study. It was therefore decided to use a siphoning procedure for the remaining 12 days.

Due to the imprecision of siphoning, it was necessary to recalibrate the discharge rate of 120 ml/min several times each day. As an additional check, the rectangular tank in which the dye solution was mixed was accurately measured to determine changes in the volume of dye. Volume changes for each 4-hour period of the study were recorded and subsequently converted to a mass basis. Table 1 presents volumes, discharge rates and related factors for the 13-day release period. Except for November 3 when a pump failure occurred and November 11-12 when a line became clogged, the dye injection rates (as shown in Table 1) were relatively uniform. During this release period, a total of 269 pounds of pure dye (4,454 pounds of 6-percent dye solution) was discharged to the Potomac Estuary.

Table 1
DYE INJECTION DATA
Blue Plains - November, 1969

| Date | Time Period | Average Dye Level (in) | Average Surface Area (sq-in) | Change in Dye Level (in) | Volume (cu-in) | Discharge Rate (ml/min) | Mass of Dye Solution (6%) Discharged (lbs) | Mass of Pure Dye Discharged (lbs) |
|---|---|---|---|---|---|---|---|---|
| 11-02 | 0800 - 1200 | 13.16 | 2532 | 0.57 | 1443 | 98.6 | 54.8 | 3.31 |
| | 1200 - 1600 | 12.58 | 2527 | 0.57 | 1440 | 98.4 | 54.7 | 3.30 |
| | 1600 - 2000 | 12.00 | 2522 | 0.57 | 1438 | 98.2 | 54.6 | 3.30 |
| | 2000 - 2400 | 11.44 | 2518 | 0.57 | 1435 | 98.0 | 54.5 | 3.29 |
| 11-03 | 0000 - 0400 | 11.08 | 2515 | 0.16 | 402 | 27.5 | 15.3 | 0.92 |
| | 0400 - 0800 | 11.00 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| | 0800 - 1200 | 10.00 | 2506 | 2.00 | 5012 | 342.3 | 190.5 | 11.51 |
| | 1200 - 1600 | 8.75 | 2495 | 0.50 | 1248 | 85.2 | 47.4 | 2.86 |
| | 1600 - 2000 | 7.94 | 2488 | 1.12 | 2787 | 190.4 | 105.9 | 6.40 |
| | 2000 - 2400 | 7.12 | 2482 | 0.50 | 1241 | 84.8 | 47.2 | 2.85 |
| 11-04 | 0000 - 0400 | 6.56 | 2477 | 0.62 | 1536 | 104.9 | 58.4 | 3.53 |
| | 0400 - 0800 | 6.00 | 2472 | 0.50 | 1236 | 84.4 | 47.0 | 2.84 |
| | 0800 - 1200 | 5.40 | 2467 | 0.69 | 1702 | 116.2 | 64.7 | 3.91 |
| | 1200 - 1600 | 4.72 | 2461 | 0.69 | 1698 | 116.0 | 64.5 | 3.90 |
| | 1600 - 2000 | 17.40 | 2568 | 1.19 | 3056 | 208.7 | 116.1 | 7.01 |
| | 2000 - 2400 | 16.65 | 2561 | 0.31 | 794 | 54.2 | 30.2 | 1.82 |
| 11-05 | 0000 - 0400 | 16.22 | 2558 | 0.56 | 1432 | 97.8 | 54.4 | 3.29 |
| | 0400 - 0800 | 15.69 | 2553 | 0.50 | 1276 | 87.2 | 48.5 | 2.93 |
| | 0800 - 1200 | 15.22 | 2550 | 0.44 | 1122 | 76.6 | 42.6 | 2.57 |
| | 1200 - 1600 | 14.69 | 2545 | 0.62 | 1578 | 107.8 | 60.0 | 3.62 |
| | 1600 - 2000 | 13.94 | 2539 | 0.875 | 2222 | 151.8 | 84.4 | 4.01 |
| | 2000 - 2400 | 13.16 | 2532 | 0.69 | 1747 | 119.3 | 66.4 | 4.01 |
| 11-06 | 0000 - 0400 | 12.47 | 2526 | 0.685 | 1730 | 118.2 | 65.7 | 3.97 |
| | 0400 - 0800 | 11.81 | 2521 | 0.625 | 1576 | 107.6 | 59.9 | 3.62 |
| | 0800 - 1200 | 11.12 | 2515 | 0.75 | 1886 | 128.8 | 71.7 | 4.33 |
| | 1200 - 1600 | 10.42 | 2509 | 0.66 | 1656 | 113.1 | 62.9 | 3.80 |
| | 1600 - 2000 | 9.80 | 2504 | 0.59 | 1477 | 100.9 | 56.1 | 3.39 |
| | 2000 - 2400 | 8.78 | 2495 | 1.44 | 3593 | 245.4 | 136.5 | 8.24 |
| 11-07 | 0000 - 0400 | 7.62 | 2486 | 0.87 | 2163 | 147.7 | 82.2 | 4.97 |
| | 0400 - 0800 | 6.97 | 2480 | 0.44 | 1091 | 74.5 | 41.5 | 2.51 |
| | 0800 - 1200 | 6.25 | 2474 | 1.00 | 2474 | 169.0 | 94.0 | 5.68 |
| | 1200 - 1600 | 5.62 | 2469 | 0.25 | 617 | 42.1 | 23.5 | 1.42 |
| | 1600 - 2000 | 18.59 | 2578 | 0.44 | 1134 | 77.4 | 43.1 | 2.60 |
| | 2000 - 2400 | 18.06 | 2573 | 0.625 | 1608 | 109.8 | 61.1 | 3.69 |
| 11-08 | 0000 - 0400 | 17.47 | 2568 | 0.56 | 1438 | 98.2 | 54.6 | 3.30 |
| | 0400 - 0800 | 16.97 | 2564 | 0.44 | 1128 | 77.0 | 42.9 | 2.59 |
| | 0800 - 1200 | 16.50 | 2560 | 0.50 | 1280 | 87.4 | 48.6 | 2.94 |
| | 1200 - 1600 | 16.06 | 2556 | 0.38 | 971 | 66.3 | 36.9 | 2.23 |
| | 1600 - 2000 | 15.44 | 2551 | 0.875 | 2232 | 152.4 | 84.8 | 5.12 |
| | 2000 - 2400 | 14.69 | 2545 | 0.625 | 1991 | 108.7 | 60.5 | 3.65 |

DYE INJECTION DATA (Cont.)
Blue Plains - November, 1969

| Date | Time Period | Average Dye Level (in) | Average Surface Area (sq-in) | Change in Dye Level (in) | Volume (cu-in) | Discharge Rate (ml/min) | Mass of Dye Solution (6%) Discharges (lbs) | Mass of Pure Dye Discharged (lbs) |
|---|---|---|---|---|---|---|---|---|
| 11-09 | 0000 - 0400 | 14.03 | 2540 | 0.69 | 1753 | 119.7 | 66.6 | 4.02 |
| | 0400 - 0800 | 13.34 | 2534 | 0.69 | 1748 | 119.4 | 66.4 | 4.01 |
| | 0800 - 1200 | 12.56 | 2527 | 0.875 | 2211 | 151.0 | 84.0 | 5.07 |
| | 1200 - 1600 | 11.94 | 2522 | 0.38 | 958 | 65.4 | 36.4 | 2.20 |
| | 1600 - 2000 | 11.28 | 2516 | 0.94 | 2365 | 161.5 | 89.9 | 5.43 |
| | 2000 - 2400 | 10.47 | 2510 | 0.69 | 1732 | 118.3 | 65.8 | 3.98 |
| 11-10 | 0000 - 0400 | 9.78 | 2504 | 0.69 | 1728 | 118.0 | 65.7 | 3.97 |
| | 0400 - 0800 | 9.10 | 2498 | 0.69 | 1724 | 117.8 | 65.5 | 3.96 |
| | 0800 - 1200 | 8.47 | 2493 | 0.56 | 1396 | 95.4 | 53.1 | 3.21 |
| | 1200 - 1600 | { 8.03 | { 2489 | { 0.31 | | | | |
| | | { 13.69 | { 2537 | { 0.375 | 1723 | 117.7 | 65.5 | 3.96 |
| | 1600 - 2000 | 13.12 | 2532 | 0.75 | 1899 | 129.7 | 72.2 | 4.36 |
| | 2000 - 2400 | 12.38 | 2526 | 0.75 | 1895 | 129.4 | 72.0 | 4.35 |
| 11-11 | 0000 - 0400 | 11.62 | 2519 | 0.75 | 1889 | 129.0 | 71.8 | 4.34 |
| | 0400 - 0800 | 10.69 | 2512 | 1.125 | 2826 | 193.0 | 107.4 | 6.49 |
| | 0800 - 1200 | 9.94 | 2505 | 0.375 | 939 | 64.1 | 35.7 | 2.16 |
| | 1200 - 1600 | 9.69 | 2503 | 0.125 | 313 | 21.4 | 11.9 | 0.72 |
| | 1600 - 2000 | 9.56 | 2502 | 0.125 | 313 | 21.4 | 11.9 | 0.72 |
| | 2000 - 2400 | 9.50 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| 11-12 | 0000 - 0400 | 9.50 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| | 0400 - 0800 | 9.50 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| | 0800 - 1200 | 9.50 | -- | 0.00 | 0 | 00.0 | 00.0 | 0.00 |
| | 1200 - 1600 | 9.25 | 2500 | 0.50 | 1250 | 85.4 | 47.5 | 2.87 |
| | 1600 - 2000 | 8.50 | 2493 | 1.00 | 2493 | 170.3 | 94.7 | 5.72 |
| | 2000 - 2400 | 7.88 | 2488 | 0.25 | 622 | 42.5 | 23.6 | 1.43 |
| 11-13 | 0000 - 0400 | 7.69 | 2486 | 0.125 | 311 | 21.2 | 11.8 | 0.72 |
| | 0400 - 0800 | 7.44 | 2484 | 0.375 | 932 | 63.7 | 35.4 | 2.14 |
| | 0800 - 1200 | 7.12 | 2482 | 0.25 | 620 | 42.4 | 23.6 | 1.43 |
| | 1200 - 1600 | 6.42 | 2476 | 1.17 | 2897 | 197.9 | 110.0 | 6.64 |
| | 1600 - 2000 | 5.23 | 2466 | 1.20 | 2959 | 202.1 | 112.4 | 6.79 |
| | 2000 - 2400 | 4.06 | 2456 | 1.13 | 2775 | 189.5 | 105.5 | 6.37 |
| 11-14 | 0000 - 0400 | 3.00 | 2447 | 1.00 | 2447 | 167.1 | 93.0 | 5.62 |
| | 0400 - 0800 | 2.00 | 2438 | 1.00 | 2438 | 166.5 | 92.6 | 5.59 |
| | 0800 - 1200 | 1.00 | 2430 | 1.00 | 2430 | 166.0 | 92.4 | 5.58 |
| | 1200 - 1600 | 0.25 | 2424 | 0.875 | 2121 | 144.9 | 80.6 | 4.87 |
| | | | TOTALS | | 117,200 | | 4,454 | 269 |

2. Monitoring System

a. Longitudinal Stations (Slack Tide)

Longitudinal sampling in the Potomac Estuary from Key Bridge to Sandy Point during high- and low-slack tide periods was conducted by CTSL. Data from 10 low-slack sampling runs and eight high-slack runs were obtained during the period November 3-December 1. A tabulation of the data as analyzed by the U. S. Geological Survey is included in this appendix.

Surface samples at mid-channel were collected from 18 stations for longitudinal monitoring of the dye release. A listing of these stations is given in Table 2.

b. Lateral and Vertical Stations

To determine the lateral and vertical mixing of the dye, transect sampling was conducted by CTSL at 14 stations, all of which coincided with the longitudinal sampling stations. These transect stations are shown in Table 2.

Five transect sampling runs were made during the period November 4-20. Due to the considerable amount of time required for transect sampling, it was not possible to limit sampling to slack-tide periods. Cross-sectional area profiles showing the sampling grids used for each station are presented in the appendix. As can be seen from these profiles, eight to 17 samples were collected at each station. It should be noted that many of the transects extended into the major embayments.

Table 2

LONGITUDINAL SAMPLING STATIONS
Potomac River

| Station Number | Location | Miles Below Chain Bridge |
|---|---|---|
| 1 * | Key Bridge | 3.35 |
| 1A | Memorial Bridge | 4.85 |
| 2 * | 14th Street Bridge | 5.90 |
| 2A | Buoy N "6" | 6.70 |
| 3 * | Hains Point | 7.60 |
| 3A | Hunter's Point | 8.70 |
| 4 * | Bellevue | 10.00 |
| 4A* | Goose Island | 11.05 |
| 5 * | Woodrow Wilson Bridge | 12.10 |
| 5A | Rosier Bluff | 13.55 |
| 6 * | Broad Creek | 15.20 |
| 7 * | Piscataway Creek | 18.35 |
| 8 * | Dogue Creek | 22.30 |
| 8A* | Gunston Cove | 24.30 |
| 9 * | Hallowing Point | 26.90 |
| 10 * | Indian Head | 30.60 |
| 11 | Possum Point | 38.00 |
| 12 | Sandy Point | 42.50 |

* Also transect stations

3. Presentation of Data

a. Tidal Conditions and Hydrology

The tidal conditions in the upper Potomac Estuary at Washington, D. C. are monitored routinely by the U. S. Coast and Geodetic Survey. Figures 1, 2, and 3 present actual tidal data at Washington for most of November 1969 and the mean tidal height at this station for the entire period of record.

As can be seen in Figures 1 through 3, there were three distinct tidal conditions during November. The first 3 days of the month were characterized by atypically high tides with considerable fluctuations in the tidal range. The predominately northwesterly winds which occurred on November 3-6 were responsible for the steadily decreasing tidal levels shown during this period. These extremely low tides had a pronounced effect on the downstream movement of dye. The remaining 3 weeks showed generally normal tidal ranges with average heights approximating the mean-tide condition. The slight decrease in tidal levels on November 19-21 was again attributed to high northwesterly winds.

Average daily flows measured at Great Falls during November 1969 are shown in Figure 4. Freshwater inflows to the upper Potomac Estuary, like tides, were influenced greatly by climatological conditions. As indicated in Figure 4, two separate flow regimes occurred. The period November 1-5 had an average flow of 1,886 cfs whereas during the remainder of the month, the average flow was 3,974 cfs. Daily flows within each period were uniform, however.

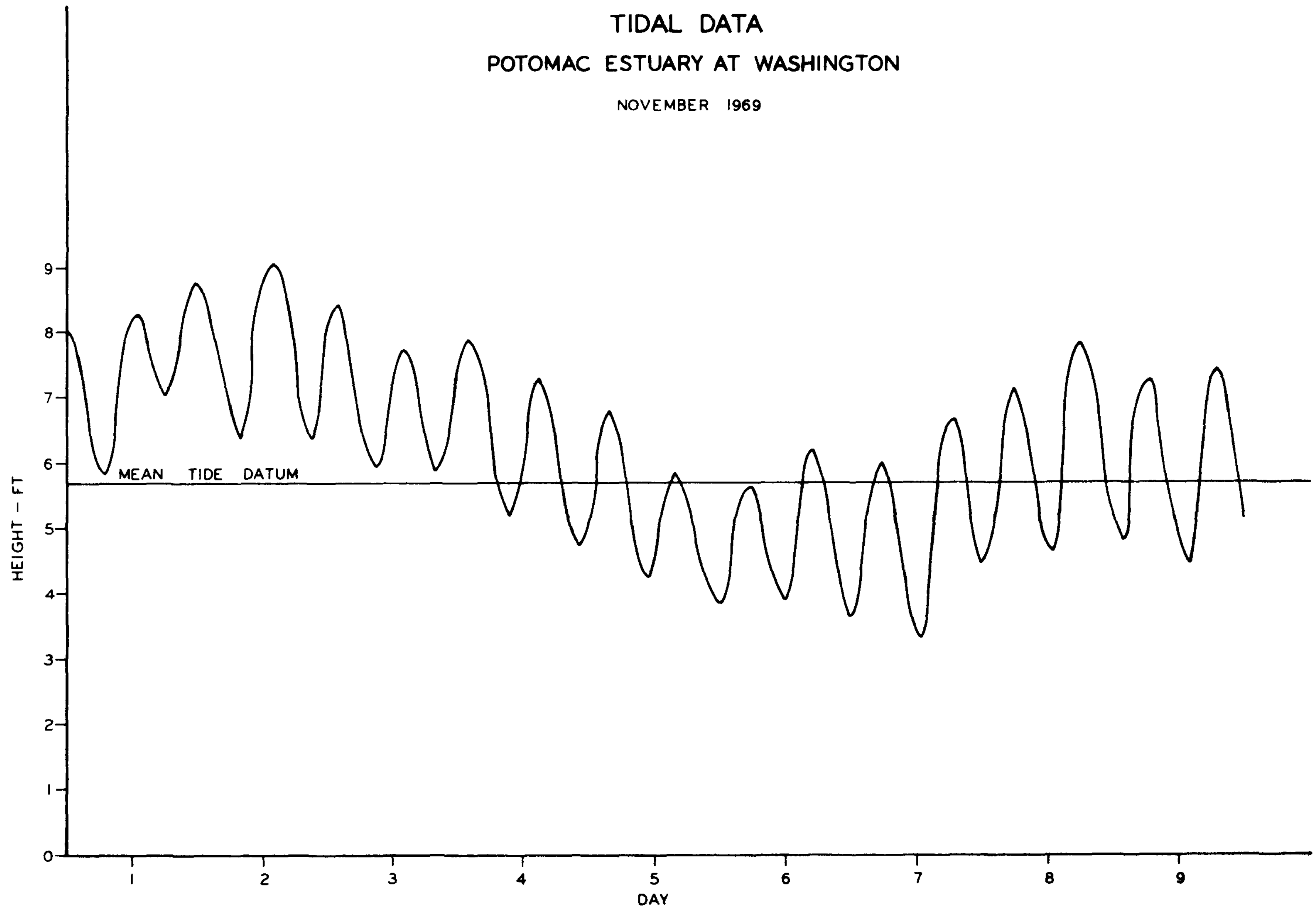

TIDAL DATA
POTOMAC ESTUARY AT WASHINGTON
NOVEMBER 1969
MEAN TIDE DATUM
HEIGHT – FT
0
1
2
3
4
5
6
7
8
9
DAY
1
2
3
4
5
6
7
8
9

FIGURE – A 1

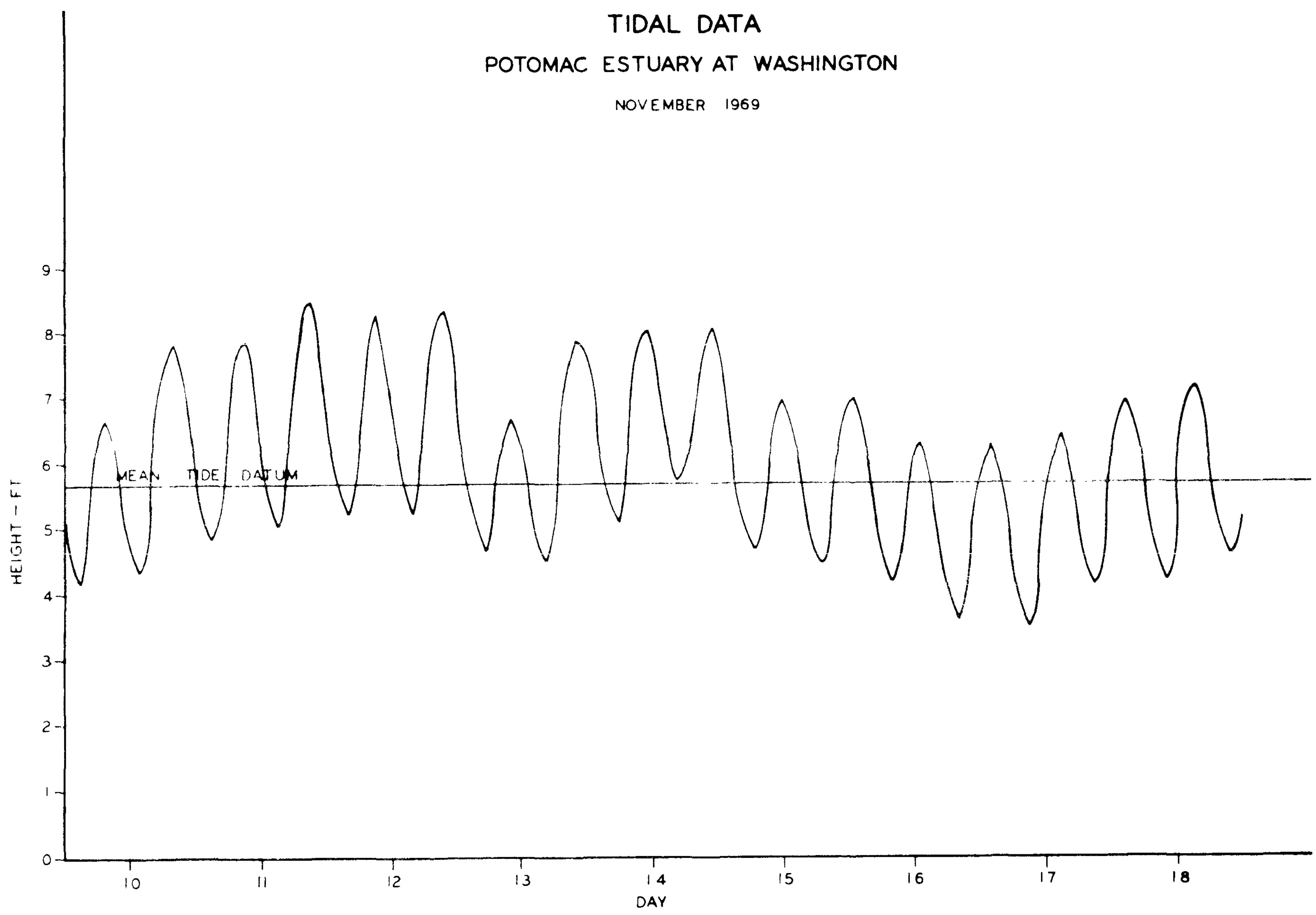

TIDAL DATA
POTOMAC ESTUARY AT WASHINGTON
NOVEMBER 1969
MEAN TIDE DATUM
HEIGHT - FT
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
DAY

FIGURE - A 2

## TIDAL DATA
### POTOMAC ESTUARY AT WASHINGTON
NOVEMBER 1969

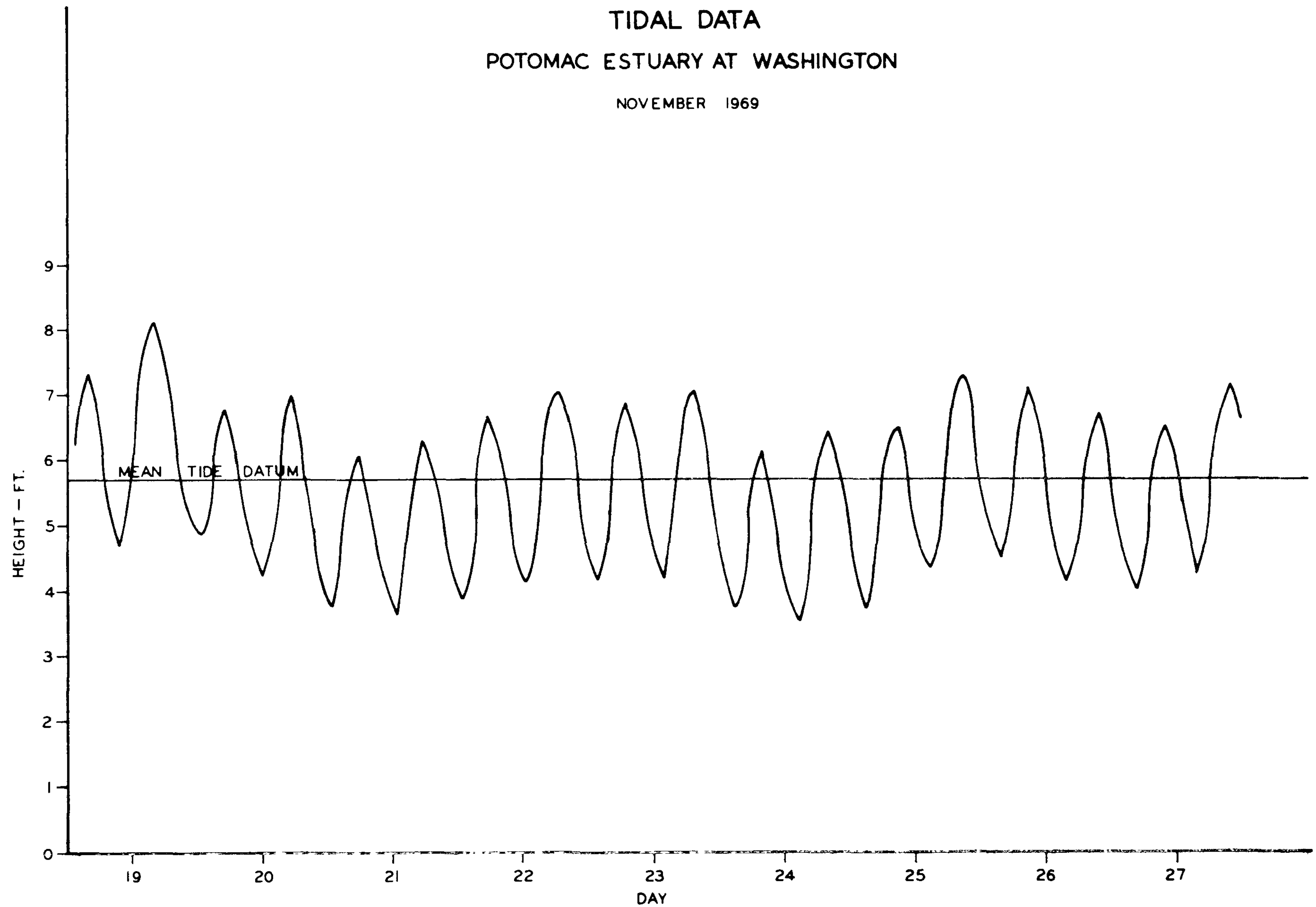



FIGURE - A 3

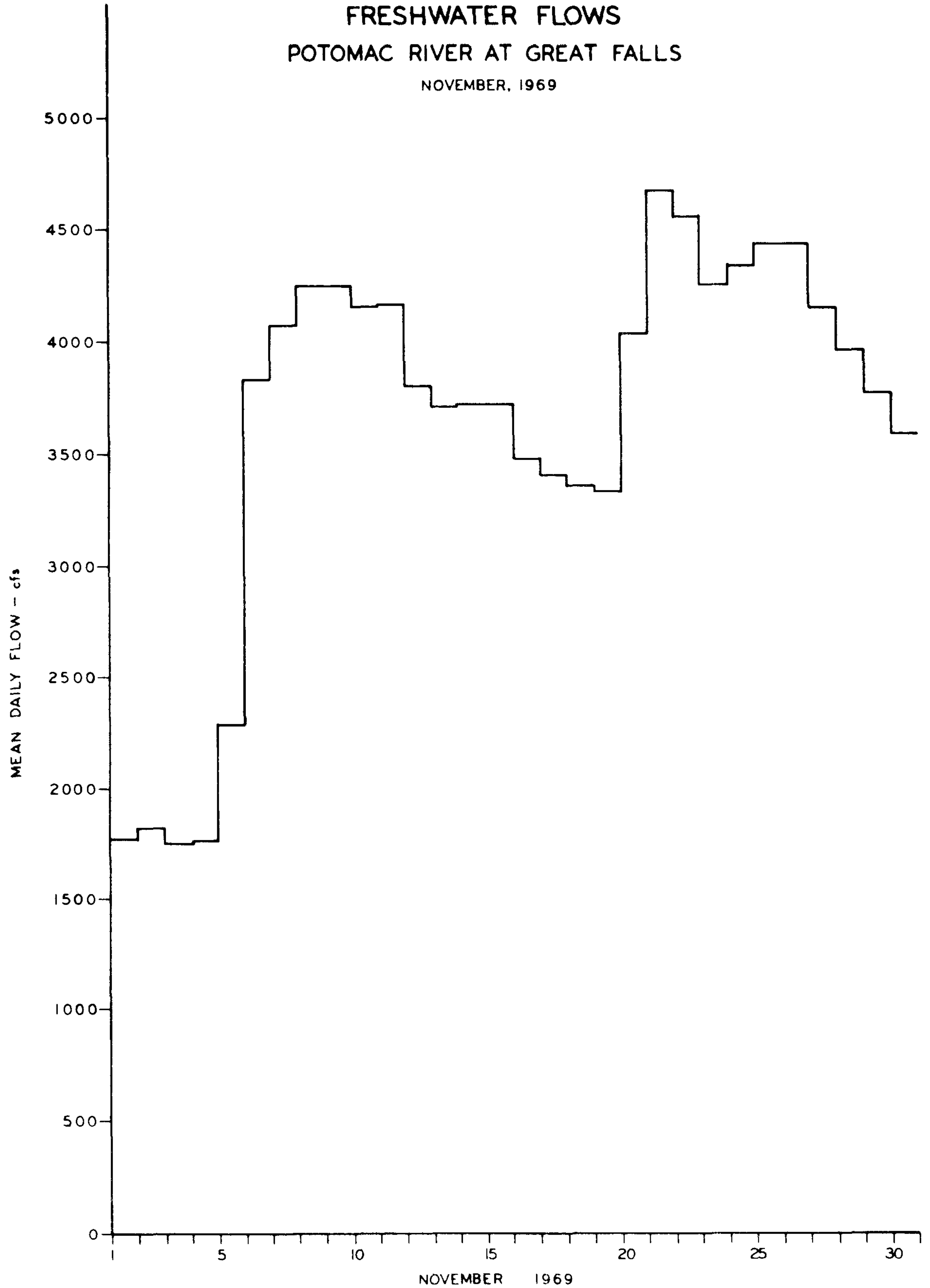

FRESHWATER FLOWS
POTOMAC RIVER AT GREAT FALLS
NOVEMBER, 1969
MEAN DAILY FLOW - cfs
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1
5
10
15
20
25
30
NOVEMBER 1969

FIGURE - A 4

Freshwater inflows account for the net advective downstream movement in a tidal system. They can also greatly affect its dispersion characteristics. Because of their importance, freshwater flows must be defined and incorporated into the hydrodynamics of a tidal system if mathematical model simulation studies are to be successful.

b. Dye Movement

The upper Potomac Estuary dye data obtained from longitudinal sampling stations between Key Bridge and Possum Point are presented in isopleth form in Figure 5 (low-slack data) and Figure 6 (high-slack data). Although dye was discharged at River Mile 10.4, Figure 5 indicates that maximum dye buildup occurred between River Mile 14 and 15. Dye concentrations between 1.0 and 2.0 ppb were observed in this area on November 5, three days after dye was initially discharged. The fact that dye peaks were located 5 miles downstream from the discharge point may have been due to (1) dye injected at a 14-foot depth with samples collected at the surface, (2) freshwater inflows which caused net downstream advective movement, (3) sampling performed at low-slack tide when maximum downstream movement could be expected. The effects of item (3) are evident when Figures 5 and 6 are compared. The high-slack tide data shown in Figure 6 indicate that maximum dye concentrations (> 1.0 ppb) occurred between River Mile 8 and 11, or approximately a complete tidal excursion range upstream from the low-slack tide peaks.

Longitudinal dye movement can be readily identified in the two isopleths. The dye cloud spread rapidly between Hains Point and Piscataway Creek as shown in Figure 5. In 3 days, it moved approximately 5 miles upstream beyond the 14th Street Bridge and approximately 14 miles downstream to Gunston Cove. This represented movement rates of 1.7 mi/day and 4.7 mi/day, respectively. The especially high downstream movement can be attributed to the very low tides observed during this period (see previous section). Downstream movement rates beyond November 5 can be estimated from the slopes of the concentration lines shown in Figures 5 and 6. The rates generally range from approximately 0.8 mi/day to 1.2 mi/day with an average of 1.1 mi/day. These rates apply only to a freshwater inflow of 4,000 cfs.

Dye was initially detected at Indian Head on November 15 and at Possum Point on November 19. Both time periods yield an average downstream movement rate of approximately 1.6 mi/day. An instantaneous dye release study conducted in the upper Potomac Estuary by the U. S. Geological Survey in August 1965 [2] showed the average velocity of net downstream movement of the dye mass centroid to be 0.6 mi/day. It should be noted, however, that the tides were relatively stable during the USGS study and that freshwater flows at Great Falls varied between 700 and 1,200 cfs, considerably smaller flows than those encountered during the 1969 dye study. The rates of movement of the leading edge and the centroid of the dye mass may also differ appreciably.

Data collected from the three complete transect runs--November 11, 18, and 20--between the 14th Street Bridge and Indian Head are plotted in Figures 7, 8, and 9. The ranges in dye concentration at each transect station and in the major embayments, mean concentrations at each transect (excluding embayments), and mid-channel concentrations are shown in these figures. Mid-channel stations correspond with the longitudinal sampling stations discussed previously. The stations comprising a transect were selected in such a way that each would have about equal weight in terms of the cross-sectional area and the flow represented.

In most cases, the total dye concentration range for a given transect was within 0.3 ppb which indicated that considerable lateral and vertical mixing had actually occurred. According to Figures 7 and 9, the dye concentration ranges measured in Broad Creek, Piscataway Creek, Dogue Creek, and Gunston Cove were generally representative of data collected at comparable main-channel stations. The extent of dye intrusion into these embayments was substantial, further indicating that tidal exchanges between the main channel and adjoining embayments should definitely be considered and, if possible, incorporated in mathematical modeling studies.

To assist in the interpretation of simulated and observed data for model verification purposes, an analysis was made of the average concentration for transect and mid-channel (surface) values. Figures 7, 8, and 9 generally show relatively small differences (< 0.5 ppb) between these two sets of data. Therefore, it would appear to be valid to compare the model predictions for a given segment with the results obtained from longitudinal sampling within that segment. Where larger deviations between mean and mid-channel concentrations were noted, no significant conclusions could be drawn concerning their relative magnitudes.

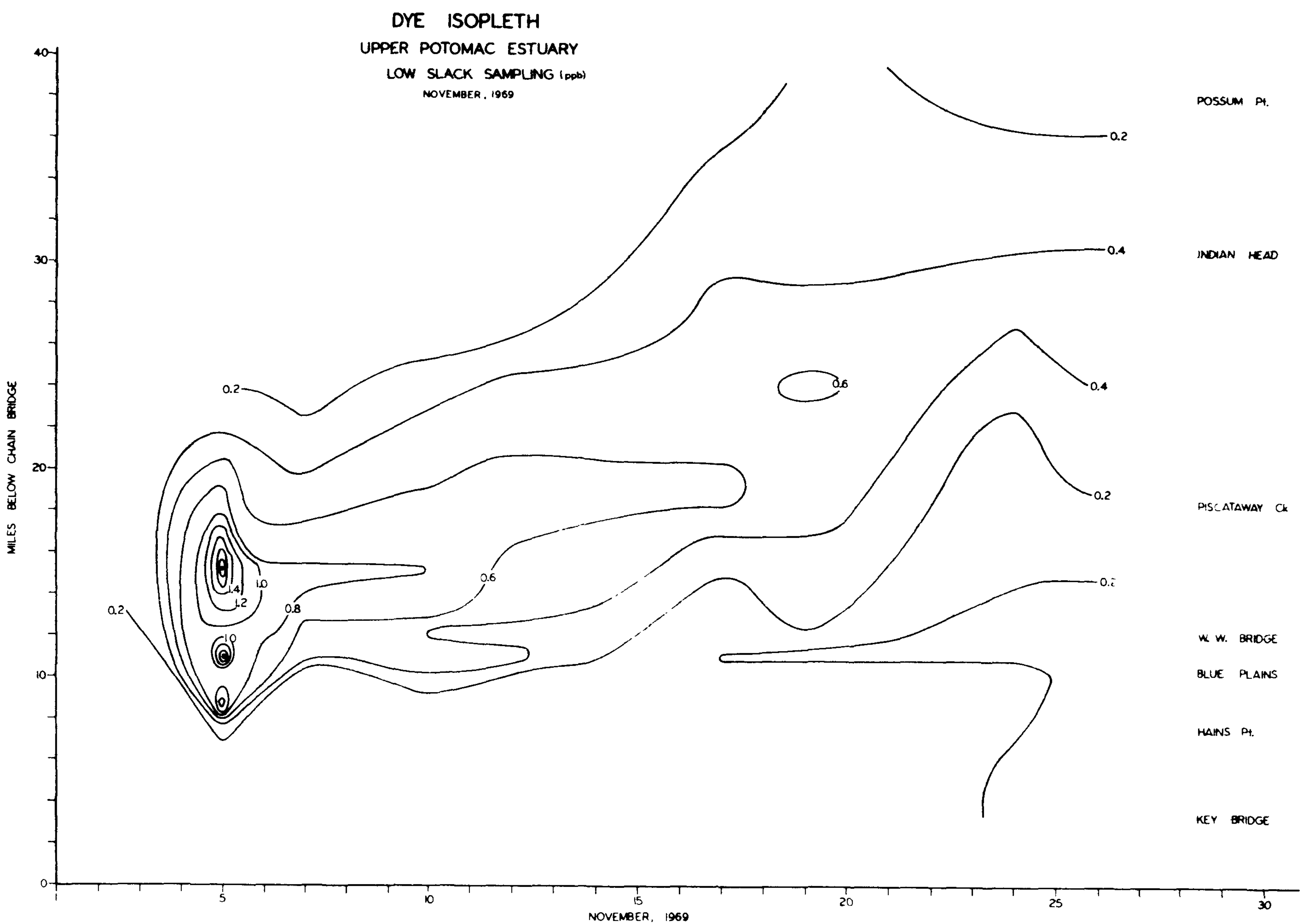

DYE ISOPLETH
UPPER POTOMAC ESTUARY
LOW SLACK SAMPLING (ppb)
NOVEMBER, 1969
MILES BELOW CHAIN BRIDGE
NOVEMBER, 1969
POSSUM Pt.
INDIAN HEAD
PISCATAWAY Ck
W. W. BRIDGE
BLUE PLAINS
HAINS Pt.
KEY BRIDGE
0
10
20
30
40
5
10
15
20
25
30
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.2
0.4
0.2
0.6
0.6
0.2
0.2
0.2
1.0

FIGURE - A 5

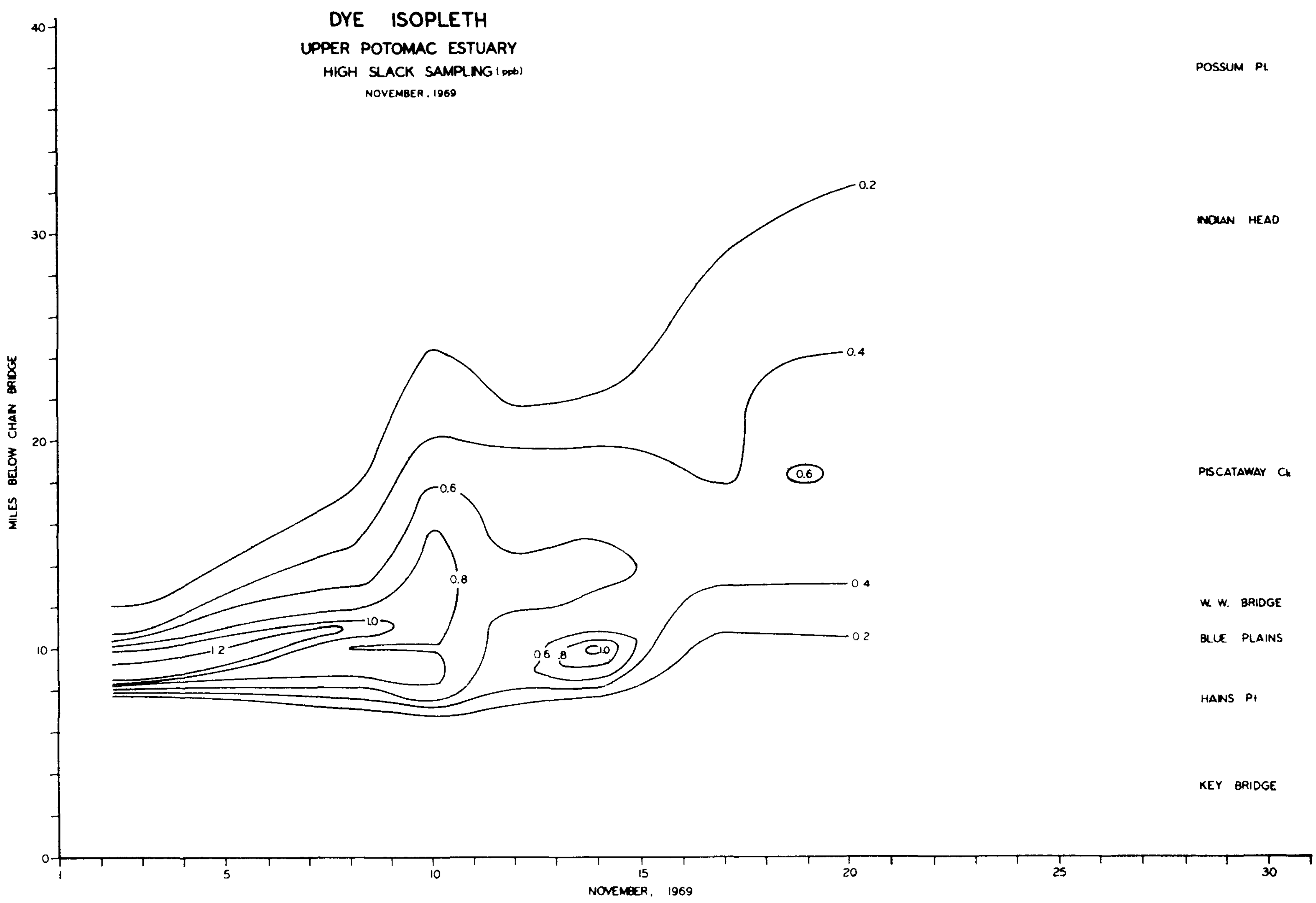

DYE ISOPLETH
UPPER POTOMAC ESTUARY
HIGH SLACK SAMPLING (ppb)
NOVEMBER, 1969
MILES BELOW CHAIN BRIDGE
NOVEMBER, 1969
POSSUM Pt.
INDIAN HEAD
PISCATAWAY Ck
W. W. BRIDGE
BLUE PLAINS
HAINS Pt
KEY BRIDGE
0.2
0.4
0.6
0.8
1.0
1.2

FIGURE - A 6

# TRANSECT DYE SAMPLING SUMMARY
## UPPER POTOMAC ESTUARY
NOVEMBER 11, 1969

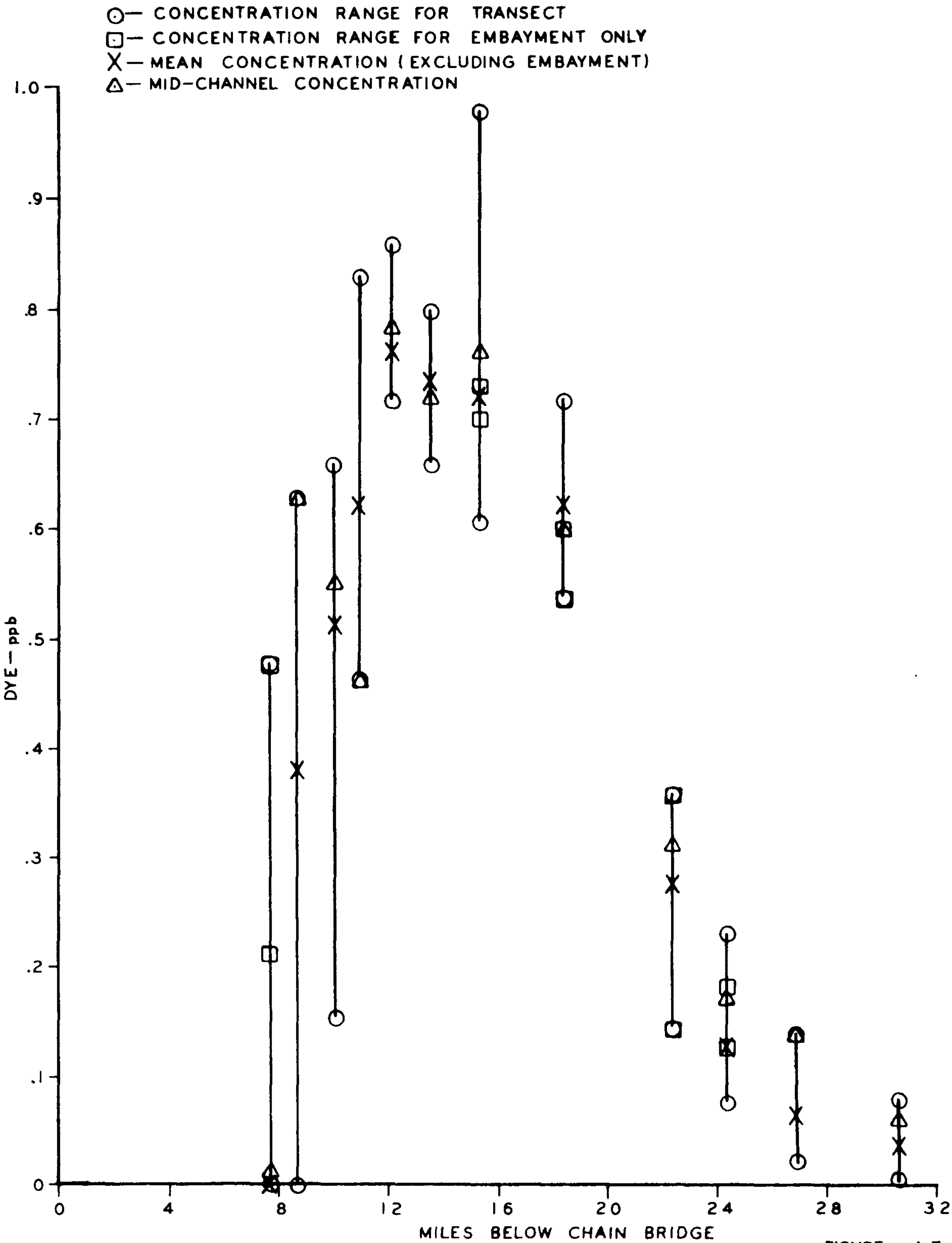



FIGURE - A 7

# TRANSECT DYE SAMPLING SUMMARY

## UPPER POTOMAC ESTUARY

NOVEMBER 18, 1969

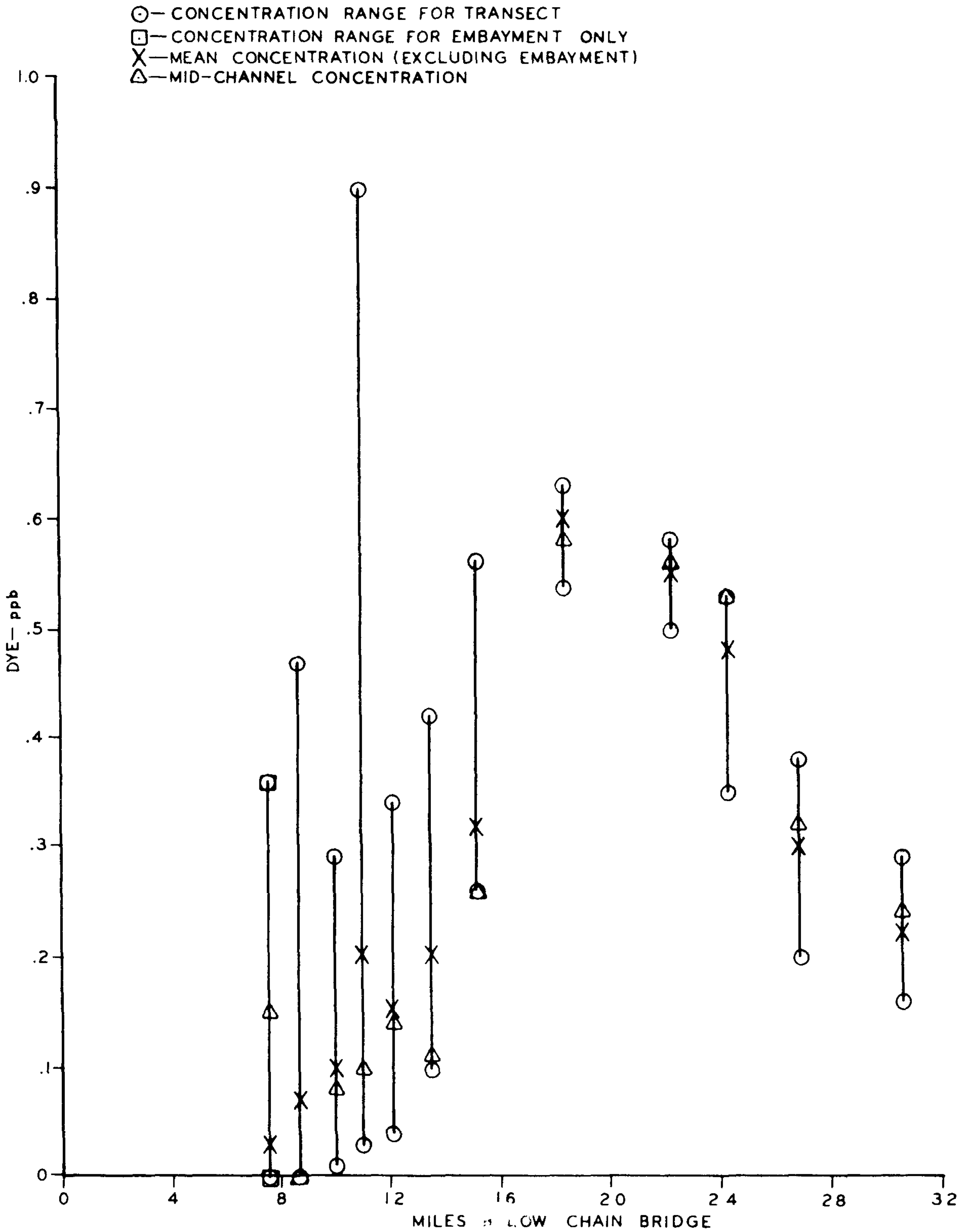



FIGURE - A 8

# TRANSECT DYE SAMPLING SUMMARY
## UPPER POTOMAC ESTUARY
NOVEMBER 20, 1969

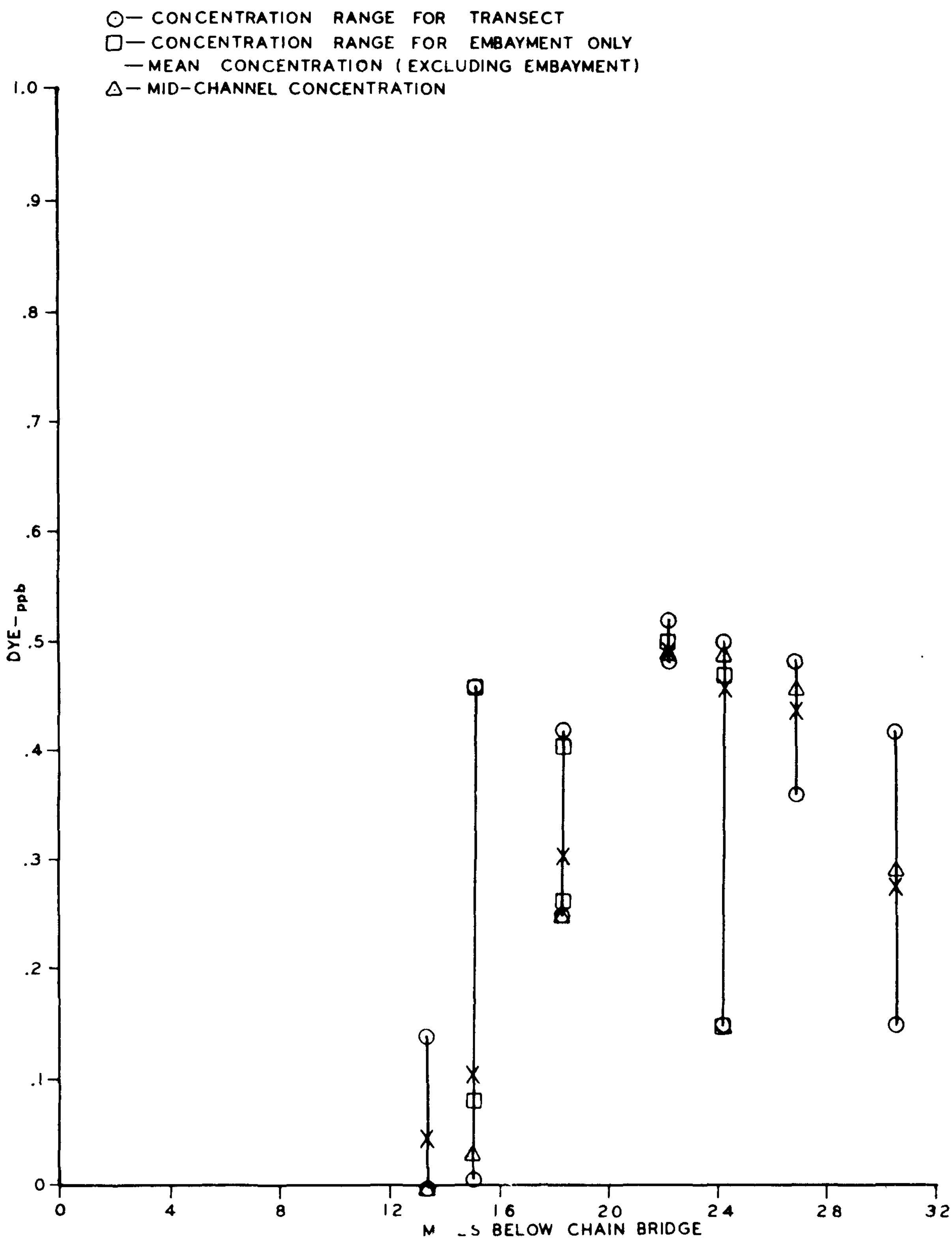



FIGURE - A9

c. Loss Rate Determination

The dye loss rate considers not only a decay or adsorption phenomenon but also reflects the inability to detect dye at low concentrations. It was estimated by computing the rate of change in the total dye mass as measured throughout the upper estuary during an 18-day period immediately following the dye release. Longitudinal sampling data, supplemented by two sets of transect data, were converted from concentrations to mass loadings per lineal foot of estuary according to the following equation:

$$\text{Mass (lbs/lineal ft.)} = \frac{C \times A \times 62.4}{10^9}$$

where: C = dye concentration (ppb) for a given sampling station

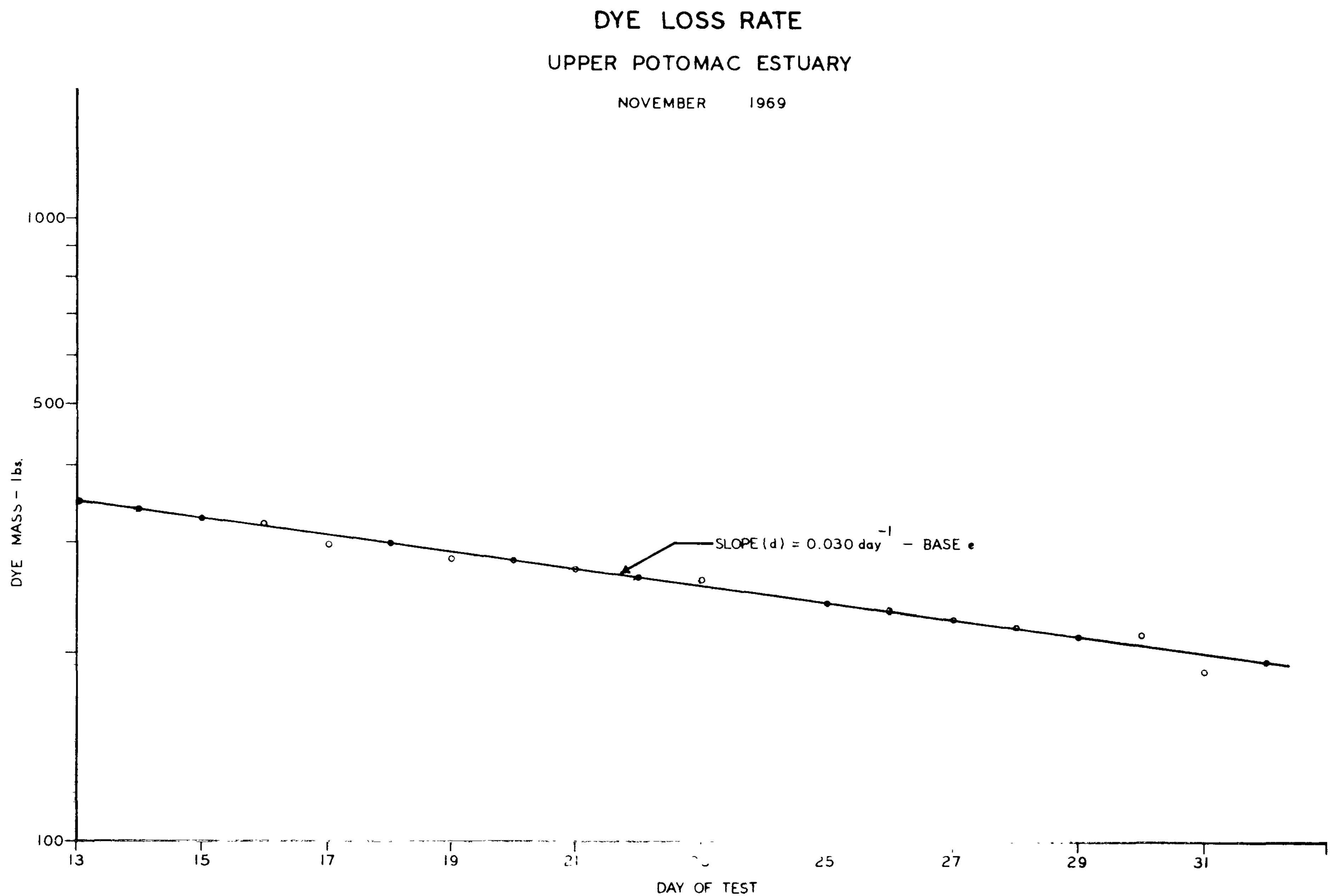
A = cross-sectional area ($ft^2$) at the sampling station

62.4 = mass of 1 cubic foot of water, and

$10^9$ = conversion factor

The mass loadings obtained were plotted as a function of distance and fitted with smooth curves. The areas under these curves were planimetered to determine the total dye mass observed at a given time. As shown in Figure 10, all such dye masses for the 18-day period appear to follow a first-order reaction. The slope of the resulting line, which is the dye loss rate, was calculated to be 0.030 per day (base e). A 1965 upper Potomac Estuary dye study by Hetling and O'Connell [3] yielded a dye loss rate of 0.034 per day (base e) which was calculated utilizing a similar approach.

The dye masses computed from measured data were always greater than the actual masses discharged during the release period. By the end of the release period (November 14), approximately 350 pounds of dye were computed to be in the estuary whereas only 269 pounds had been discharged. This 80-pound difference, excluding dye losses to November 14, can perhaps be attributed to (1) naturally occurring background fluoresence which was not defined quantitatively, (2) possible unrepresentative sampling, especially near the injection site, or (3) inaccuracy in analysis. For purposes of computing dye loss rate, these factors should have a uniform relationship over the entire sampling period.



DYE LOSS RATE
UPPER POTOMAC ESTUARY
NOVEMBER 1969
1000
500
100
DYE MASS – lbs.
SLOPE (d) = 0.030 day$^{-1}$ – BASE e
13
15
17
19
21
25
27
29
31
DAY OF TEST


FIGURE – A 10

## B. ANACOSTIA DYE STUDY - 1970

### 1. Release Conditions

A 20-percent solution of Rhodamine WT dye was discharged continuously into the Anacostia River from April 22-28, 1970, to determine the advective transport characteristics of the Anacostia tidal system and to provide additional data upon which mathematical model verification studies could be based. The dye was discharged into the main channel of the Anacostia River approximately 1 foot below the low water surface at the Washington Suburban Sanitary Commission's marina in Bladensburg, Maryland (River Mile 8.1). This area exhibits an average tidal range of approximately 3 feet but nontidal conditions exist 1/2 mile upstream.

A diaphragm type controlled volume pump, precalibrated to discharge 40 lbs/day, was utilized for this study. The container of dye was placed on a scale so that weight could be read and recorded several times each day as a further check of the actual mass pumped. A total of 280 pounds of the 20-percent dye solution or 56 pounds of pure dye was discharged to the Anacostia during this study.

2. Monitoring System

Longitudinal monitoring of the dye cloud was performed daily during periods of high- and low-slack water. Coverage extended from the confluence of the Northeast and Northwest Branches to the mouth of the Anacostia River at Hains Point. Thirteen high-slack and 10 low-slack water sampling runs were made during the period April 22-May 27. All samples were analyzed by CTSL using a Turner fluorometer modified with a high sensitivity kit to obtain concentrations as low as 0.1 ppb. The sampling data is shown in this appendix.

There were 19 stations routinely sampled. All samples were collected at mid-channel and within 1 foot of the surface. A description of these stations is presented in Table 3.

In addition to the stations given in Table 3, several samples were collected within Kingman Lake to determine the effect of tidal exchange between this embayment and the main stem Anacostia River. However, neither lateral nor vertical sampling was routinely performed at any of the sampling stations. As was discussed in a previous chapter on model verification, the lack of transect data raised some doubt as to the representativeness of those stations actually sampled.

Table 3

LONGITUDINAL SAMPLING STATIONS
Anacostia River

| Station Number | Location | Miles Upstream from Mouth |
|---|---|---|
| 1 | Hains Point . . . . . . . . . . . . | 0.00 |
| 2 | Mouth of Washington Channel . . . . | - |
| 3 | Opposite U. S. Naval Station . . . . | 0.55 |
| 4 | Upstream from Buzzard Point . . . . | 1.00 |
| 5 | Douglass Bridge . . . . . . . . . | 1.45 |
| 6 | Opposite Washington Naval Yard . . . | 1.95 |
| 7 | 11th Street Bridge . . . . . . . . | 2.45 |
| 8 | Sousa Bridge . . . . . . . . . . | 3.10 |
| 9 | Southern Entrance to Kingman Lake . . | 3.75 |
| 10 | East Capitol Street Bridge . . . . . . | 4.35 |
| 11 | Benning Bridge . . . . . . . . . . | 4.90 |
| 12 | Northern Entrance to Kingman Lake . . | 5.65 |
| 13 | Opposite Kenilworth Aquatic Gardens . . | 6.25 |
| 14 | Route 50 Bridge . . . . . . . . . | 6.90 |
| 16 | Upstream from Unnamed Tributary . . . | 7.45 |
| 17 | Southern Edge of Marina . . . . . . . | 7.95 |
| 18 | Bladensburg Road Bridge . . . . . . . | 8.45 |
| 19 | Northwest Branch at Rhode Island Avenue Bridge . . . . . . . . . . . . . | - |
| 20 | Northeast Branch at Baltimore Avenue Bridge . . . . . . . . . . . . . | 9.00 |

3. Presentation of Data

a. Tidal Conditions and Hydrology

There are no tidal monitoring stations in the Anacostia River and consequently detailed tidal data during the dye study were not obtained. It has been reported by the U. S. Coast and Geodetic Survey that the mean tidal range at both Benning Bridge and Anacostia Bridge is 2.9 feet. The observed tidal range at the Bladensburg marina, which is farther upstream, was also estimated to be approximately 3 feet. Time differences for Benning Bridge referenced to the Washington gage average +16 minutes for high water and +04 minutes for low water.

Average daily flows entering the tidal portion of the Anacostia River were measured by USGS gaging stations on the Northwest Branch at Hyattsville and the Northeast Branch at Riverdale. The flows for the study period are shown in Figure 11. Except for the initial 9 days when flows averaged 180 cfs, the freshwater inflows were generally between 60 and 100 cfs. Unusually high flows, i.e., 200-500 cfs, also occurred during the study but they were "flashy" in nature.

b. Dye Movement

The Anacostia River dye data obtained from the sampling stations outlined previously are presented in isopleth form in Figure 12 (high-slack data) and Figure 13 (low-slack data). As can be seen in Figure 12, maximum dye concentrations were observed at River Mile 7.5 on April 27-28, which were the last two days of dye discharge. Concentrations in this area were initially 6 to 7 ppb but as the study progressed, dye concentrations exceeded 10 ppb. Figure 13 also showed a maximum dye buildup of similar magnitude on April 27-28 but at River Mile 6.9. Evidently, the 0.6 mile difference can be attributed to the tidal excursion between slack water periods. The relatively high freshwater flows that occurred prior to April 28 were probably responsible for the net advective downstream movement of the dye peak from River Mile 8.1 to River Mile 7.5 or 6.9, depending on the tidal phase.

The longitudinal dye movement occurred quite rapidly between the point of injection and the southern entrance to Kingman Lake. Under low-slack conditions, when maximum downstream movement could be expected, dye concentrations exceeding 1.0 ppb were observed at that downstream station the second day (April 23) after discharge started. This translates to a velocity of approximately 2.5 mi/day. The rate of dye movement decreased farther downstream due to a significant increase in the volume of the Anacostia River. From April 23 to May 4, the average rate of downstream movement based upon the slopes of the concentration lines shown in Figure 13 was approximately 0.3 mi/day for the existing flows.

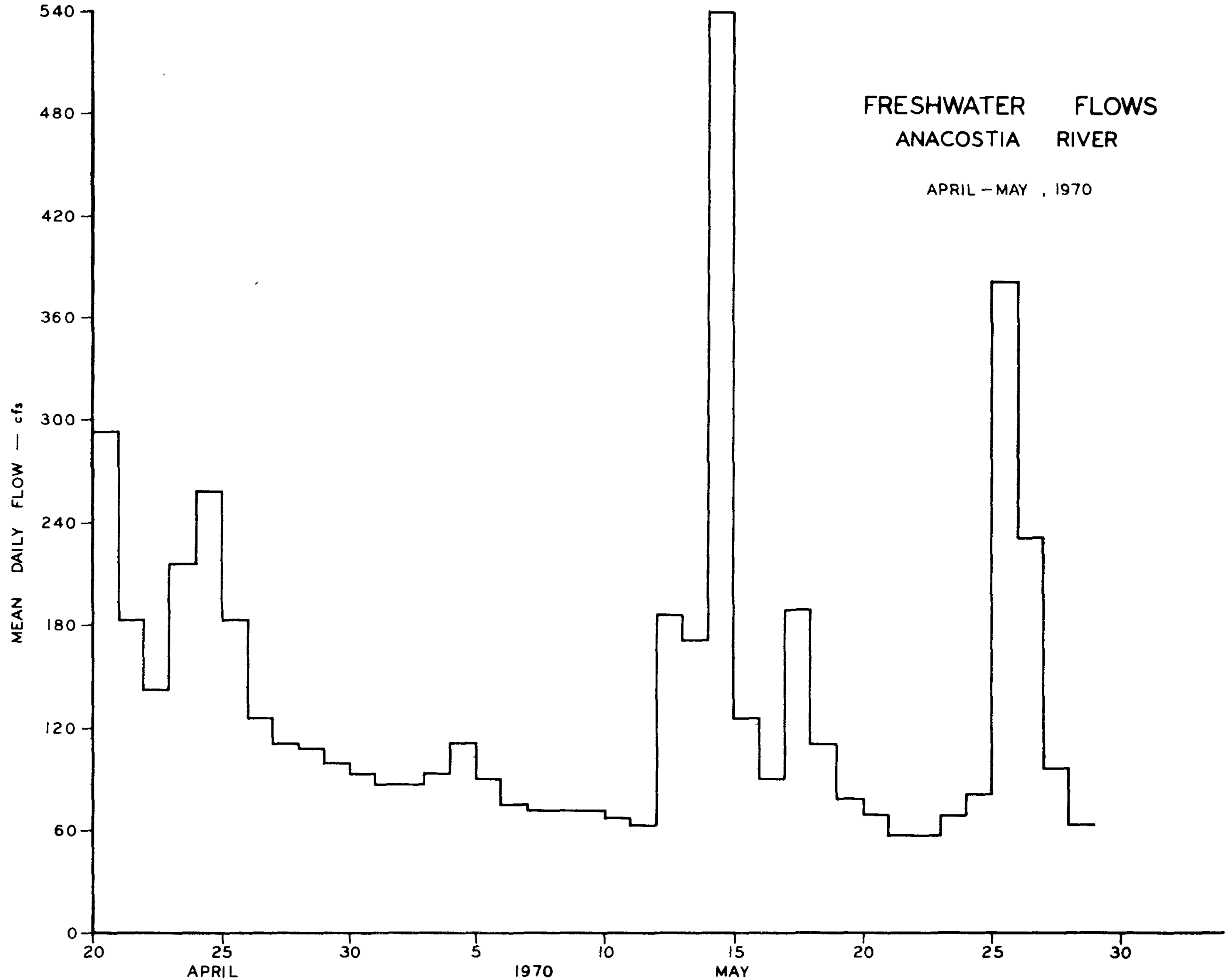

FRESHWATER FLOWS
ANACOSTIA RIVER
APRIL – MAY, 1970
MEAN DAILY FLOW — cfs
540
480
420
360
300
240
180
120
60
0
20
25
30
5
10
15
20
25
30
APRIL
1970
MAY

FIGURE - A 11

During this period, the leading edge of the dye cloud progressed downstream to the mouth of the Anacostia River.

As shown in Figures 12 and 13, there was very little upstream movement of the dye which is attributable to the fact that tidal effects do not extend much above the discharge point. Moreover, the trailing edge of the dye cloud appeared to move downstream at a slightly greater rate than the leading edge. The samples collected within Kingman Lake indicated that comparable amounts of dye were present there as in adjacent reaches of the main stem Anacostia River. The tidal and mass exchange between these two bodies of water therefore appears to be quite significant.

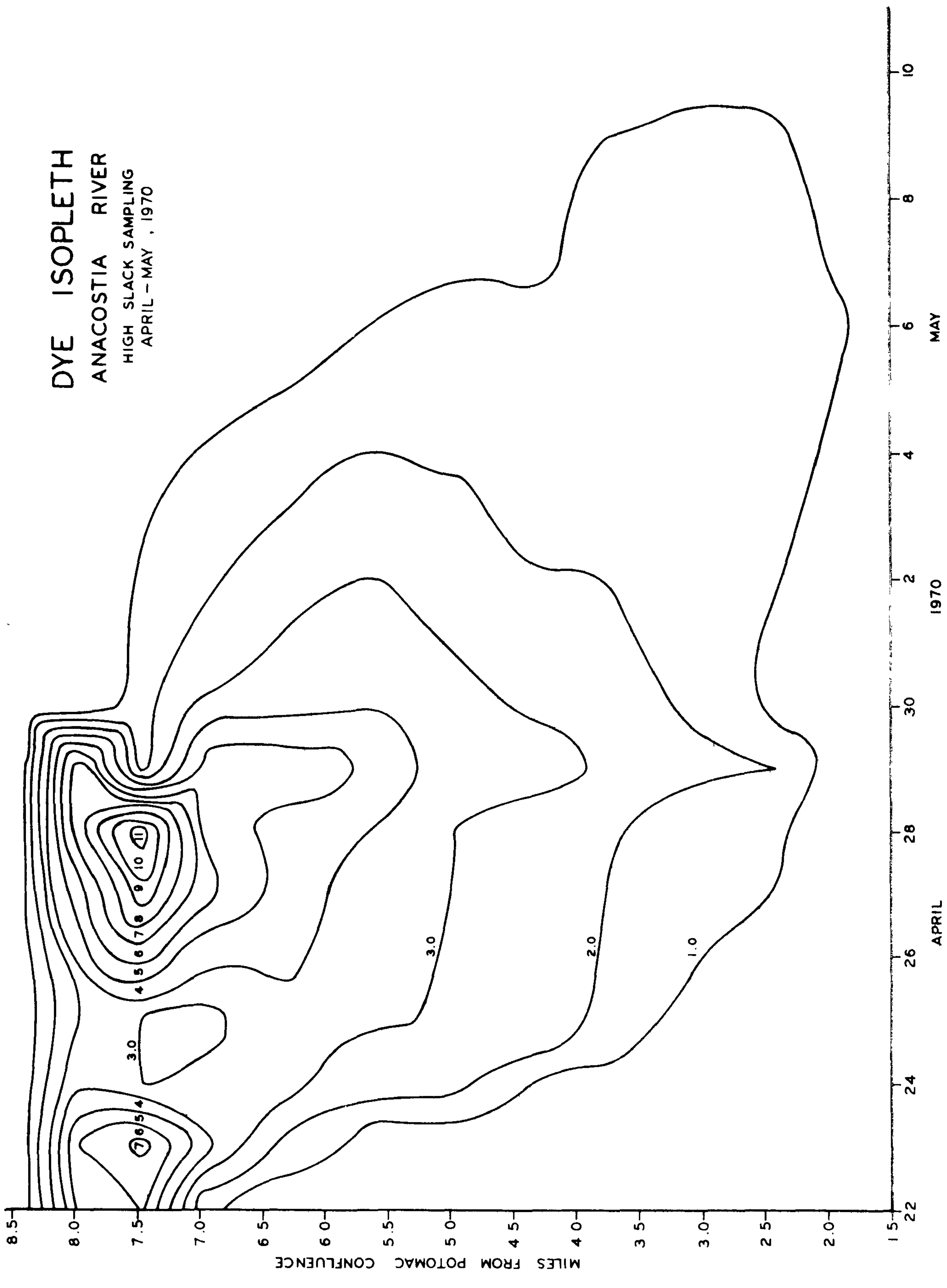

DYE ISOPLETH
ANACOSTIA RIVER
HIGH SLACK SAMPLING
APRIL - MAY , 1970
MILES FROM POTOMAC CONFLUENCE
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
22
24
26
28
30
2
4
6
8
10
APRIL
1970
MAY
1.0
2.0
3.0
3.0
4
5
6
7
8
9
10
11
7
6
5
4

FIGURE - A 12

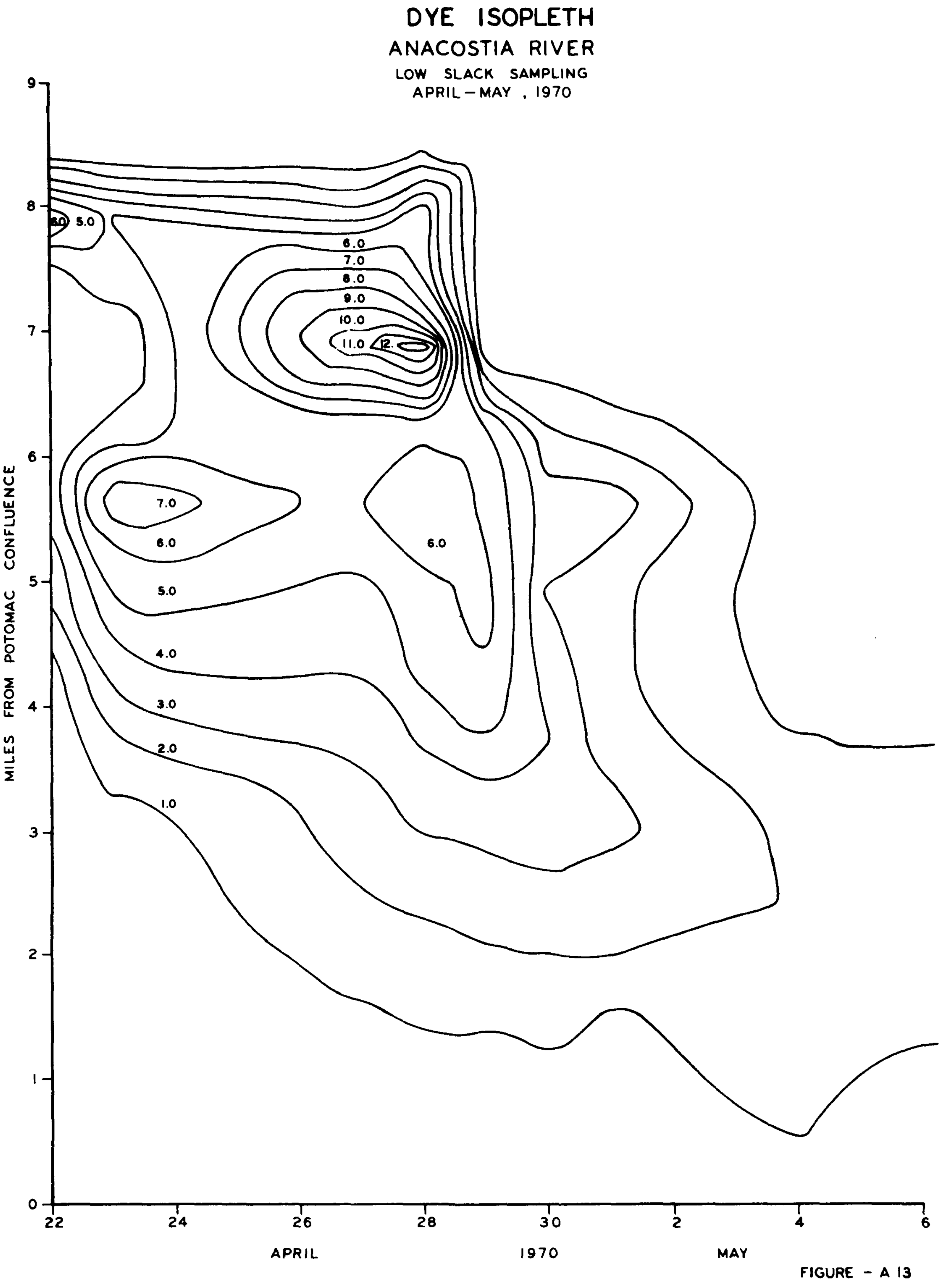

DYE ISOPLETH
ANACOSTIA RIVER
LOW SLACK SAMPLING
APRIL – MAY , 1970
MILES FROM POTOMAC CONFLUENCE
0
1
2
3
4
5
6
7
8
9
22
24
26
28
30
2
4
6
APRIL
1970
MAY
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.
7.0
6.0
6.0
5.0
4.0
3.0
2.0
1.0

FIGURE - A 13

c. Loss Rate Determination

An estimate of the dye loss rate in the Anacostia River was obtained using a method similar to that discussed previously for the Potomac dye study. The total quantities of dye observed during a 25-day period following the release are shown in Figure 14. The dye loss rate for the Anacostia study which again followed first-order kinetics was computed to be 0.050/day.

Although 56 pounds of dye were discharged during the study period, the initial mass of dye observed in the Anacostia River was approximately 63 pounds. A relatively high natural background concentration (0.1 - 0.3 ppb) was measured prior to dye injection and may be responsible for this 7-pound difference.

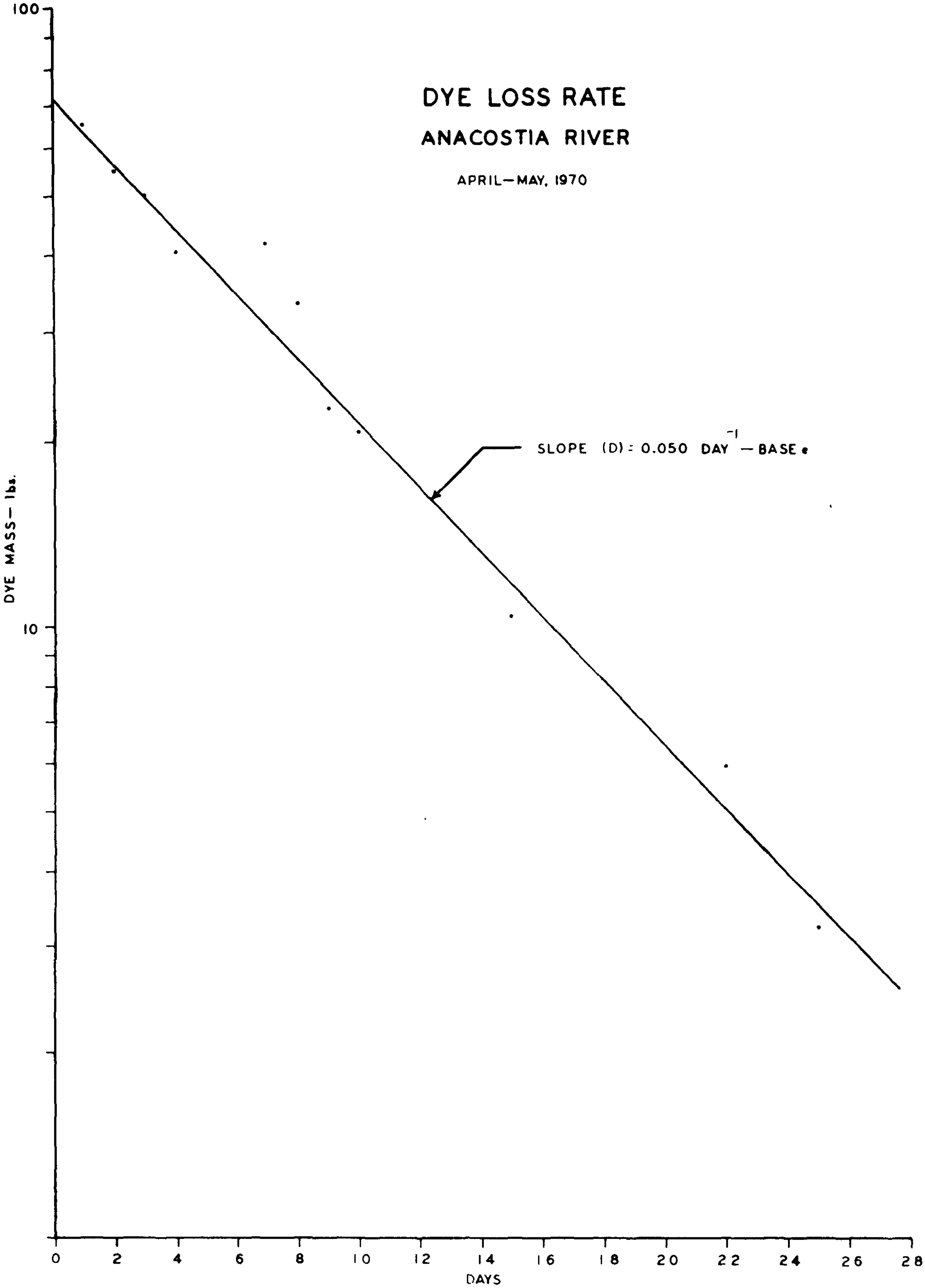

DYE LOSS RATE
ANACOSTIA RIVER
APRIL—MAY, 1970
SLOPE (D) = 0.050 DAY⁻¹ — BASE e
DYE MASS— lbs.
100
10
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DAYS

FIGURE - A14

Table 4

Summary of Dye Concentration Data - Potomac Estuary - November 1969*

High Slack Tide Data

(ppb)

| Stations | 1 | 1A | 2 | 2A | 3 | 3A | 4 | 4A | 5 | 5A | 6 | 7 | 8 | 8A | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | | | | | | | | | | |
| 11/03 | 0.01 | 0.10 | 0.07 | 0.02 | ---- | 1.39 | 0.98 | 0.33 | 0.20 | 0.20 | 0.10 | 0.01 | 0.19 | 0.08 | ---- | ---- | ---- |
| 11/08 | ---- | 0.01 | 0.01 | 0.01 | 0.01 | 0.40 | 0.80 | 0.80 | 1.17 | 0.71 | 0.52 | 0.36 | 0.12 | 0.03 | ---- | ---- | ---- |
| 11/10 | 0.13 | 0.14 | 0.15 | 0.19 | 0.64 | 0.88 | 0.80 | 0.80 | 0.81 | 0.86 | 0.82 | 0.82 | 0.55 | 0.24 | 0.20 | 0.21 | 0.20 |
| 11/12 | ---- | 0.01 | 0.13 | 0.02 | 0.29 | 0.55 | 0.53 | 0.45 | 0.66 | 0.66 | 0.56 | 0.50 | 0.15 | 0.11 | 0.03 | 0.04 | 0.14 |
| 11/14 | ---- | 0.03 | ---- | ---- | 0.15 | 0.70 | 1.07 | 0.56 | 0.58 | 0.63 | 0.60 | 0.49 | 0.20 | ---- | ---- | ---- | ---- |
| 11/17 | ---- | ---- | 0.01 | 0.02 | 0.03 | 0.07 | 0.15 | 0.22 | 0.28 | 0.50 | 0.59 | 0.36 | 0.39 | 0.39 | 0.25 | 0.16 | 0.02 |
| 11/19 | 0.02 | 0.03 | 0.04 | 0.02 | 0.06 | 0.13 | 0.15 | 0.24 | 0.31 | 0.46 | 0.54 | 0.61 | 0.50 | 0.38 | 0.31 | 0.22 | ---- |
| 12/01 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 0.01 | 0.02 | 0.10 | 0.20 | 0.21 | 0.24 | 0.26 | 0.12 |

* USGS dye analysis

Table 5
Summary of Dye Concentration Data - Potomac Estuary - November 1969*
Low Slack Tide Data
(ppb)

| Stations | 1 | 1A | 2 | 2A | 3 | 3A | 4 | 4A | 5 | 5A | 6 | 7 | 8 | 8A | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | | | | | | | | | | | |
| 11/03 | 0.22 | 0.02 | 0.02 | ---- | ---- | ---- | 0.12 | 0.10 | 0.16 | 0.32 | 0.35 | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 11/05 | 0.24 | 0.20 | 0.15 | 0.18 | 0.29 | 1.31 | 0.67 | 1.73 | 0.86 | 1.33 | 2.04 | 0.90 | 0.31 | ---- | ---- | ---- | ---- | ---- |
| 11/06 | 0.08 | 0.77 | 0.08 | 0.12 | 0.10 | 0.07 | 0.77 | 0.62 | 0.92 | 0.98 | 0.84 | 0.30 | ---- | ---- | ---- | ---- | ---- | ---- |
| 11/07 | 0.01 | ---- | ---- | 0.01 | 0.02 | 0.03 | 0.03 | 0.48 | 0.49 | 0.79 | 0.82 | 0.51 | 0.22 | 0.05 | 0.02 | 0.08 | ---- | ---- |
| 11/10 | ---- | ---- | ---- | 0.01 | 0.02 | 0.14 | 0.29 | 0.68 | 0.39 | 0.82 | 0.80 | 0.62 | 0.48 | 0.29 | 0.05 | 0.02 | 0.08 | ---- |
| 11/12 | 0.03 | 0.02 | 0.03 | 0.05 | 0.13 | 0.13 | 0.16 | 0.50 | 0.31 | 0.56 | 0.55 | 0.70 | 0.52 | 0.47 | 0.14 | 0.05 | 0.01 | ---- |
| 11/17 | ---- | 0.04 | ---- | 0.01 | 0.03 | 0.03 | ---- | 0.21 | 0.12 | 0.13 | 0.22 | 0.61 | 0.59 | 0.54 | 0.50 | 0.35 | 0.12 | ---- |
| 11/19 | 0.04 | 0.05 | 0.03 | 0.05 | 0.08 | 0.12 | 0.11 | 0.23 | 0.13 | 0.56 | 0.28 | 0.53 | 0.59 | 0.61 | 0.49 | 0.32 | 0.85 | ---- |
| 11/24 | ---- | ---- | 0.26 | 0.23 | 0.13 | 0.12 | 0.11 | 0.22 | 0.23 | 0.24 | 0.14 | 0.10 | 0.18 | 0.25 | 0.40 | 0.40 | 0.16 | 0.03 |
| 11/25 | ---- | ---- | 0.28 | 0.35 | 0.38 | 0.24 | 0.21 | 0.24 | 0.25 | 0.29 | 0.16 | 0.14 | 0.29 | 0.36 | 0.49 | 0.40 | 0.16 | 0.10 |

* USGS dye analysis

Table 6

Summary of Dye Concentration Data - Anacostia River - April-May, 1970
High Slack Tide Data
(ppb)

| Stations | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | | | | | | | | | | | | |
| 4/22 | - | - | - | - | .14 | .14 | .13 | .14 | .14 | .15 | .16 | .21 | .23 | 1.15 | 6.0 | 5.3 | * | * | * |
| 4/23 | * | * | * | * | .12 | .16 | .15 | .16 | .20 | .35 | .60 | .74 | 1.45 | 4.05 | 7.2 | 6.1 | * | * | * |
| 4/24 | * | * | * | * | .13 | .24 | .21 | .34 | .80 | 1.00 | 2.10 | 2.30 | 3.20 | 3.20 | 3.0 | 3.8 | .11 | .11 | .13 |
| 4/25 | * | * | * | .12 | .28 | .28 | .39 | .78 | 1.50 | 3.70 | 2.80 | 3.20 | 3.90 | 2.80 | 3.0 | .3 | .11 | .13 | .10 |
| 4/27 | .28 | .24 | .21 | .22 | .74 | .52 | 1.00 | 1.25 | 2.00 | 2.30 | 2.95 | 3.30 | 4.60 | 6.10 | 9.6 | 5.0 | * | - | - |
| 4/28 | .14 | .14 | * | .17 | .35 | .52 | 1.19 | 1.19 | 2.19 | 2.13 | 2.97 | 4.00 | 4.67 | 5.45 | 11.3 | 7.7 | * | - | - |
| 4/29 | * | .31 | * | .26 | .41 | .70 | 2.01 | 2.29 | 2.80 | 3.54 | 3.33 | 4.81 | 5.62 | 5.80 | 1.8 | .7 | * | - | - |
| 4/30 | * | * | * | .19 | .22 | .61 | .92 | 1.82 | 2.34 | 2.83 | 3.33 | 3.96 | 3.78 | 3.33 | 1.7 | * | * | - | - |
| 5/06 | .11 | .20 | .15 | .41 | .78 | 1.08 | 1.47 | 1.54 | 1.50 | 1.19 | 1.30 | 1.00 | .54 | .30 | .2 | .1 | * | - | - |
| 5/07 | .23 | .24 | .16 | .52 | .68 | .96 | 1.34 | 1.36 | 1.22 | .89 | .88 | .69 | .48 | .19 | * | * | - | - | - |
| 5/12 | * | .21 | * | .25 | .35 | .44 | .68 | .70 | .68 | .61 | .56 | .45 | .34 | .25 | * | * | - | - | - |
| 5/22 | * | * | * | * | .11 | .14 | .17 | .20 | .20 | .21 | .23 | .21 | .20 | .19 | .2 | .2 | .14 | - | - |
| 5/27 | * | * | * | * | * | * | * | * | .12 | .12 | .19 | .18 | .20 | .20 | .2 | * | - | - | - |

* Less than .1

Table 7

Summary of Dye Concentration Data - Anacostia River - April-May, 1970
Low Slack Tide Data
(ppb)

| Stations | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | | | | | | | | | | | | | | | | | | |
| 4/22 | * | * | .14 | .15 | .15 | .16 | .15 | .15 | .24 | .78 | 2.2 | 3.5 | 2.3 | 8.0 | 3.5 | 6.2 | * | * | * |
| 4/23 | * | * | .13 | .15 | .16 | .18 | .31 | .62 | 1.94 | 3.50 | 5.0 | 7.4 | 4.7 | 3.1 | 4.8 | 5.0 | .2 | .13 | .19 |
| 4/27 | .19 | * | .51 | .61 | .90 | 1.18 | 1.96 | 2.62 | 3.25 | 4.05 | 4.7 | 6.0 | 5.2 | 10.8 | 7.6 | 3.4 | * | - | - |
| 4/28 | .24 | .13 | .54 | .58 | 1.03 | 1.58 | 2.24 | 3.22 | 4.21 | 5.38 | 5.9 | 7.0 | 5.8 | 12.7 | 6.0 | 5.5 | 1.0 | - | - |
| 4/29 | .30 | .20 | .45 | .52 | 1.05 | 1.81 | 2.48 | 3.26 | 4.84 | 5.94 | 6.2 | 5.9 | 5.0 | .3 | .1 | * | * | - | - |
| 4/30 | .11 | .38 | .57 | .69 | 1.39 | 1.89 | 2.66 | 3.75 | 4.00 | 3.57 | 2.9 | 3.8 | 2.0 | .1 | * | * | * | - | - |
| 5/01 | * | .29 | .52 | .66 | .82 | 1.96 | 2.48 | 3.33 | 2.62 | 2.24 | 2.1 | 3.4 | 1.3 | .2 | .1 | .1 | - | - | - |
| 5/04 | .44 | .95 | .99 | 1.32 | 1.62 | 1.84 | 1.92 | 1.70 | 1.08 | .52 | .3 | .3 | .4 | .1 | * | * | .1 | - | - |
| 5/05 | .28 | .51 | .82 | .95 | 1.36 | 1.61 | 1.57 | 1.50 | .95 | .62 | .4 | .9 | .3 | .1 | * | * | 2.1 | - | - |
| 5/19 | .12 | .15 | .14 | .18 | .22 | .17 | .20 | .19 | .20 | .21 | .2 | .3 | .2 | .2 | .1 | .1 | - | - | - |

* Less than .1

# TRANSECT # 1 — KEY BRIDGE

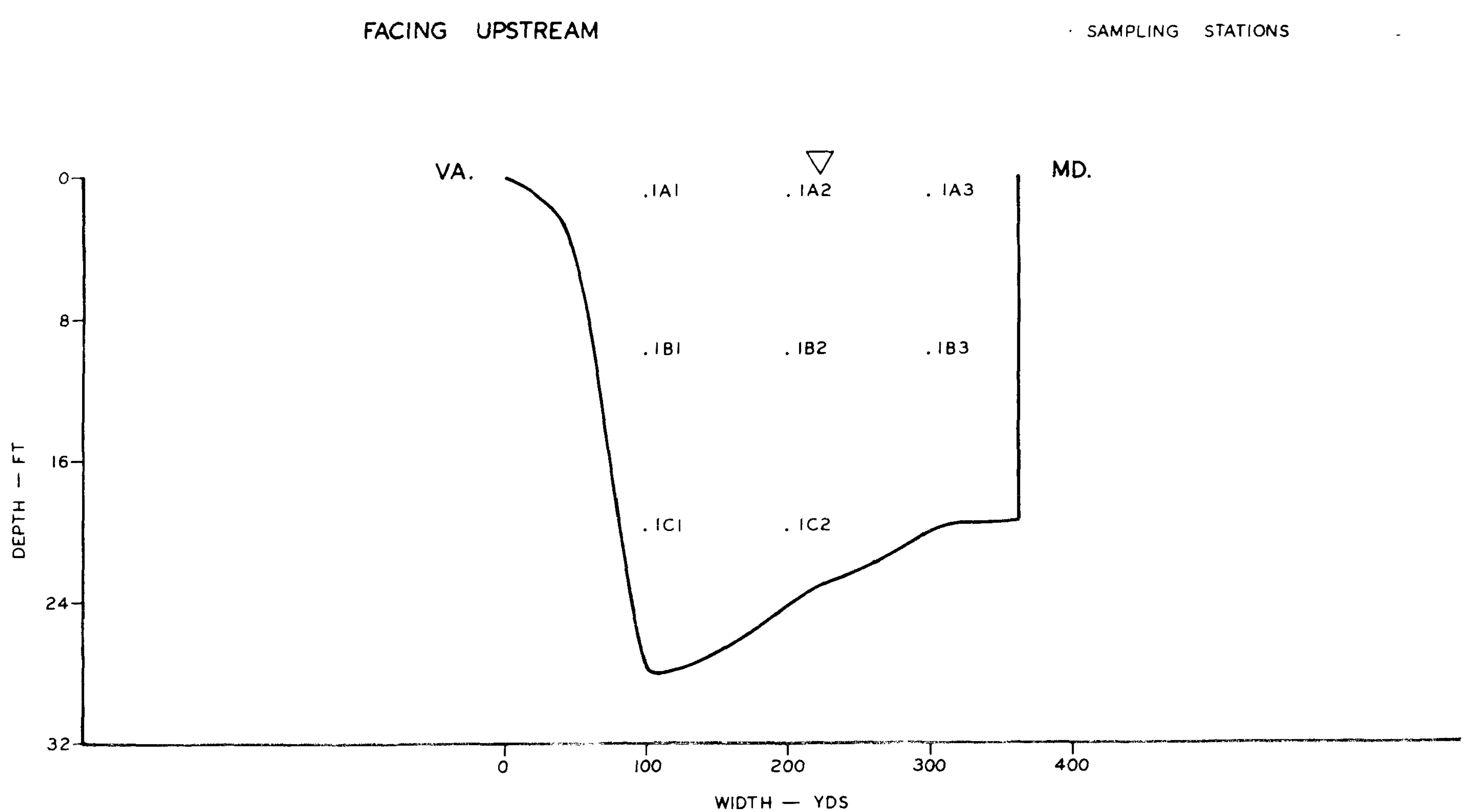



FIGURE A-15

## TRANSECT # 2 — 14th STREET BRIDGE

FACING UPSTREAM

· SAMPLING STATIONS

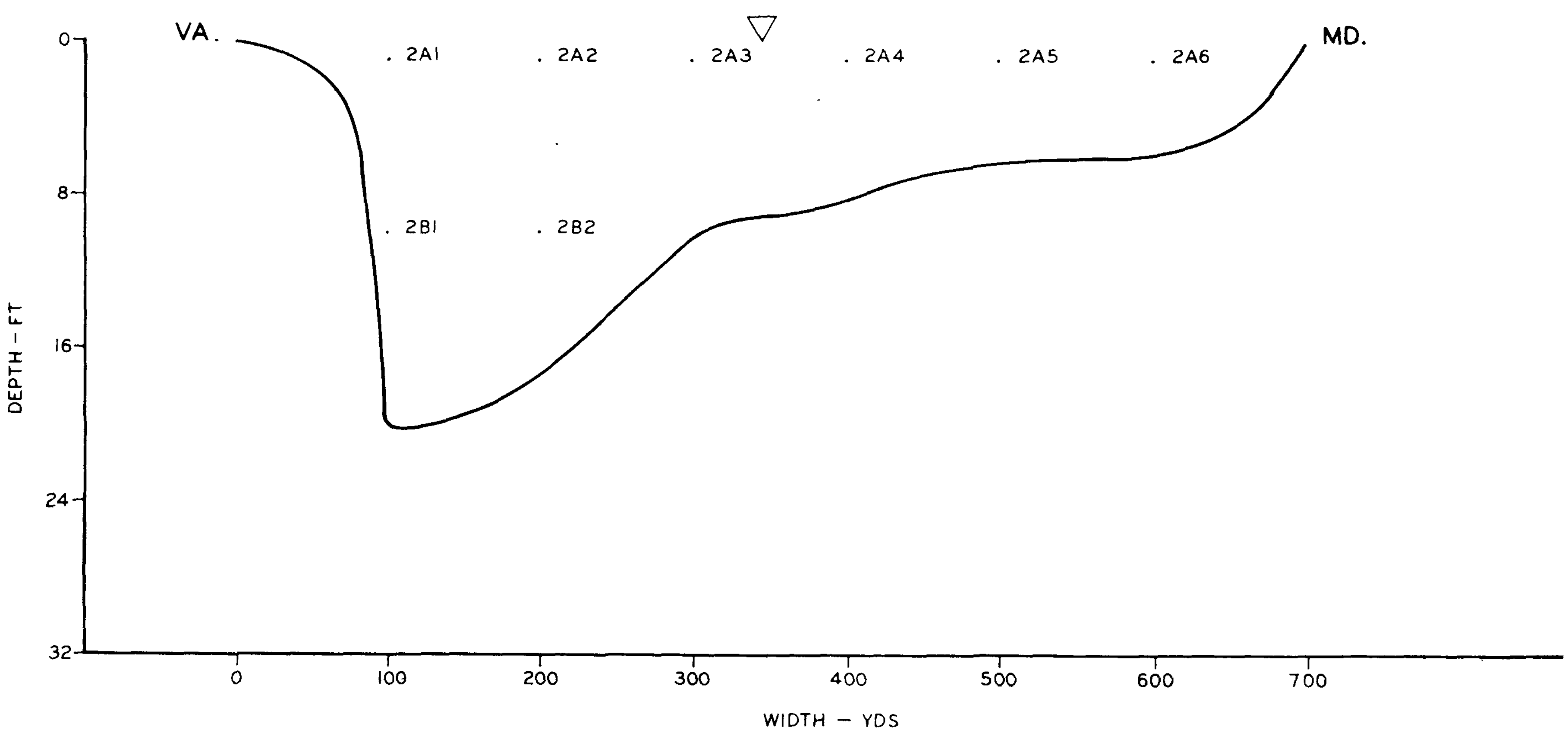



FIGURE A-16

## TRANSECT # 3 — HAINS POINT

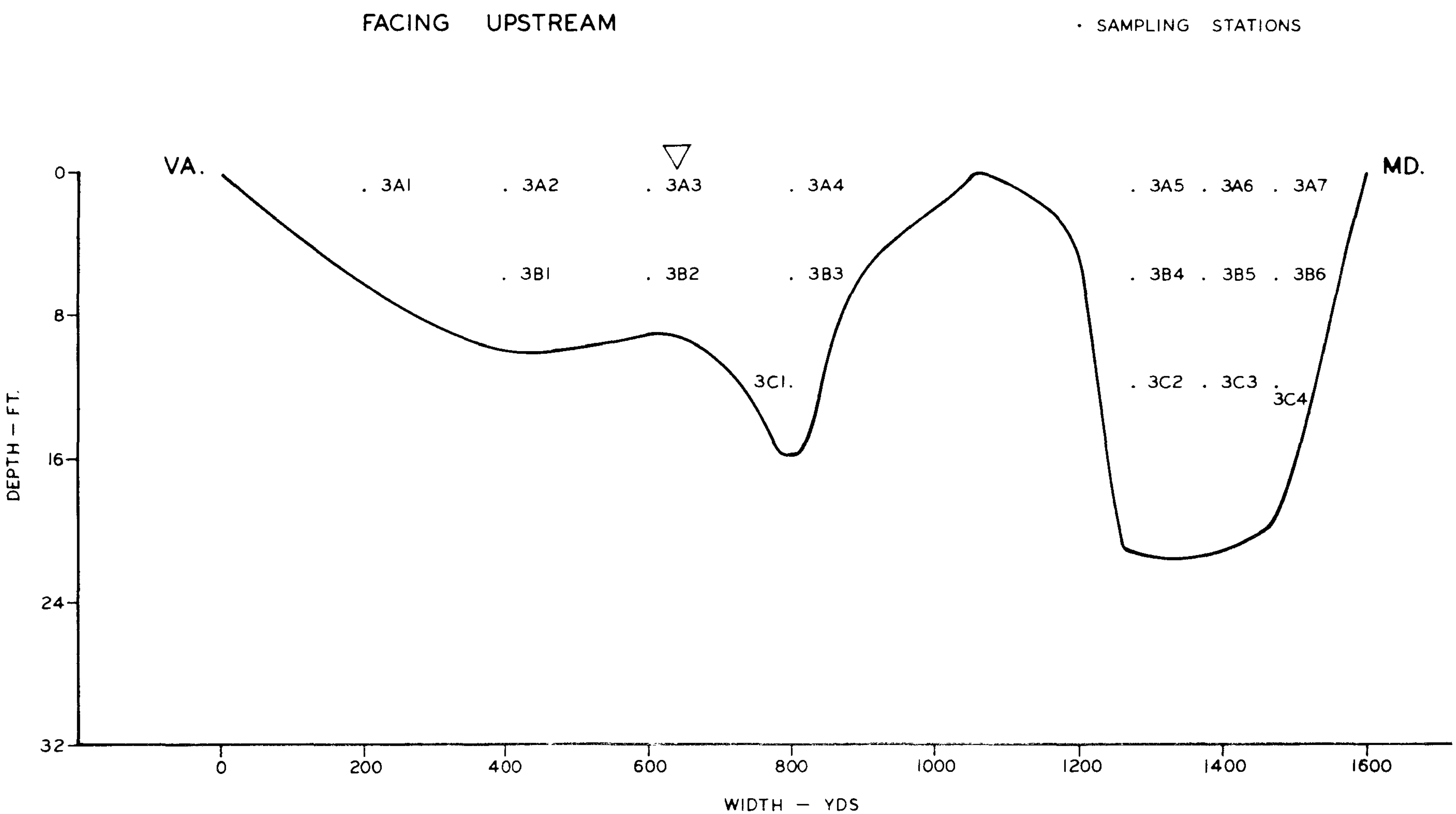



FIGURE A-17

# TRANSECT # 3A — HUNTER POINT

FACING UPSTREAM

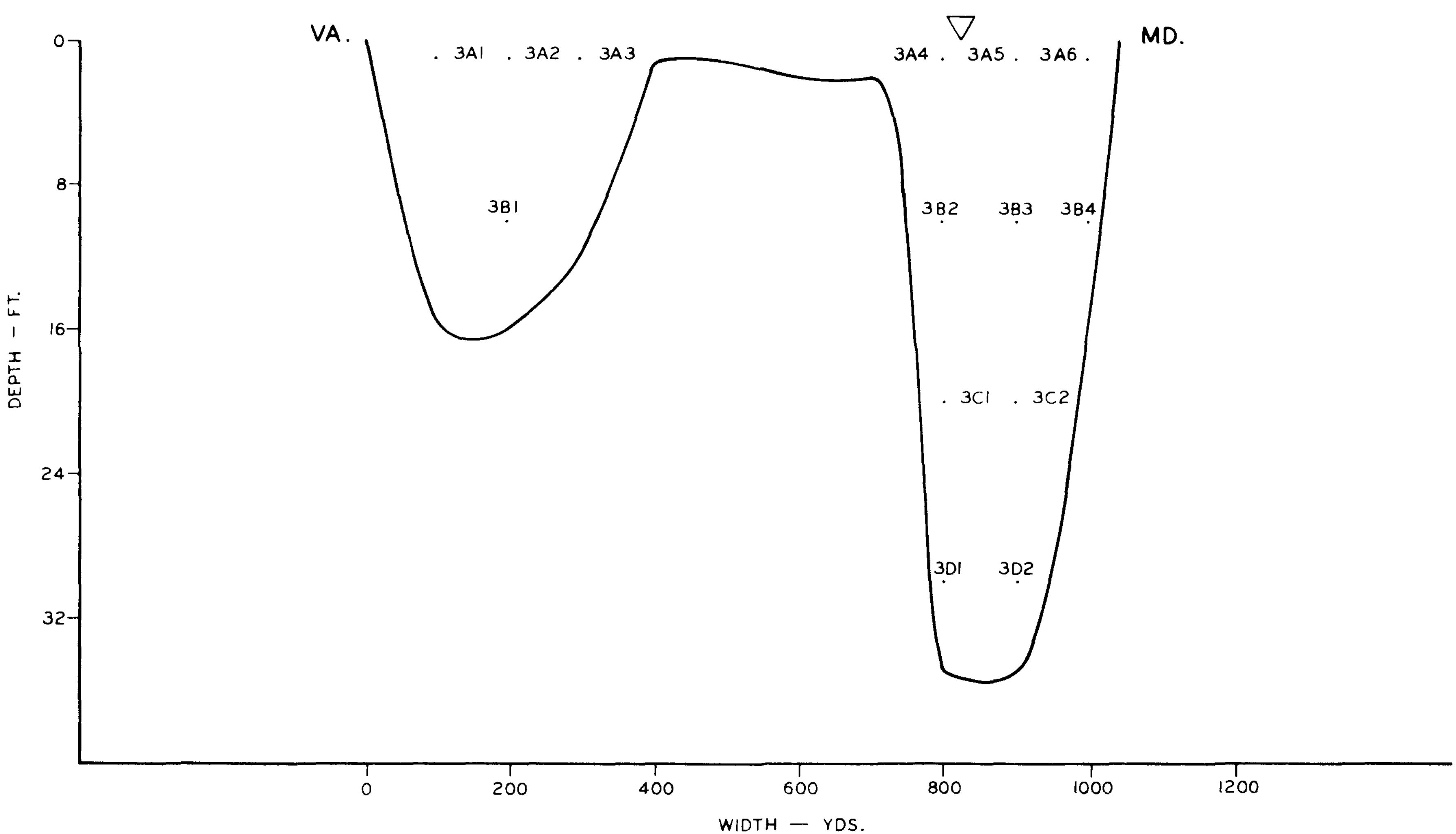



FIGURE A-18

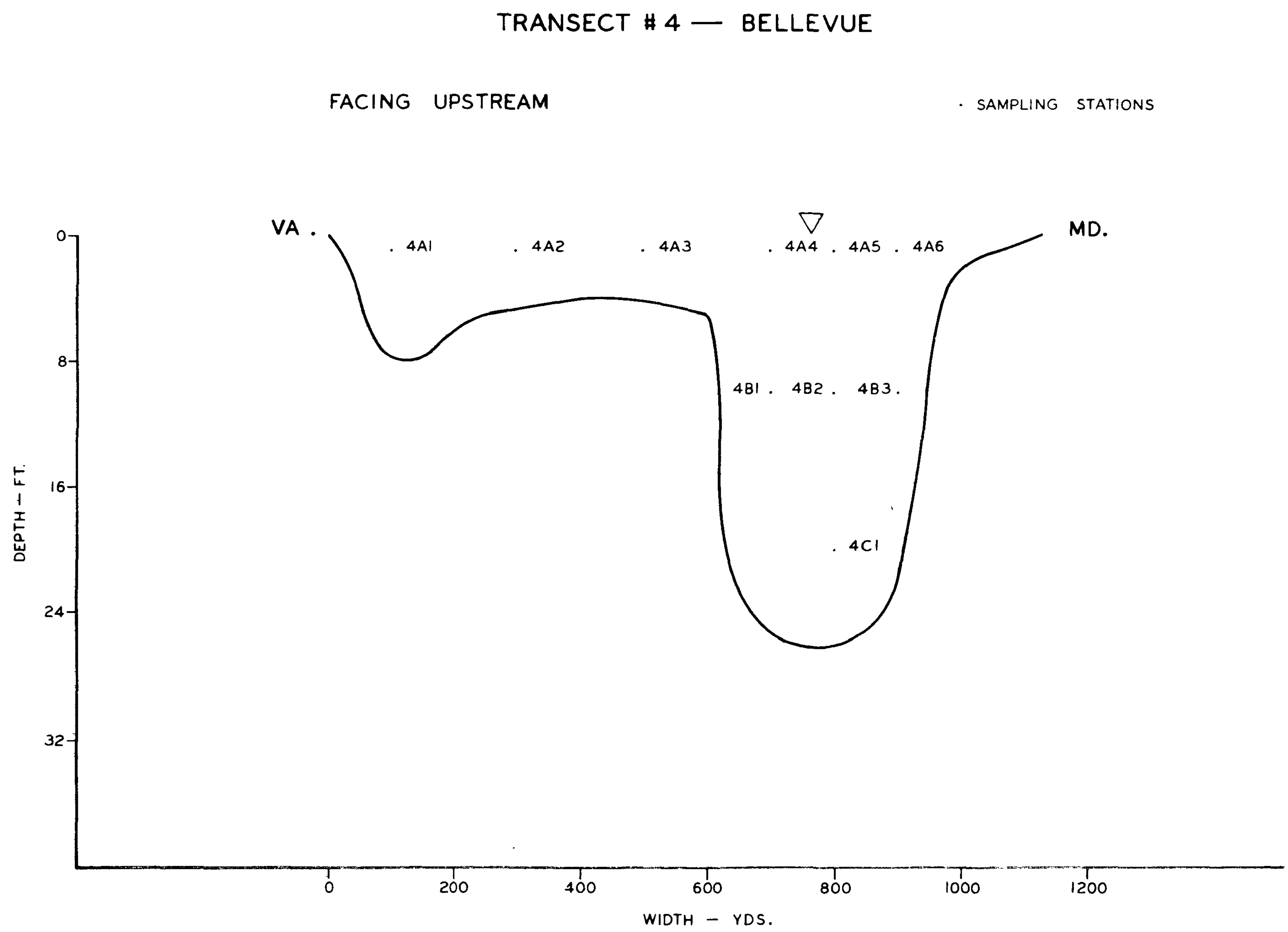

TRANSECT # 4 — BELLEVUE
FACING UPSTREAM
· SAMPLING STATIONS
VA .
MD.
. 4A1
. 4A2
. 4A3
. 4A4
. 4A5
. 4A6
4B1 .
4B2 .
4B3 .
. 4C1
0
8
16
24
32
DEPTH — FT.
0
200
400
600
800
1000
1200
WIDTH — YDS.

FIGURE A-19

# TRANSECT #4A — GOOSE ISLAND

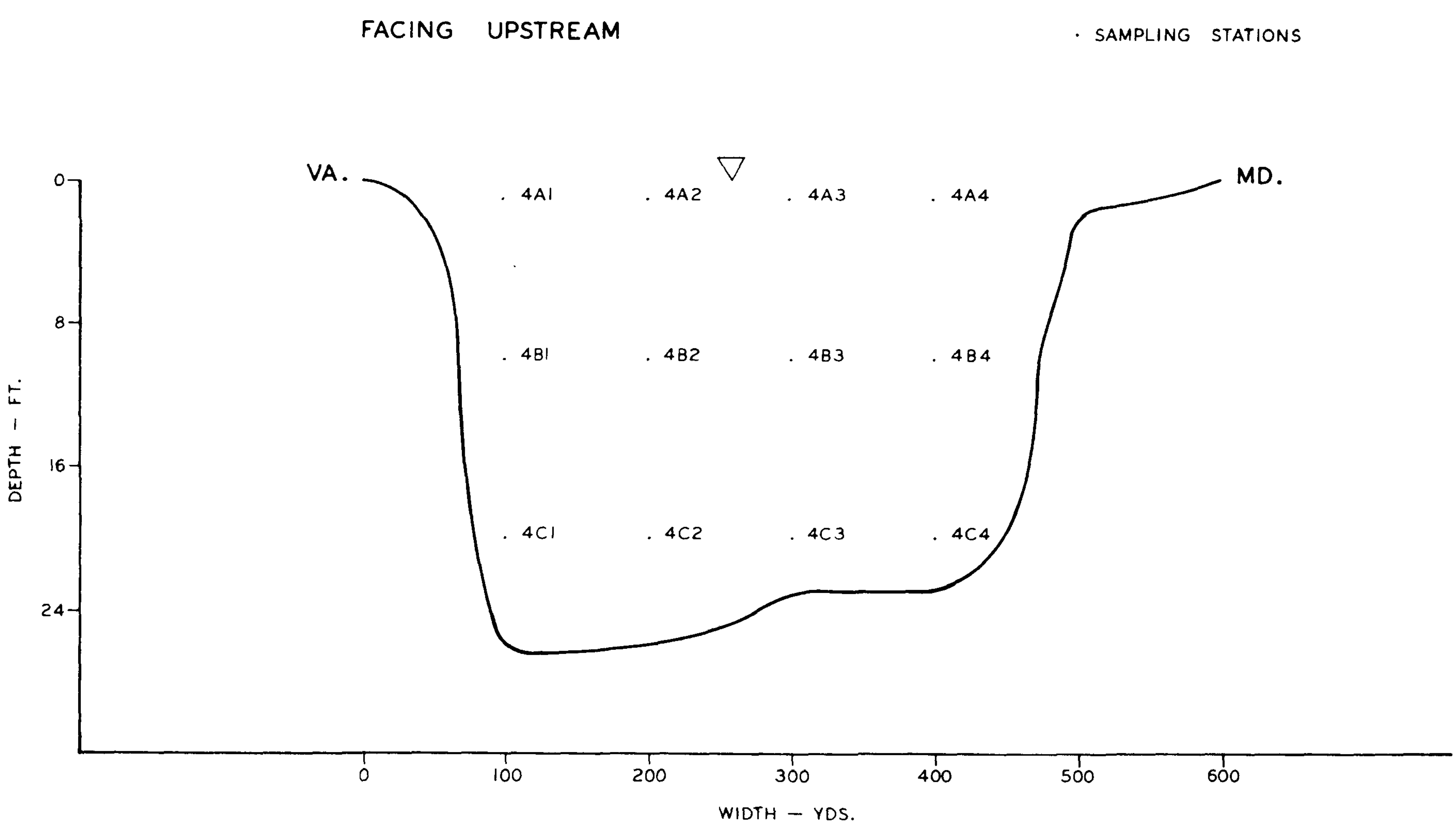



FIGURE A-20

# TRANSECT # 5 — WOODROW WILSON

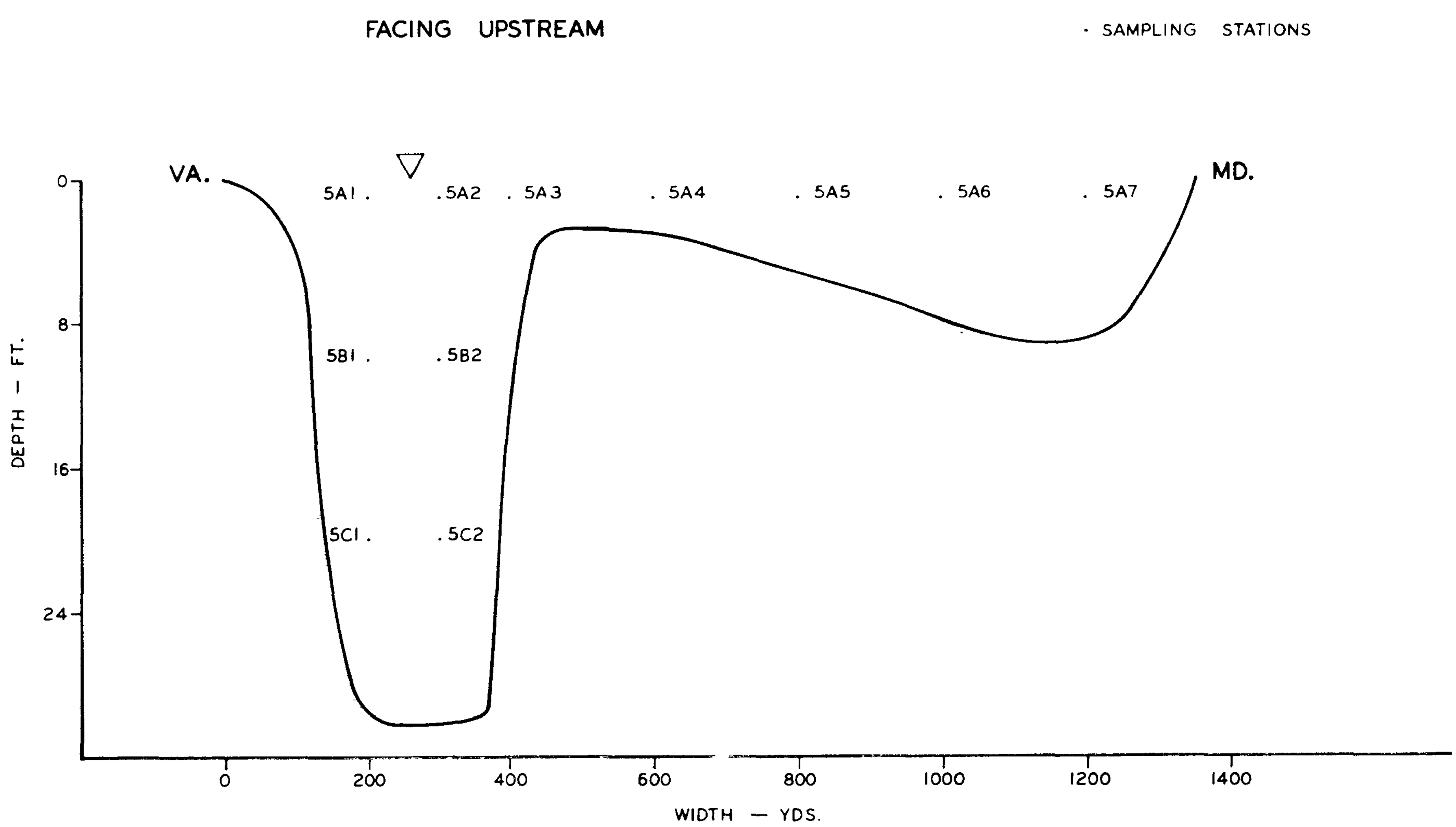



FIGURE A-21

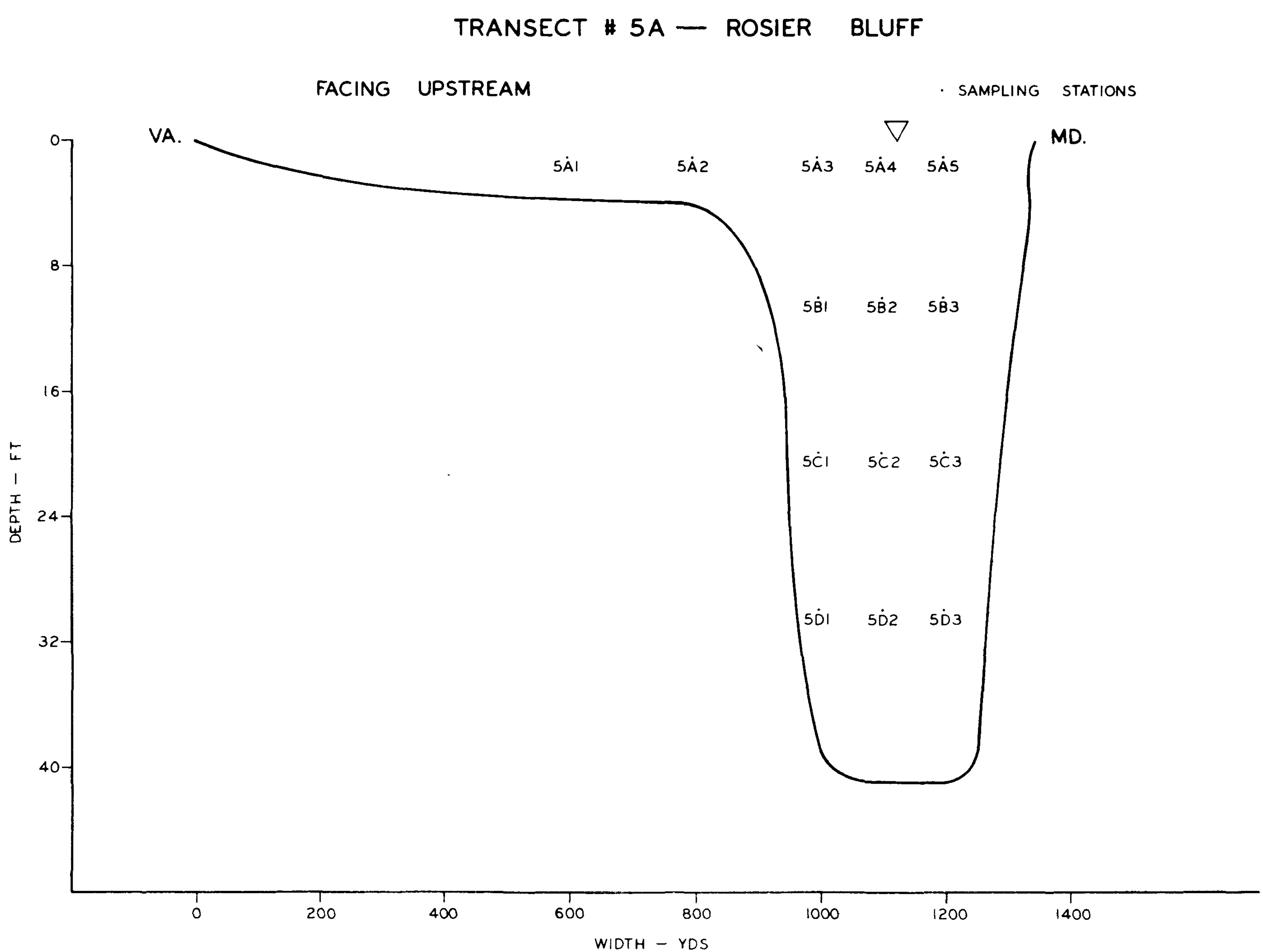

TRANSECT # 5A — ROSIER BLUFF
FACING UPSTREAM
· SAMPLING STATIONS
VA.
MD.
5A1
5A2
5A3
5A4
5A5
5B1
5B2
5B3
5C1
5C2
5C3
5D1
5D2
5D3
DEPTH — FT
0
8
16
24
32
40
0
200
400
600
800
1000
1200
1400
WIDTH — YDS

FIGURE A-22

# TRANSECT #6 — BROAD CREEK

FACING UPSTREAM

· SAMPLING STATIONS

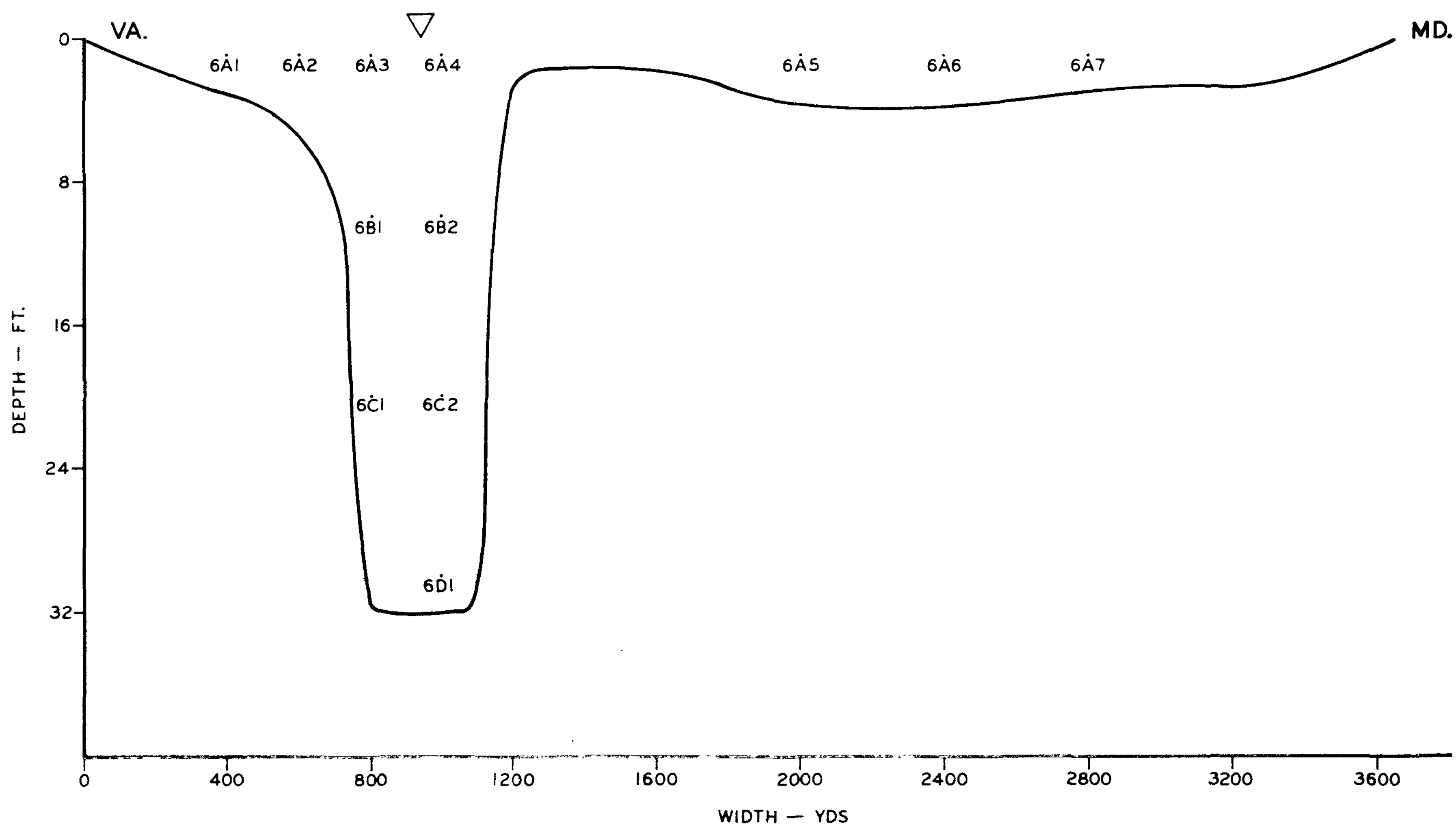



FIGURE A-23

## TRANSECT # 7 — PISCATAWAY CREEK

FACING UPSTREAM

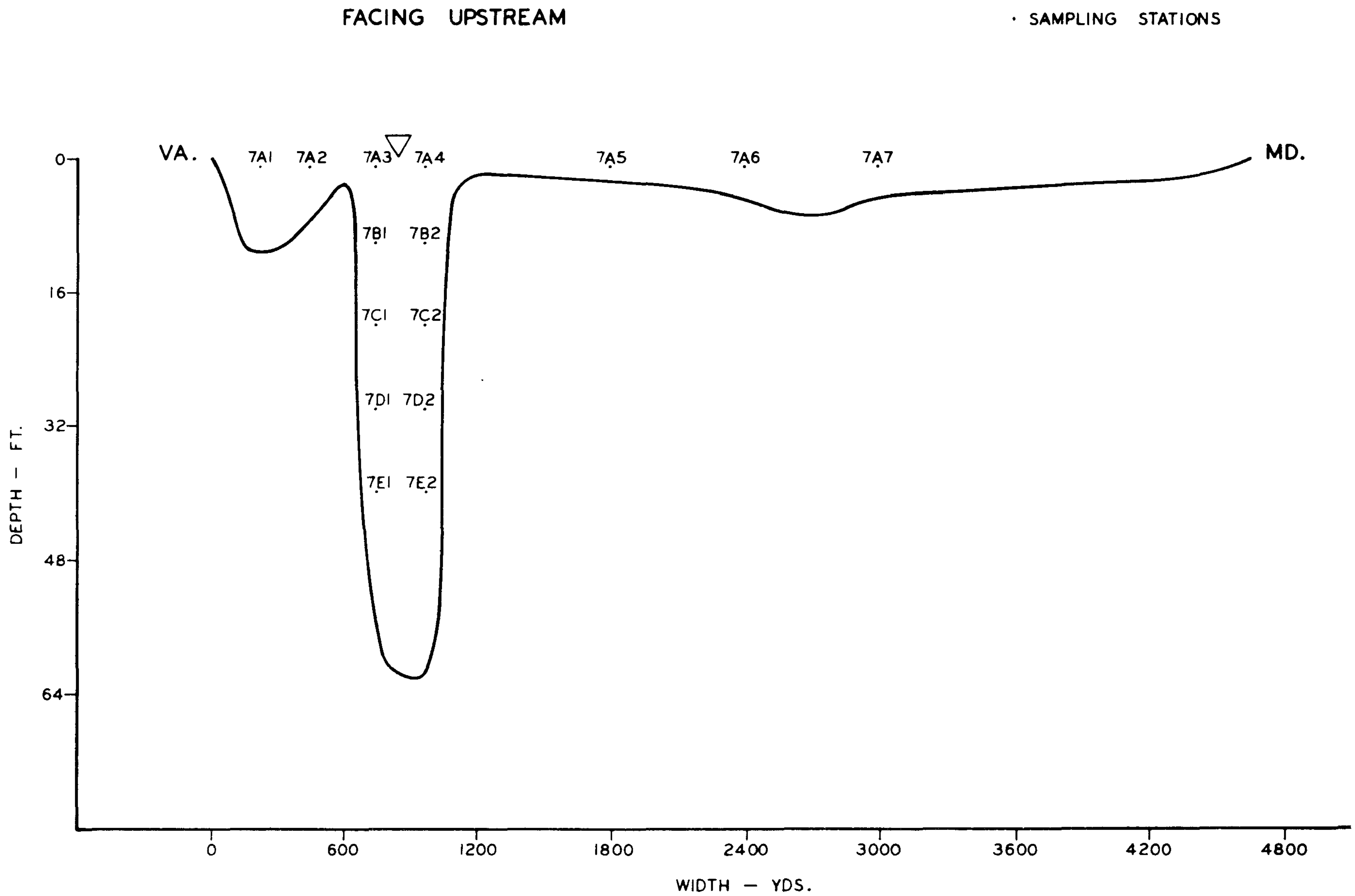



FIGURE A-24

## TRANSECT # 8 — DOGUE CREEK

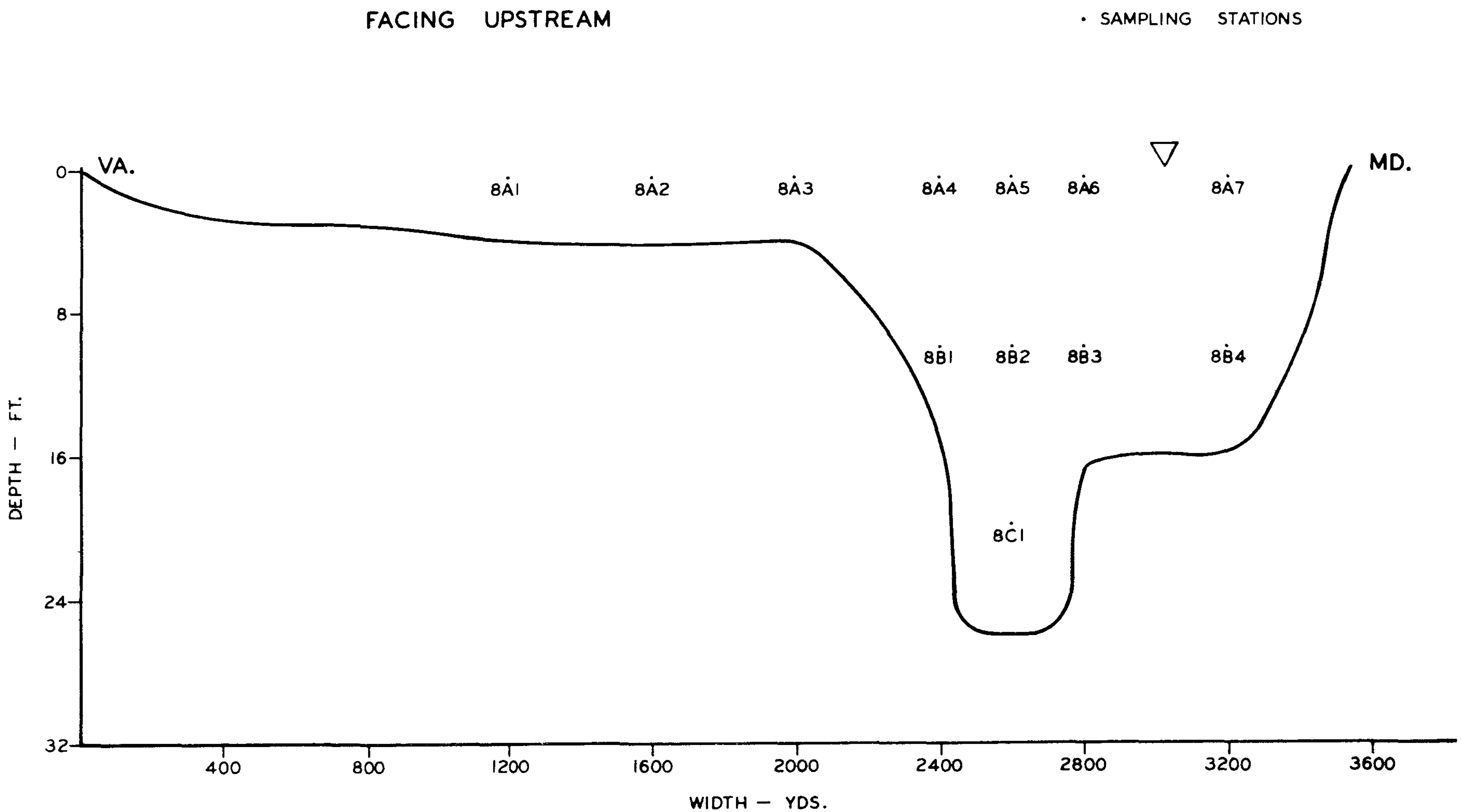



FIGURE A-25

# TRANSECT # 8A — GUNSTON COVE

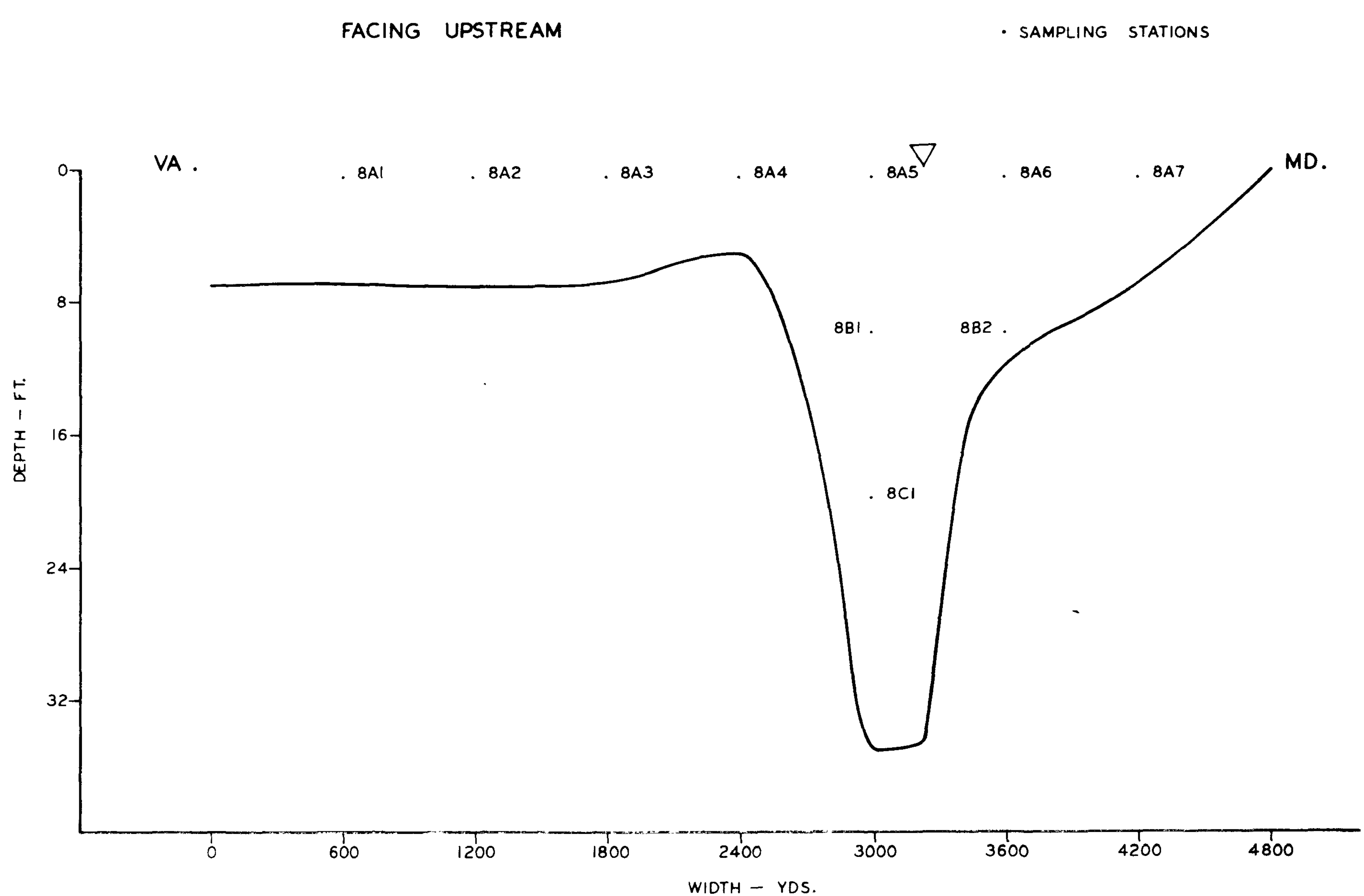



FIGURE A-26

# TRANSECT # 9 — HALLOWING POINT

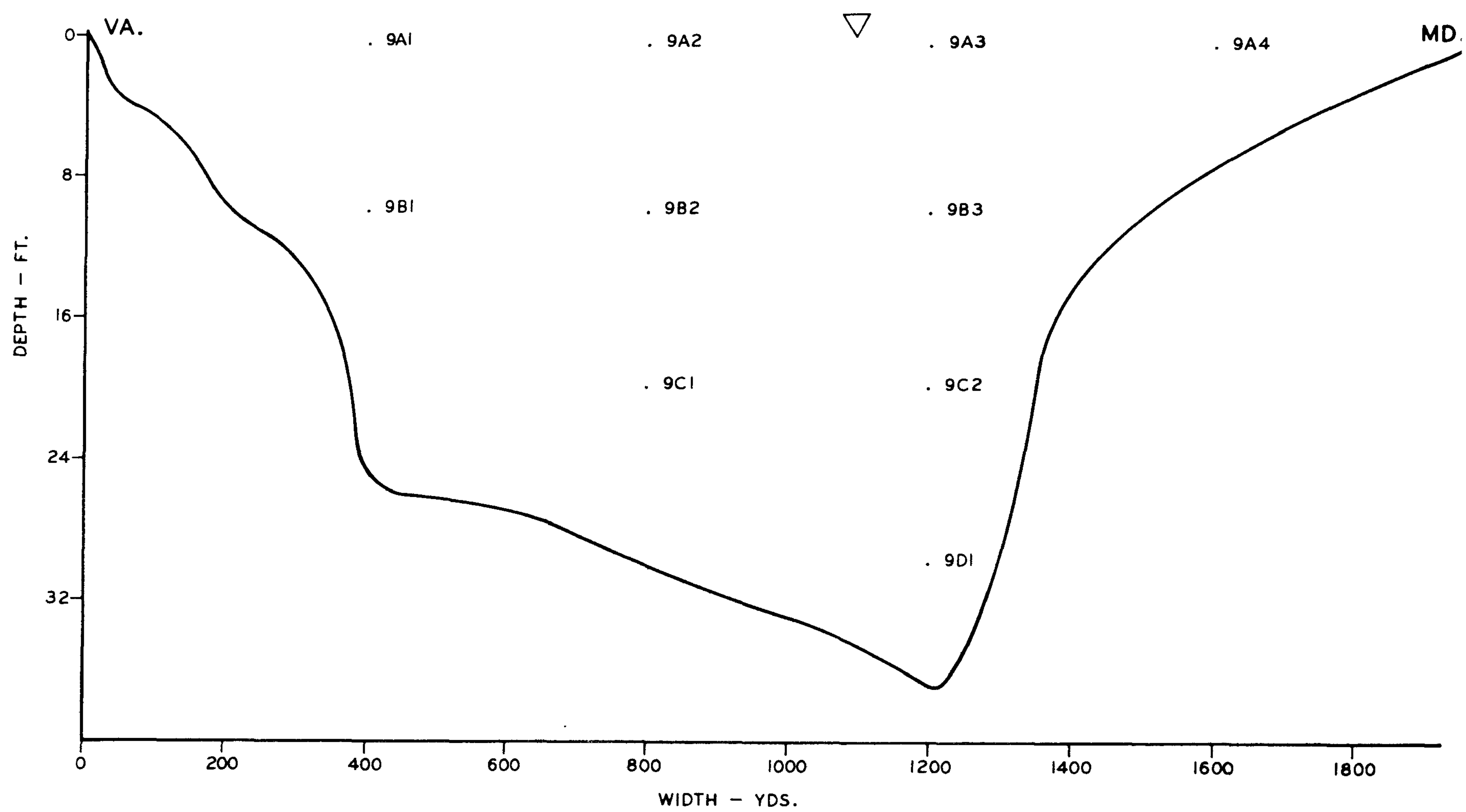



FIGURE A-27

TRANSECT # 10 — INDIAN HEAD

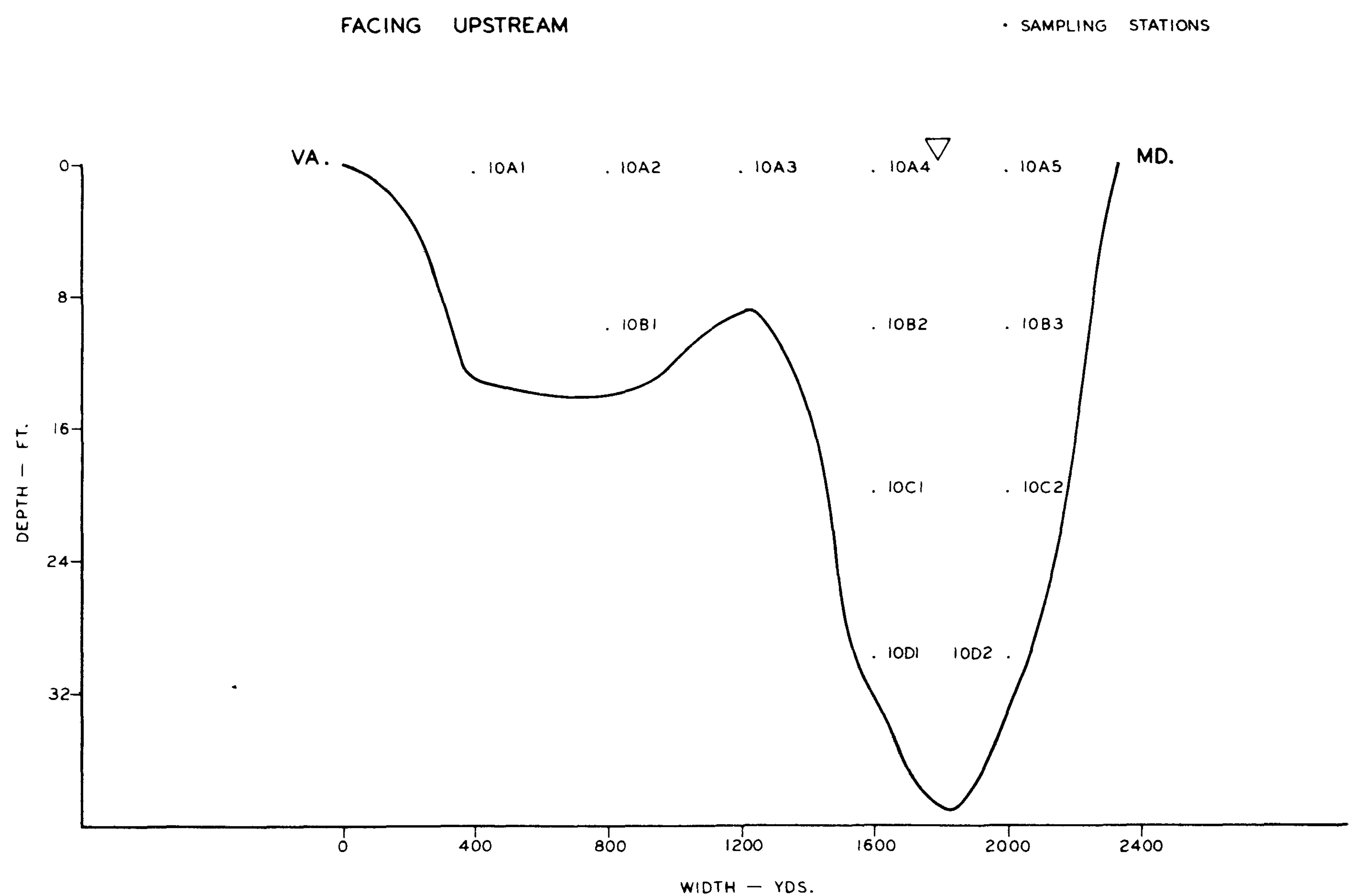



FIGURE A-28

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Chesapeake Technical Support Laboratory
Middle Atlantic Region
Water Quality Office
Environmental Protection Agency

# A WATER RESOURCE-WATER SUPPLY STUDY

# OF THE

# POTOMAC ESTUARY

Technical Report 35

April 1971

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# CHAPTER I

## INTRODUCTION

At the third session of the Conference on the Matter of Pollution of the Interstate Waters of the Potomac River and Its Tributaries in the Washington Metropolitan Area held April 2, 3, 4 and again on May 8, 1969, the conferees agreed upon 15 recommendations to enhance the water quality of the Potomac and to assure adequate sewerage services for the area.

At the progress evaluation meeting of the conference held on November 6-7, 1969, a technical advisory committee was established to determine the studies required to evaluate water quality management needs of the upper estuary.

In November 1969, the Assistant Secretary of the Interior also requested a study of the water supply potential of the upper Potomac Estuary. Incorporating both the suggestions of the Potomac Enforcement Technical Advisory Committee and the request of the Assistant Secretary of the Interior, a detailed water quality-water resources study of the Potomac Estuary was undertaken by the Chesapeake Technical Support Laboratory.

The study included (1) an evaluation of pollution sources including nutrients, (2) the development and refinement of mathematical models to predict the effects of the various pollutants on water quality, (3) the projection of water supply needs and wastewater loadings, (4) an evaluation of the estuary as a potential water supply source, (5) the determination of the maximum pound loadings by zone for the various pollutants under various flow conditions, (6) an investigation of alternative waste treatment plans, and (7) an estimate of the cost of wastewater treatment required to maintain water quality standards.

During this study, close cooperation was maintained with the North Atlantic Division of the U. S. Army Corps of Engineers who were investigating the water supply potential of the upper Potomac Estuary as part of their Northeast Water Supply Study (NEWS) for the Washington metropolitan area.

# CHAPTER II

## SUMMARY AND CONCLUSIONS

A detailed study of the interrelationships among wastewater discharges, water supply withdrawals, freshwater inflow, and water quality in the Potomac Estuary was undertaken in November 1969. This study had two purposes: (1) to refine the allowable oxygen demanding and nutrient loadings previously established for Zones I, II, and III of the upper Potomac Estuary and (2) to determine the feasibility of using the estuary as a municipal water supply source. The latter study was conducted in cooperation with the U. S. Army Corps of Engineers. The study findings as related to wastewater management are presented below:

1. The Potomac River Basin has a drainage area of 14,670 square miles. The average discharge rate of the Potomac River at Great Falls is 10,780 cubic feet per second (cfs) with a minimum of 610 cfs and a maximum of over 484,000 cfs.

2. Of the present 3.3 million population in the Potomac River Basin, 2.8 million live within the study area which encompasses the entire Washington metropolitan region.

3. The present municipal water use within the study area is 370 mgd with 72 percent (265 mgd) supplied from the Potomac River above Washington. The industrial water use is 2,750 mgd with cooling water for electric power production accounting for 99 percent.

4. Recreational facilities on or near the Potomac Estuary include a national park, three state parks, seven fish and game areas and 226 county recreational sites. A recent study by the Bureau of Outdoor Recreation indicated that the recreational potential of the 637 miles of shoreline has barely been developed.

5. In 1969, approximately 17-million pounds of fish, crabs, clams, and oysters were taken from the Potomac tidal system with a dockside value of some $4.7 million. A study in 1961 indicated that about $0.6 million was spent during 6 months of sport fishing in the Potomac Estuary. There are approximately 95 marina facilities in the tidal Potomac which accommodate over 5,200 recreational watercraft.

6. Effluents from the 18 major wastewater treatment facilities and combined sewer overflows, with a total flow of 325 mgd, contribute 450,000, 24,000, and 60,000 lbs/day of ultimate oxygen demand (UOD*), phosphorus, and nitrogen respectively to the waters of the upper Potomac Estuary.

7. Under low-flow conditions, the ultimate oxygen demand, phosphorus, and nitrogen loadings from the upper basin and local runoff were estimated as 66,000, 1,000, and 2,300 lbs/day, respectively.

8. The major sources of nutrients and ultimate oxygen demand in the Potomac Estuary are the local wastewater discharges. Under low-flow conditions approximately 88, 90, and 96 percent of the ultimate oxygen demand, nitrogen, and phosphorus are from treated waste effluents.

* UOD - Ultimate Oxygen Demand is defined as the sum of 1.45 times the 5-day biochemical oxygen demand and 4.57 times the unoxidized nitrogen.

At median freshwater inflows, approximately 62, 60, and 82 percent respectively are from these wastewater discharges.

9. Since the first sanitary surveys in 1913, the water quality of the upper Potomac Estuary has generally deteriorated. This is attributable to the increased pollution originating in the Washington area.

10. Fecal coliform densities have recently proved an exception to the general degradation as shown by the water quality indicators. Since the summer of 1969, the high fecal coliform densities previously found near the waste discharge points have been significantly reduced by continuous wastewater effluent chlorination. At present, the largest sources of bacterial pollution in the upper estuary are from sanitary and combined sewer overflows, where at times about 10 to 20 mgd of untreated sewage enters the estuary because of inadequate sewer and treatment capacities.

To achieve the adopted fecal coliform water quality standards, there must be both continuous disinfection of wastewater effluents and elimination or drastic reduction in overflows from sanitary and combined sewers.

11. The most pronounced effect of thermal discharges is in the Anacostia tidal river where a five-degree rise above ambient water temperature frequently occurs and readings as high as 33°C have been recorded during the summer months.

12. Since 1938, dissolved oxygen levels in the upper estuary had been decreasing. A slight upward trend occurred in the early 1960's

due to the provision of a higher degree of wastewater treatment. However, with increasing population, the amount of organic matter discharged has increased to a record high in 1970 resulting in a critical dissolved oxygen stress in the receiving water. In recent years, dissolved oxygen concentrations of less than 1.0 mg/l have occurred during low-flow, high-temperature periods.

13. Mathematical model simulation of the dissolved oxygen budget including carbonaceous, nitrogenous, benthic, and algal demands indicate that the nitrogenous demand is the greatest cause of dissolved oxygen deficit in the critical reach near the wastewater discharges and that algal growths have the greatest effect on DO from Piscataway to Indian Head, at times depressing it below 5.0 mg/l.

14. On the average, approximately 3-billion pounds per year of sediments enter the Potomac Estuary of which 2.2-billion pounds per year originate in the upper Potomac River Basin. The sediment yield from the Washington area on a lbs/sq mi/yr basis is about seven times greater than that from the upper basin.

15. Since 1913, the wastewater discharge quantities have increased over sevenfold from 42 to 325 mgd, the phosphorus load increased 22-fold from 1,100 to 24,000 lbs/day; nitrogen ninefold, from 6,400 to 60,000 lbs/day; and carbon approximately twofold, from 40,000 to 100,000 lbs/day. When ecological plant successions from a balanced toward an unbalanced system (primarily one dominated by blue-green algae) are related to wastewater loading trends, it can be concluded that the

ecological successions are the result of increases in nutrients. Moreover, it appears that the ecological changes are due primarily to the large increases in phosphorus and nitrogen.

16. In recent years, large populations of blue-green algae, often forming thick mats, have been observed in the Potomac Estuary from the Potomac River Bridge (Route 301) to the Woodrow Wilson Bridge during the months of June through October. In September of 1970, after a period of low-stream flow and high temperatures, the algal mats extended upstream beyond Hains Point and included the first nuisance growth within the Tidal Basin. The effects of the massive blue-green algal blooms in the middle and upper portions of the Potomac Estuary are (1) large increases of over 490,000 lbs/day in total oxygen demand, (2) an overall decrease in dissolved oxygen due to algal respiration in waters 12 feet and greater in depth, (3) creation of nuisance and aesthetically objectionable conditions, and (4) reduction in the feasibility of using the upper estuary as a potable water supply source because of potential toxin, taste, and odor problems.

17. To reduce the effects of excessive algal blooms on water quality and designated beneficial uses, it has been determined that during the summer months, the standing crop should be reduced to a minimum of 75 to 90 percent of the current level or to a chlorophyll a concentration at or below 25 ug/l.

18. From six independent methods of analysis, it appears that if the upper concentration limit of inorganic nitrogen is maintained between 0.3 and 0.5 mg/l as N and the upper limit of total phosphorus at

0.03 to 0.1 mg/1 as P, the algal standing crop can be maintained below nuisance levels under summer conditions. The lower limits of nutrient concentration apply to the embayments and middle portion of the estuary where growing conditions are more favorable, whereas the higher concentrations are applicable to the upper portion of the estuary where lack of light penetration limits algal growth.

19. Significant accumulations of various heavy metals in sediments have been detected near the major wastewater discharges. A study of the possible long-term toxic effects of these heavy metals on the biota of the Potomac Estuary, especially shellfish, is essential.

20. Population and water supply needs have been projected as follows:

| | | Water Supply Needs | | |
|---|---|---|---|---|
| Year | Population | Yearly avg. (mgd) | Maximum Month (mgd) | Maximum Daily (mgd) |
| 1969 | 2,700,000 | 370 | 470 | 660 |
| 1980 | 4,000,000 | 570 | 720 | 1000 |
| 2000 | 6,700,000 | 1010 | 1310 | 1820 |
| 2020 | 9,300,000 | 1570 | 2040 | 2820 |

21. Even with the seven proposed upper Potomac River Basin reservoirs operational, the following withdrawals will be required from the estuary or from direct wastewater reuse to meet the water supply requirements:

| Low-flow Characteristics Before Water Supply Diversion | | Withdrawal from the Potomac Estuary or from Direct Reuse* | | |
|---|---|---|---|---|
| Recurrence Interval (years) | Minimum Monthly Fresh Inflow (mgd) | 1980 For a 720 mgd Need (mgd) | 2000 For a 1310 mgd Need (mgd) | 2020 For a 2040 mgd Need (mgd) |
| 5 | 1300 | none | 210 | 940 |
| 20 | 1170 | none | 340 | 1070 |
| 50 | 910 | none | 600 | 1330 |

* Withdrawal based on minimum 30-day low flow concurrently with a maximum 30-day water supply withdrawal and a 200 mgd minimum base flow over Great Falls into the estuary.

22. The projected wastewater volumes and loading characteristics before treatment are as follows:

| Year | Flow (mgd) | BOD (lbs/day) | Nitrogen (lbs/day) | Phosphorus (lbs/day) |
|---|---|---|---|---|
| 1969 | 325 | 483,500 | 63,500 | 27,300 |
| 1980 | 475 | 823,500 | 95,600 | 43,100 |
| 2000 | 860 | 1,463,500 | 155,700 | 70,300 |
| 2020 | 1,340 | 2,195,000 | 215,600 | 97,400 |

23. To aid in determining the allowable pollutant loadings from wastewater discharges, mathematical models have been developed and verified for predicting (1) phosphorus transport, (2) nitrogen transport and assimilation, (3) effects of benthic, carbonaceous, and nitrogenous oxygen demand, including the effects of algal photosynthesis

and respiration on the dissolved oxygen budget, and (4) chloride and total dissolved solid intrusions from the Chesapeake Bay, and their buildup as a result of water supply withdrawals from the estuary.

24. Based upon the study of projected wastewater quantities and the recently adopted metropolitan Washington wastewater treatment implementation schedule, the following can be concluded:

(1) Between the years 1980 and 2000, the Potomac (Dulles) Interceptor, with its current capacity of 65 mgd, will be overloaded.

(2) To provide for future wastewater collection and treatment facilities in areas currently projected to be served by the Potomac Interceptor, either the capacity of the interceptor would have to be significantly increased or additional wastewater treatment facilities constructed on the Potomac River above Washington.

(3) With the Blue Plains wastewater treatment capacity limited to 309 mgd, a need exists not only for one or more facilities to serve the Anacostia Valley but also to serve a portion of the upper Potomac area currently served by Blue Plains via the Dulles Interceptor.

(4) Large wastewater volumes are projected in the Occoquan and Pohick watersheds in the Virginia counties downstream from Washington, indicating a need for long-range water resources planning in this area.

25. Three basic alternative wastewater treatment systems were investigated to determine the effects of the discharge locations on

receiving water quality including chloride and total dissolved solid intrusions, as follows:

(1) Alternative I consisted of the following plants: Pentagon, Arlington, Blue Plains, Alexandria, Piscataway (also serving Andrews Air Force Base), Lower Potomac (serving Pohick, Accotink, Dogue, and Little Hunting Creek watersheds including Fort Belvoir), Mattawoman, Neabsco (serving the Occoquan watershed), and Port Tobacco.

(2) Alternative II consisted of the nine treatment plants as in Alternative I plus a facility serving the Anacostia Valley and located just above the Maryland-D. C. Line, and

(3) Alternative III consisted of the same facilities as Alternative II plus an upper Potomac plant discharging near Chain Bridge and serving the upper Potomac region.

Two other systems designated as Alternatives IV and V were also investigated. These were identical to III, except that for Alternative IV, all effluents were assumed to be discharged into the main channel of the Potomac; while for Alternative V, all effluents were assumed to be conveyed downstream to a common discharge point below Indian Head, Maryland.

26. Data from the chloride, total dissolved solids, and other simulations where the estuary was used as a potable water supply source indicate the following:

(1) The position of the salt wedge with respect to intrusion from the Chesapeake Bay is a function of (a) duration and magnitude

of any selected flow, (b) location of the wastewater treatment facility discharges, and (c) consumptive losses in the water distribution system.

(2) Even with no water supply withdrawals from the estuary, for comparable flow conditions, intrusion of chlorides and total dissolved solids from the Chesapeake Bay will occur farther upstream in the future as a result of the greater percentages of wastewater discharged downstream into the salt wedge and the projected increases in consumptive loss, with the latter having the most pronounced effect.

(3) The number of days during which the estuary can be used for water supply depends upon (a) the position of the wedge prior to the withdrawal, (b) magnitude of the withdrawal, (c) freshwater inflow during withdrawal, (d) location of the wastewater discharges, and (e) the increase in chlorides and total dissolved solids as a result of water use.

(4) The maximum possible number of days that the estuary could be used for a water supply source was determined by using a total dissolved solids concentration in the blended water of 500 mg/l maximum as a criterion since this parameter was determined to be more critical than chlorides. TDS water use increments* of 40 and 240 mg/l

* Water use increment is the amount that the concentration of TDS or any other parameter is increased from the point of water intake to the point of discharge as a result of water supply treatment, municipal use, and wastewater treatment.

were applied at both the upstream and downstream location extremes of the saltwater wedge to give the results in the table below:

Alternative I

Maximum Days of Use of Estuary

| Year | Water Withdrawal From Estuary (cfs) | Upper Position of Wedge Water Use Increment 40 mg/l | 240 mg/l | Lower Position of Wedge Water Use Increment 40 mg/l | 240 mg/l |
|---|---|---|---|---|---|
| 1980 | 500 | >166 | >166 | >166 | >166 |
| 2000 | 1250 | 90 | 35 | 140 | 45 |
| 2020 | 2000 | 45 | 15 | 95 | 20 |

(5) For the year 2020 and using the upper position of the wedge (as observed in early September 1966--the lowest flow on record), the number of days that the estuary can be used as a water supply and yet maintain a maximum 500 mg/l total dissolved solids standard in the blended water is given below as a function of freshwater flow before water supply diversions:

Maximum Days of Use of Estuary

| Freshwater Flow (cfs) | Alternative I Water Use Increment 40 mg/l (days | 240 mg/l (days) | Alternative V Water Use Increment 40 mg/l (days) | 240 mg/l (days) |
|---|---|---|---|---|
| 400 | 45 | 15 | 18 | 18 |
| 1100 | >166 | 42 | >166 | 41 |
| 1800 | >166 | >166 | >166 | >166 |

(6) Since the projected water supply needs for the year 2020 cannot be met completely either by withdrawals from the estuary or

from the seven proposed upper basin reservoirs for drought periods extending over a month, both sources will eventually be needed to meet the future water requirements for the Washington metropolitan area. It appears that an increase of approximately 860 cfs (from 940 to 1800 cfs) in the Potomac River discharge at Washington will be required to maintain an acceptable blended water with respect to total dissolved solids for a 240 mg/l water reuse increase. If the increase is less than 240 mg/l, the flow regulation requirements will decrease.

(7) While other aspects of water supply requirements such as viruses and carbon chloriform extractables need to be considered in more detail, it appears that the estuary can be used as a supplementary water supply source if wastewater discharges and water supply withdrawals are subjected to adequate treatment.

27. Direct reuse of the renovated wastewater is another solution to meet water supply needs. This alternative has numerous advantages over withdrawals from the estuary because:

(1) Any need for consideration of salt intrusion from the Chesapeake Bay for water supply purposes is eliminated,

(2) Localized runoff and combined sewer overflows will not degrade the high quality renovated water,

(3) The need for flow regulation from upstream reservoirs to meet the projected Washington area water supply requirements is reduced to a total flow of approximately 1100 cfs (before water supply diversion) or an increase of about 150 cfs above unregulated conditions.

Excluding the psychological objections to treated wastewater reuse and the problems of physical transport of the wastewater to the water intake, the major disadvantage, especially from the technical viewpoint, would be the need to maintain the present maximum total dissolved solids buildup of 140 mg/l through the water supply treatment, water use, and wastewater renovation processes whenever more than 80 percent of the water supply is taken directly from renovated wastewater.

28. When the water resource needs of the entire basin are considered, the long-range solution to the water supply-wastewater disposal problem may initially be a combination of water supply withdrawals from the estuary and flow regulation, with direct reuse becoming increasingly feasible by early in the 21st Century.

29. The maximum allowable ultimate oxygen demand loadings have been determined as given below for various zones and subzones of the upper estuary for a 29°C temperature, a freshwater inflow after water supply diversion of 300 cfs, a DO of 6 mg/l in the treated effluent, and based upon maintaining 5 mg/l DO in the receiving waters.

MAXIMUM UOD LOADINGS FOR POTOMAC ESTUARY

| Zone | | Allowable UOD* (lbs/day) |
|---|---|---|
| I-a | (Upstream from Hains Point) | 4,000 |
| I-b | (Anacostia River) | 3,000 |
| I-c | (Hains Point to Broad Creek) | 75,000 |
| II | (Broad Creek to Indian Head) | 190,000 |
| III | (Indian Head to Smith Point) | 380,000 |

* These loadings are the maximum allowable loadings for each zone assuming adjacent zones are loaded to their maximum capacities.

30. For the three freshwater inflows (before water supply withdrawal) investigated, i.e., 1800, 1100, and 400 cfs, the maximum UOD loadings were not affected significantly except for Alternative III which included a treated waste discharge in Zone I-a near Chain Bridge.

When the DO in the effluents in mathematical model simulations was decreased from 6.0 to 2.0 mg/l, the most pronounced effect was in Zone I-c in which the UOD loading decreased from 75,000 to 56,000 lbs/day.

31. Allowable UOD loadings for the Piscataway and Gunston Cove embayments have been developed for the projected wastewater volumes and conditions specified in Number 29 and are given below:

MAXIMUM UOD LOADINGS FOR PISCATAWAY CREEK AND GUNSTON COVE

| Piscataway Creek | | Gunston Cove | |
|---|---|---|---|
| Wastewater Flow (mgd) | Maximum UOD Load (lbs/day) | Wastewater Flow (mgd) | Maximum UOD Load (lbs/day) |
| 24 | 10,000 | 50 | 7,000 |
| 49 | 11,000 | 103 | 11,000 |
| 79 | 12,000 | 170 | 16,000 |

32. Since nitrification (the conversion of ammonia nitrogen to nitrate nitrogen) has little effect on the oxygen resources of the estuary at temperatures below 15°C, nitrogen removal from the wastewater effluents to meet DO standards will be required whenever the water temperature is above 15°C, usually during the months of April through October.

In order to prevent formation of sludge deposits, to eliminate objectionable floating matter, and to prevent low DO concentrations during periods of ice cover, a minimum of 70-percent UOD removal and an effluent concentration of less than 15 mg/l suspended solids are required year-around for all discharges.

33. Using an average freshwater inflow of 300 cfs to the Potomac Estuary after water supply diversions, the allowable loadings of phosphorus by zones were determined based on maintaining an average maximum of 0.067 mg/l as P in Zones I and II, and 0.03 mg/l as P in Zone III for algal control. The allowable loadings are presented below:

MAXIMUM PHOSPHORUS LOADINGS FOR POTOMAC ESTUARY

| Zone | | Allowable Phosphorus (lbs/day) |
|---|---|---|
| I-a | (Upstream from Hains Point) | 200 |
| I-b | (Anacostia River) | 85 |
| I-c | (Hains Point to Broad Creek) | 900 |
| II | (Broad Creek to Indian Head) | 1500 |
| III | (Indian Head to Smith Point) | 2000 |

34. Allowable phosphorus loadings for the Piscataway and Gunston Cove embayments for phosphorus concentration in the receiving waters of 0.03 mg/l as P are shown below as a function of wastewater flow:

PHOSPHORUS LOADINGS TO EMBAYMENTS

| Piscataway Creek | | Gunston Cove | |
|---|---|---|---|
| Wastewater Flow (mgd) | Maximum Phosphorus Load (lbs/day) | Wastewater Flow (mgd) | Maximum Phosphorus Load (lbs/day) |
| 24 | 35 | 50 | 35 |
| 49 | 50 | 103 | 60 |
| 79 | 65 | 170 | 140 |

35. To prevent excessive algal growth and to enhance the water quality in the upper and middle reaches of the estuary, it appears that it will be necessary to remove phosphorus on a continuous or a year-around basis for discharges into the upper estuary. Moreover, the control of at least 50 percent of the phosphorus load originating in the upper Potomac River Basin appears necessary if the aforementioned phosphorus criteria are to be achieved. To accomplish this reduction, the current phosphorus loading from all wastewater discharges in the upper Potomac River Basin must be decreased from 6100 to 700 lbs/day.

36. Using a freshwater inflow of 300 cfs and average maximum inorganic nitrogen concentrations of 0.5, 0.4, and 0.3 mg/l in Zones I, II, and III, respectively, for algal control, the maximum nitrogen loadings for warm temperature conditions were determined as follows:

NITROGEN LOADINGS FOR POTOMAC ESTUARY

| Zone | | Allowable Total Nitrogen (lbs/day) |
|---|---|---|
| I-a | (Upstream from Hains Point) | 1000 |
| I-b | (Anacostia River) | 300 |
| I-c | (Hains Point to Broad Creek) | 3400 |
| II | (Broad Creek to Indian Head) | 5800 |
| III | (Indian Head to Smith Point) | 9000 |

37. Allowable total nitrogen loadings for the Piscataway and Gunston Cove embayments based upon maintaining 0.3 mg/l of inorganic nitrogen under warm temperature conditions and for varying wastewater flows follow:

NITROGEN LOADINGS TO EMBAYMENTS

| Piscataway Creek | | Gunston Cove | |
|---|---|---|---|
| Wastewater Flow (mgd) | Maximum Nitrogen Load (lbs/day) | Wastewater Flow (mgd) | Maximum Nitrogen Load (lbs/day) |
| 24 | 120 | 50 | 130 |
| 49 | 170 | 103 | 270 |
| 79 | 270 | 170 | 460 |

38. Considering the present difficulty in controlling nitrogen in the upper basin and its transport characteristics in the estuary, it appears that the need for nitrogen removal for algal control at wastewater treatment plants will be limited to those periods when the water temperature exceeds 15°C, normally from April through October. With the large projected increases in nitrogen from wastewater discharges, there may be a need for year-around nitrogen control by the year 2000.

39. Because of the lack of transport and assimilative capacity in the upper portions of small tidal embayments and also because of ideal algal growing conditions, maximum concentrations of UOD, phosphorus and nitrogen in effluents discharged to these areas should be less than 10.0, 0.2, and 1.0 mg/l, respectively. A detailed analysis for each embayment is required to determine the minimum cost of either extending the discharge outfall to the main channel of the Potomac or discharging within the embayment and providing a very high degree of wastewater treatment, approaching ultimate wastewater renovation. Unless this high degree of removal is provided, effluents from Alexandria, Arlington, Piscataway, and the Lower Potomac facilities should be discharged into the main channel of the Potomac Estuary.

40. The present worth cost of additional wastewater treatment from the year 1970 to 2020, including operation, maintenance, and amortization costs, has been estimated to be $1.34 billion with a total average annual cost of $64.8 million. The unit treatment processes assumed include activated sludge, biological nitrification-denitrification, lime clarification, filtration, effluent aeration, and chlorination.

41. The cost of wastewater treatment on a per capita basis is as follows:

| Item | 1970-1980 | 1980-2000 | 2000-2020 |
|---|---|---|---|
| Average Population | 3,350,000 | 5,350,000 | 8,000,000 |
| Initial Capital Cost/Person/Year | $17.0 | $ 4.90 | $ 7.30 |
| Operation and Maintenance Cost/Person/Year | $ 7.50 | $ 8.60 | $ 9.10 |
| Total Cost/Person/Year | $24.50 | $13.50 | $16.40 |

# CHAPTER III

# STUDY AREA DESCRIPTION

## A. POTOMAC RIVER TIDAL SYSTEM

The Potomac River Basin, with a drainage area of 14,670 square miles, is the second largest watershed in the Middle Atlantic States. From its headwaters on the eastern slope of the Appalachian Mountains, the Potomac flows first northeasterly then generally southeasterly in direction some 400 miles to the Chesapeake Bay.

Above Washington, D. C., the Potomac traverses the Piedmont Plateau to the Coastal Plain at the Fall Line. Below the Fall Line, the Potomac is tidal and extends 114 miles southeastward to its discharge point into the Chesapeake Bay.

The tidal portion is several hundred feet in width at its uppermost reach near Washington and broadens to nearly six miles at its mouth. A shipping channel with a minimum depth of 24 feet is maintained upstream to Washington. Except for this channel and a few short reaches with depths up to 100 feet, the tidal portion is relatively shallow with an average depth of about 18 feet.

The mean tidal range is about 2.9 feet in the upper portion near Washington and about 1.4 feet near the Chesapeake Bay. The lag time for the tidal phase between Washington and the Chesapeake Bay is about 6.5 hours.

Of the 3.3 million people living in the entire basin, approximately 2.8 million reside in the Washington metropolitan area. The remaining area of the tidal portion, which drains 3,216 square miles, is sparsely populated.

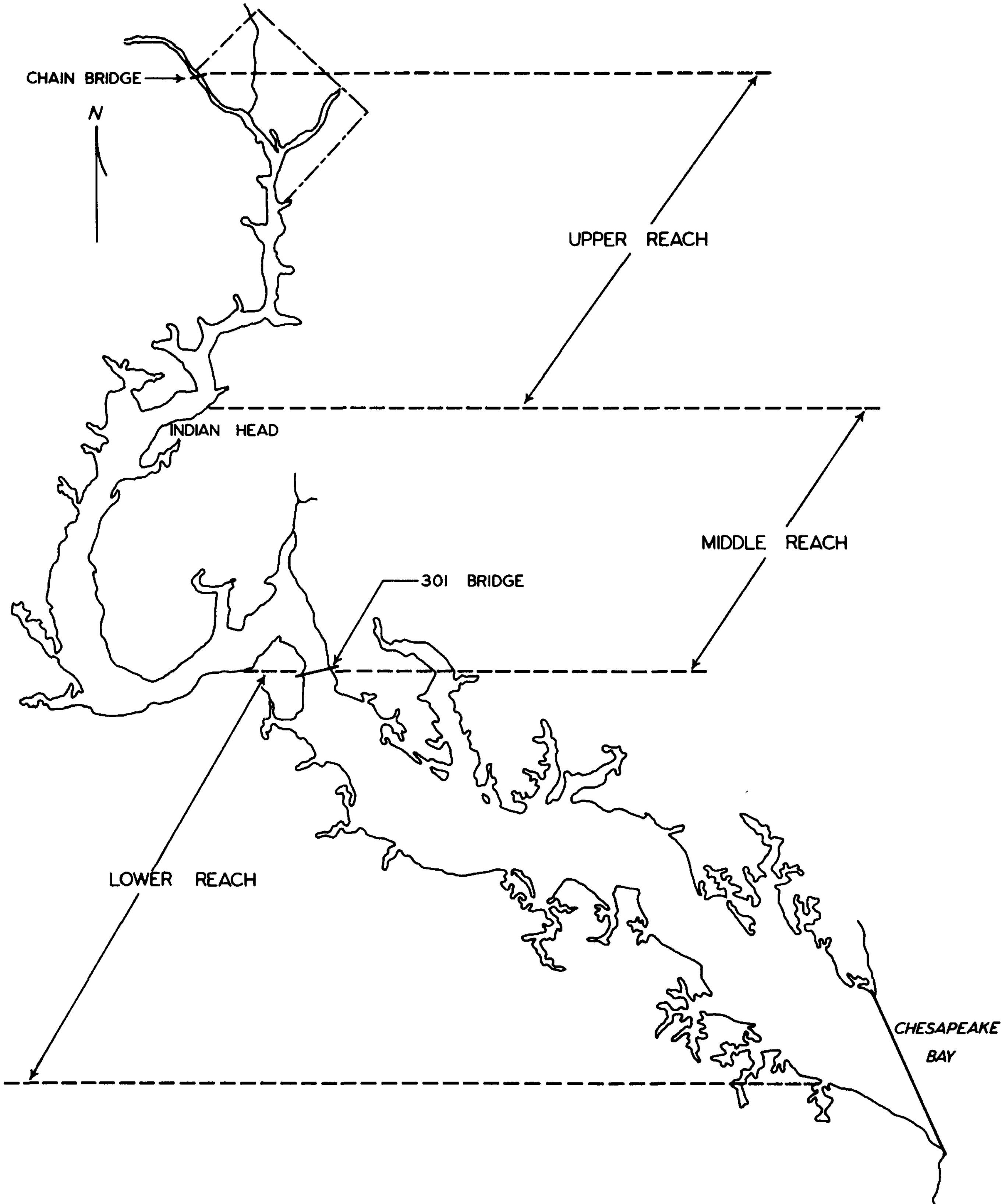
For purposes of discussion and investigation, the tidal portion of the Potomac River has been divided into three reaches as shown in Figure III-1 and described below:

| Reach | Description | River Mile | Volume cu.ft.x$10^9$ |
|---|---|---|---|
| Upper | From Chain Bridge to Indian Head | 114.4 to 73.8 | 9.3 |
| Middle | From Indian Head to Rte. 301 Bridge | 73.8 to 47.0 | 36.2 |
| Lower | From Rte. 301 Bridge to Chesapeake Bay | 47.0 to 00.0 | 175.4 |

The upper reach, although tidal, contains fresh water. The middle reach is normally the transition zone from fresh to brackish water. The lower reach is saline with chloride concentrations near the Chesapeake Bay ranging from about 7,000 to 11,000 mg/l.

To facilitate determination of water quality control requirements, the upper and middle reaches of the estuary have been segmented into 15-mile zones of similar physical characteristics beginning at Chain Bridge.

River mile distances from both the Chesapeake Bay and Chain Bridge for the three upper zones are given in Table III-1. This zone concept was adopted by the conferees at the Potomac Enforcement Conference on May 8, 1969.




POTOMAC RIVER TIDAL SYSTEM

FIGURE III-1

Table III-1

ZONES OF THE UPPER AND MIDDLE REACHES OF THE POTOMAC ESTUARY

| Zone and Description | River Mile of Upper End of Zone | | River Mile of Lower End of Zone | |
|---|---|---|---|---|
| | from Chain Bridge | from Chesapeake Bay | from Chain Bridge | from Chesapeake Bay |
| I | | | | |
| Chain Bridge to Broad Creek | 0.0 | 114.4 | 15.0 | 99.4 |
| II | | | | |
| Broad Creek to Indian Head | 15.0 | 99.4 | 30.0 | 84.4 |
| III | | | | |
| Indian Head to Smith Point | 30.0 | 84.4 | 45.0 | 69.4 |

B. HYDROGRAPHIC ANALYSIS

The major source of freshwater inflow into the Potomac Estuary is from the upper Potomac River Basin. The average flow, measured at Great Falls before diversions for municipal water supply for the period from 1930-1968, was 10,768 cfs with a minimum flow of 610 cfs that occurred on September 10, 1966.

The monthly flow characteristics for the Potomac at Great Falls are tabulated below for the reference period of 1931-1960.

| Month | 25 Percent Quartile | Mean Flow (cfs) | 75 Percent Quartile |
|---|---|---|---|
| January | 7,600 | 13,600 | 17,200 |
| February | 8,700 | 16,600 | 24,600 |
| March | 13,900 | 21,100 | 24,400 |
| April | 12,800 | 20,000 | 26,900 |
| May | 8,800 | 14,500 | 17,900 |
| June | 6,100 | 8,700 | 10,300 |
| July | 3,500 | 5,500 | 6,400 |
| August | 2,700 | 6,000 | 7,400 |
| September | 2,000 | 4,700 | 6,800 |
| October | 2,000 | 6,300 | 6,400 |
| November | 3,000 | 6,600 | 9,600 |
| December | 3,800 | 9,900 | 13,100 |

In water resource management, especially for the water quality aspects, low-flow frequencies are used to determine assimilation and transport capacities of receiving waters. The low-flow frequency utilized for water quality control in the Potomac Estuary as set by the State of Maryland and the District of Columbia is the seven-consecutive-days-of-low-flow with a recurrence interval of once-in-10-years. For the Potomac at Washington, this is 954 cfs (before the diversions for water supply). See Table III-2 for complete analyses of low-flow frequency information.

Table III-2
MAGNITUDE AND FREQUENCY OF LOW FLOWS
POTOMAC RIVER NEAR WASHINGTON, D. C.
1930-1966 WATER YEARS
(Before Water Supply Diversions)

| Period | Discharge for indicated recurrence interval | | | | | |
|---|---|---|---|---|---|---|
| | 1.02 years | 2.0 years | 5.0 years | 10.0 years | 20.0 years | 50.0 years |
| (Consecutive days) | (cfs) | | | | | |
| 7 | 3,440 | 1,620 | 1,150 | 954 | 814 | 670 |
| 14 | 3,850 | 1,700 | 1,210 | 1,000 | 862 | 730 |
| 30 | 4,470 | 1,890 | 1,340 | 1,130 | 976 | 840 |
| 60 | 6,620 | 2,300 | 1,540 | 1,260 | 1,070 | 900 |
| 90 | 8,630 | 2,660 | 1,740 | 1,420 | 1,210 | 1,000 |
| 120 | 8,770 | 3,110 | 2,060 | 1,670 | 1,400 | 1,150 |
| 183 | 11,200 | 4,280 | 2,800 | 2,220 | 1,830 | 1,480 |

## C. PROPOSED RESERVOIR DEVELOPMENT

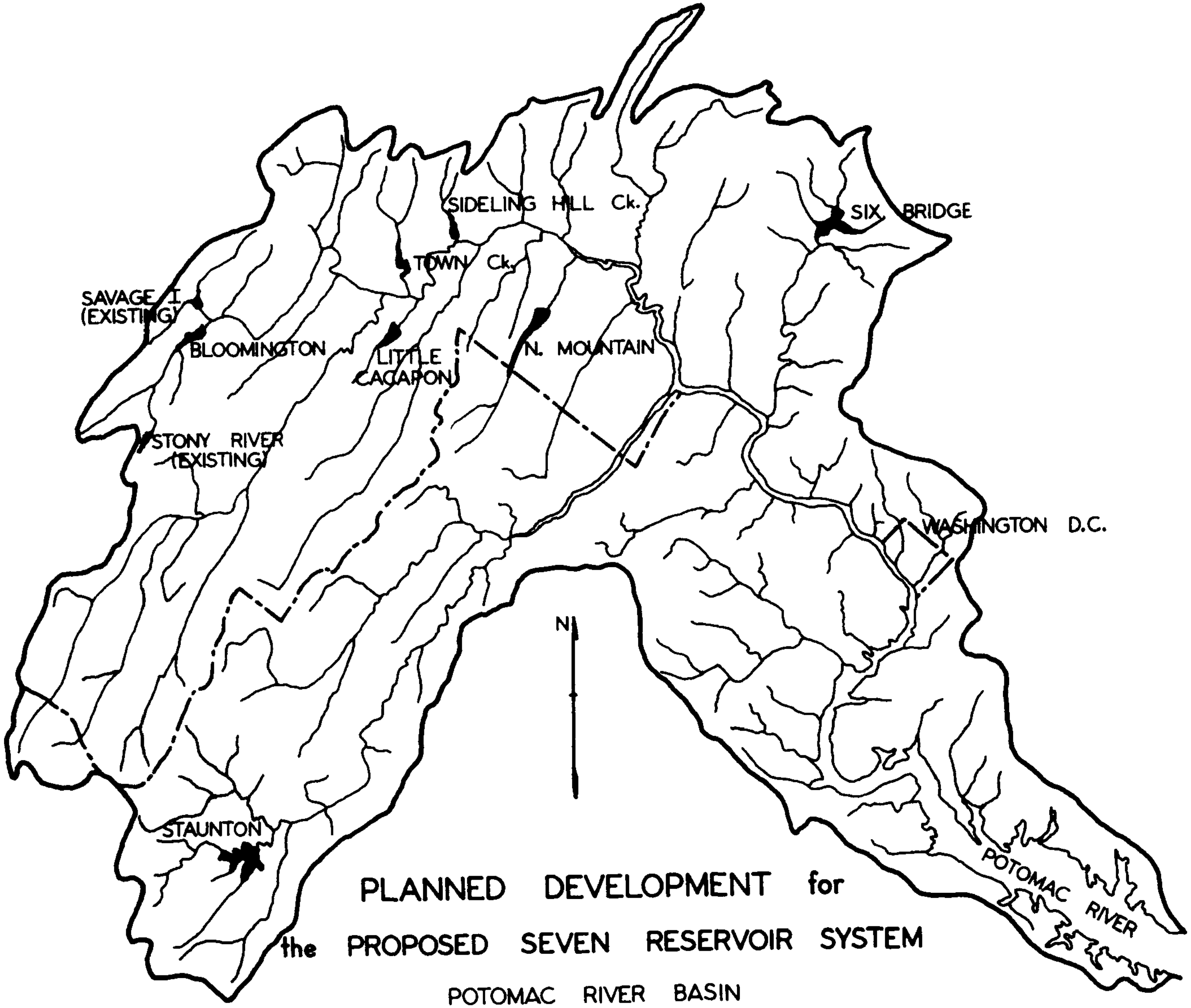
In 1956, the U. S. Army initiated a study of the water resources of the Potomac River Basin. The result of this study was a plan for development of water and related land resources of the basin including (1) water supply, (2) water quality, (3) flood control, and (4) recreational needs.

The plan recommended a 16-reservoir system to provide for orderly development, conservation, and utilization of the basin water resources to meet the needs of the next 50 years [1]. To provide additional water supply resources for the Washington metropolitan area, three alternative reservoir systems were suggested. These three systems were:

| System | |
|---|---|
| I | Bloomington |
| II | Bloomington, Verona, and Sixes Bridge |
| III | Bloomington, Verona, Sixes Bridge, Town Creek, North Mountain, Sideling Hill, and Little Cacapon |

The locations of the seven reservoirs in System III plus the two existing impoundments are shown in Figure III-2. The initial cost of the seven impoundments based on the 1967 cost index would be $204.4 million. See Table III-3 for individual reservoir cost.

Using data from 1929 to 1968 and a river-flow mathematical model, the U. S. Army Corps of Engineers simulated the effects of the three reservoir systems on river flows over Great Falls. The low-flow frequency analysis for the three systems is given in Table III-4.




PLANNED DEVELOPMENT for
the PROPOSED SEVEN RESERVOIR SYSTEM
POTOMAC RIVER BASIN

FIGURE III - 2

Table III-3

RESERVOIR PROJECTS, STORAGE, AND COST*
Potomac River Basin

| Project | Total Storage (acre-feet) | Total Initial Cost ($) | Allocated Cost ($) Downstream Water Supply | Allocated Cost ($) Preserve Stream Environment |
|---|---|---|---|---|
| Bloomington | 137,500 | 90,400,000 | 30,000,000 | 36,800,000 |
| Staunton | 143,000 | 22,870,000 | 756,000 | 3,473,000 |
| Sixes Bridge | 103,000 | 20,510,000 | 1,112,000 | 5,005,000 |
| Town Creek | 96,800 | 13,190,000 | 2,039,000 | 4,136,000 |
| North Mountain | 195,000 | 24,450,000 | 3,953,000 | 7,312,000 |
| Sideling Hill | 75,000 | 13,600,000 | 2,753,000 | 5,557,000 |
| Little Cacapon | 82,500 | 19,350,000 | 3,872,000 | 7,857,000 |
| Total | 832,800 | $204,370,000 | $44,485,000 | $70,140,000 |

* Based on data supplied by the U. S. Army Corps of Engineers, Baltimore District, September 1970

Table III-4

LOW-FLOW FREQUENCY ANALYSES FOR VARIOUS RESERVOIR SYSTEMS
Potomac River near Washington

Reservoir System
Number I

| Period (days) | Discharge in cfs for Indicated Recurrence Interval (5 years) | (10 years) | (50 years) |
|---|---|---|---|
| 30 | 1600 | 1200 | 1000 |
| 60 | 1900 | 1600 | 1050 |
| 90 | 2100 | 1700 | 1100 |
| 120 | 2600 | 2000 | 1500 |
| | | Number II | |
| 30 | 1900 | 1700 | 1200 |
| 60 | 2000 | 1900 | 1400 |
| 90 | 2200 | 2100 | 1500 |
| 120 | 2600 | 2200 | 1600 |
| | | Number III | |
| 30 | 2000 | 1800 | 1400 |
| 60 | 2150 | 2000 | 1500 |
| 90 | 2300 | 2200 | 1600 |
| 120 | 2800 | 2300 | 1700 |

D. WATER RESOURCE USES

1. Water Supply Use

a. Municipal

The municipal water supply needs of the Washington metropolitan area are obtained from five major sources. The largest source is the Potomac River above Washington, D. C. For 1969-1970, water withdrawal data for the five sources are presented below:

| Source | Withdrawal (mgd) |
|---|---|
| Potomac River above Great Falls | 265 |
| Patuxent River near Laurel | 46 |
| Goose Creek | 6 |
| Occoquan Creek | 42 |
| Wells and other minor sources | 11 |
| Total | 370 |

Currently, there is no municipal water withdrawn from the freshwater portion of the Potomac Estuary. However, during the drought in the summer of 1969, an emergency estuary intake would have been constructed and used had the lows flows continued.

b. Industrial

In the Washington metropolitan area, the amount of water used for manufacturing is insignificant. The major industrial use is as cooling water.

There are currently six major cooling water users in the Potomac River tidal system with another being proposed near Sandy Point. The total cooling water use is 2,748 mgd as follows:

| Facility | Water Usage (mgd) | Receiving Water | Remarks |
|---|---|---|---|
| PEPCO at Benning Rd. (Washington, D. C.) | 568 | Anacostia River | Also Uses Cooling Towers |
| PEPCO, Buzzard Point (Washington, D. C.) | 570 | Anacostia River | |
| Virginia Heating (Arlington, Va.) | 40 | Boundary Channel of Potomac Estuary | |
| PEPCO Generating Station (Alexandria, Va.) | 450 | Potomac Estuary | |
| VEPCO, Possum Point (Quantico, Va.) | 400 | Potomac Estuary | |
| PEPCO, Sandy Point | -- | Potomac Estuary | Proposed Facility |
| PEPCO, Morgantown (Charles Co., Md.) | 720 | Potomac Estuary | Ultimate Usage to be 1440 mgd |
| Total | 2,748 | | |

Navigational use of the Potomac Estuary waters is primarily to provide commercial transport via river barges. Two commercial firms presently transport various petroleum products from tank farms located in the lower Potomac and in the Chesapeake Bay proper to the Washington metropolitan area.

Sand and gravel mining is also a water related industrial use of the estuary bed. Currently, dredging for this purpose is being conducted in the estuary below Indian Head, Maryland.

2. Recreation and Boating

Aside from enhancing the suburban environment, the water and land resources of the Potomac Estuary and its tributaries contribute to the aesthetics of the nation's capital. From Washington, where large numbers of tourists visit the numerous monuments, museums, public buildings, and parks, to the remote park at Point Lookout near the Chesapeake Bay, the Potomac's amenities are widely used. These include freshwater and tidal sport fishing, boating, hunting, swimming, camping, and picnicking.

At the present time, there are approximately 95 marina facilities in the Potomac River tidal system. These marinas offer slips and moorings to accommodate over 5,200 recreational watercraft. They also provide boat rentals and launching areas for small craft.

Expanses of open water below Washington with large populations of several popular species have stimulated the growth of sport fishing in the Potomac Estuary. A study in 1959-1961, estimated that 101,000 angler trips produced approximately 1,200,000 fish weighing almost 642,000 pounds [2].

The most popular fish caught are striped bass, bluefish, spot, and perch. For a 5-month period during the 1961 survey, an estimated $594,000 was spent by Potomac Estuary anglers [2].

A recent study by the Bureau of Outdoor Recreation indicated the following regarding recreational facilities and the potential of the Potomac Estuary [3]:

1. Of the 637 miles of shoreline and 207,000 acres of water surface, which are rich in natural resources, the recreational potential has barely been touched.

2. At the present time, there is one national park, three state parks, three state forests, seven game and fish areas, and 226 county recreation sites in the estuary drainage area. Most of these areas are located inland without direct access to the water.

3. The recreational potential remains relatively undeveloped because of poor access to many shoreline areas and because extensive acreage is controlled by private and government interests.

4. There are few public beaches, but lack of such development is probably due more to poor water quality and the hazard of stinging jellyfish than to a lack of suitable locations.

3. Commercial Fisheries

The Potomac River tidal system supports a substantial commercial fishery. There are approximately 160 species in the Potomac Estuary ecosystem of which the anadromous* and the semi-anadromous** species such as striped bass, shad, white and yellow perch, winter flounder, and herring are the most significant economically.

Another group of commercially important fish species spawns and winters outside of the Chesapeake Bay in the Atlantic Ocean and utilizes the Potomac for a nursery area and feeding ground. Included in this group are the menhaden, croaker, silver perch, sea trout, and drum.

Oysters are indigenous to the lower reaches of the Potomac Estuary. These reaches are considered prime shellfish waters.

Soft clams, like oysters, are indigenous to the Chesapeake Bay and occur in the same general areas. Only in recent years, however, have they been harvested commercially and the resource far exceeds the demand.

The lower Potomac is a favorable habitat for the growth of blue crabs. As juveniles, the young crabs feed and grow in the estuary before completing their life cycle at the mouth of the Chesapeake Bay.

* Anadromous - fish which spend most of their lives in the ocean and ascend freshwater streams and rivers to spawn

** Semi-anadromous - fish which spend most of their lives in a brackish water and ascend freshwater streams to spawn

In 1969, approximately 9 million pounds of fish, 1.9 million pounds of crabs, 1.4 million pounds of clams, and 5.3 million pounds of oysters were harvested from the waters of the Potomac and its tributaries [4]. The dockside value of the 1969 harvest was computed to be over $4.6 million. See Table III-5.

There are currently about 29,000 acres of oyster beds in the Potomac Estuary and its embayments. Of these, approximately 970 acres, mainly in the embayments, are closed because of high bacterial densities resulting from domestic sewage pollution.

Numerous fish kills have occurred in the Potomac Estuary in recent years. While the cause of many of these kills is unknown, several have been attributed to low dissolved oxygen concentrations resulting from domestic waste discharges such as the large kill near Washington during May 1969.

Table III-5

MARYLAND AND VIRGINIA LANDINGS OF FISH AND SHELLFISH
POTOMAC RIVER AND TRIBUTARIES
1969

| Species | Maryland | | Virginia | | Total | |
|---|---|---|---|---|---|---|
| | Pounds | Value | Pounds | Value | Pounds | Value |
| Fish | 1,250,668 | $ 183,563 | 7,780,549 | $ 347,974 | 9,031,217 | $ 531,537 |
| Crabs - | | | | | | |
| Hard | 628,702 | 75,686 | 1,249,774 | 142,460 | 1,878,476 | 218,146 |
| Soft & Peeler | 20,348 | 8,260 | 28,000 | 11,659 | 48,348 | 19,919 |
| Clam | 1,090,140 | 389,292 | 322,092 | 114,331 | 1,412,232 | 503,623 |
| Oyster | 2,923,275 | 1,771,812 | 2,457,770 | 1,642,866 | 5,381,045 | 3,414,678 |
| Total | 5,913,133 | $2,428,613 | 11,838,185 | $2,259,290 | 17,751,318 | $4,687,903 |

# CHAPTER IV

# WASTEWATER LOADINGS AND RUNOFF CONTRIBUTIONS

## A. WASTEWATER LOADINGS AND TRENDS

In the upper reach from Great Falls to Indian Head, Maryland, a domestic wastewater flow of approximately 325 mgd is discharged into the Potomac River tidal system. Eighteen facilities currently serve approximately 2.5 million people in the Washington metropolitan area with the largest facility being the Blue Plains Plant of the District of Columbia (Table IV-1). Of the 325 mgd, 41.5, 23.1, and 35.4 percent come from Maryland, Virginia, and the District of Columbia respectively.

An analysis of the loading trends since 1913 indicates that wastewater volumes have increased eightfold, from 42 to 325 mgd. Similar trends have occurred for total nitrogen and phosphorus with 10-fold and 24-fold increases respectively (Table IV-2).

Of major significance has been the increase in ultimate oxygen demand (UOD) loadings. The carbonaceous UOD increased from 84,000 lbs/day in 1913 to about 297,000 lbs/day in the late 1950's. With the construction of the secondary treatment facilities, including completion of the Blue Plains Plant of the District of Columbia, the carbonaceous loading was reduced to 110,000 lbs/day. The nitrogenous loading has increased steadily from 1913 to the present loading of 254,000 lbs/day, which exceeds the current carbonaceous loading of 204,000 lbs/day.

Table IV-1

WASTEWATER LOADINGS TO THE UPPER POTOMAC ESTUARY AND TRIBUTARIES
GREAT FALLS TO INDIAN HEAD 1970

| Facility | Population Served | Flow | $BOD_5$ | | Suspended Solids | | T. Phosphorus as P | TKN | $NO_2 + NO_3$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | Untreated | Treated | Untreated | Treated | Treated | Treated | Treated |
| | | mgd | (lbs/day) | (lbs/day) | (lbs/day) | (lbs/day) | (lbs/day) | (lbs/day) | (lbs/day) |
| Pentagon | 10,600* | 1.060 | 2,100 | 360 | 2,100 | 310 | 65 | 290 | 20 |
| Arlington | 247,000 | 19.390 | 33,500 | 5,460 | 37,400 | 14,300 | 1,650 | 1,020 | 1,465 |
| Sewer Overflows D. C. System | 18,300** | 2.516 | 3,740 | 3,740 | 3,700 | 3,700 | 170 | 460 | 20 |
| Naval Laboratory White Oaks, Md. | 950* | 0.095 | 25 | 7 | 32 | 12 | 7 | 25 | 1 |
| District of Columbia | 1,830,000 | 251.660 | 373,700 | 103,800 | 369,900 | 102,000 | 17,300 | 46,200 | 2,000 |
| Alexandria | 190,000 | 23.300 | 38,000 | 13,800 | 36,200 | 12,600 | 2,300 | 3,690 | 20 |
| Fairfax-Westgate | 124,400 | 11.570 | 12,500 | 10,900 | 9,600 | 8,200 | 1,280 | 1,830 | 40 |
| Piscataway, WSSC | 55,000 | 5.810 | 6,300 | 540 | 7,300 | 1,310 | 320 | 630 | 100 |
| Andrews AFB No. 1 | 8,200* | 0.820 | 1,200 | 110 | 770 | 110 | 45 | 50 | 30 |
| Andrews AFB No. 4 | 860* | 0.086 | 104 | 16 | 80 | 10 | 5 | 3 | 3 |
| Naval Comm. Station Cheltenham, Md. | 670* | 0.067 | 110 | 15 | 140 | 14 | 3 | 2 | 1 |
| Fairfax-Hunting Cr. | 25,000 | 3.260 | 4,060 | 1,390 | 3,880 | 1,130 | 380 | 620 | 15 |
| Fairfax-Dogue Cr. | 20,000 | 2.441 | 4,048 | 915 | 4,010 | 760 | 270 | 365 | 20 |
| Fort Belvoir No. 1 | 3,600 | 0.600 | 1,100 | 120 | 110 | 70 | 30 | 25 | 25 |
| Fort Belvoir No. 2 | 18,400 | 2.340 | 3,500 | 380 | 3,800 | 325 | 175 | 430 | 20 |
| Fairfax-Lower Potomac**** | - | - | - | - | - | - | - | - | - |
| Naval Ordnance Station Indian Head, Md. | | | | | | | | | |
| Site I | 2,500* | 0.250 | 155 | 90 | 200 | 160 | 12 | 25 | 1 |
| Site II | 3,600* | 0.360 | 355 | 140 | 430 | 80 | 8 | 5 | 1 |
| Site III | 60* | 0.006 | 2 | 1 | 2 | 1 | 1 | 1 | 1 |
| Site IV | 10* | 0.001 | 2 | 1 | 2 | 1 | 1 | 1 | 1 |
| TOTAL | | 325.632 | 483,501 | 140,985 | 479,656 | 145,093 | 24,022 | 55,672 | 3,784 |

* Based on 100 gcpd
** Based on dry weather flow to wastewater facility
*** Under construction

Table IV-2
WASTEWATER LOADING TRENDS
WASHINGTON METROPOLITAN AREA

| Year | Population Served | Flow[1] (mgd) | Untreated 5-Day BOD (lbs/day) | Removal 5-Day BOD % | Treated 5-Day BOD (lbs/day) | Ultimate[2] Car. BOD (lbs/day) | Ultimate[4] Nit. BOD (lbs/day) | Total Ultimate BOD (Car.+ Nit.) (lbs/day) | Total Nitrogen (lbs/day) | Total Phos. as P (lbs/day) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1913 | 320,000 | 42 | 58,000 | 0 | 58,000 | 84,000 | 29,000 | 113,000 | 6,400 | 1,100 |
| 1932 | 575,000 | 75 | 103,000 | 0 | 103,000 | 149,000 | 52,000 | 201,000 | 11,400 | 2,000 |
| 1944 | 1,149,000 | 167 | 235,000 | 40 | 141,000 | 205,000 | 105,000 | 310,000 | 23,000 | 4,000 |
| 1954 | 1,390,000 | 195 | 280,000 | 28 | 200,000 | 290,000 | 145,000 | 435,000 | 31,700 | 5,500 |
| 1957 | 1,680,000 | 210 | 305,000 | 33 | 204,000 | 297,000 | 153,000 | 450,000 | 33,500 | 8,600 |
| 1960 | 1,860,000 | 222 | 370,000 | 70 | 110,000 | 160,000 | 170,000 | 330,000 | 37,200 | 10,000 |
| 1965 | 2,100,000 | 285 | 417,000 | 70 | 125,000 | 182,000 | 192,000 | 384,000 | 42,000 | 18,300 |
| 1968 | 2,415,000 | 319 | 423,000 | 70 | 130,000 | 188,000 | 226,000 | 414,000 | 50,000 | 20,100 |
| 1969 | 2,480,000 | 320 | 439,000 | 71 | 129,000 | 186,000 | 222,000 | 408,000 | 55,000 | 21,100 |
| 1970 | 2,535,000 | 322 | 484,000 | 71 | 141,000 | 204,000 | 254,000 | 456,000 | 60,000 | 24,000 |

1. Includes estimated sewer overflow loadings
2. Ultimate carbonaceous BOD = 1.45 x 5-day BOD
3. Ultimate nitrogenous BOD = 4.57 x unoxidized nitrogen

As can be seen in Figure IV-1, the current total oxygen demanding carbonaceous and nitrogenous loading is over 450,000 lbs/day, the highest loading rate ever discharged into the estuary although the percent removal of 5-day BOD has remained at about 70 percent. Since 1960, the increase in wastewater volumes and the continual increase in nitrogenous UOD has resulted in a total oxygen demanding load to the estuary similar to that which occurred before the secondary treatment facility at Blue Plains was completed in the late 1950's.

There are 82 wastewater point source discharges into the middle and lower reaches of the Potomac Estuary and their tributaries. The estimated BOD, total phosphorus as P, and nitrogen as N are 4,000, 500, and 1,000 lbs/day, respectively.

The major sources of domestic wastewater discharges are listed below:

| | Wastewater Volume (mgd) | Receiving Water |
|---|---|---|
| Mannassas Park No. 1 | 0.109 | Bull Run |
| Mannassas Park No. 2 | 0.221 | Bull Run |
| Manassas | 0.786 | Bull Run |
| Greenbrier | 0.214 | Bull Run |
| Fairfax-Flatlick | 0.111 | Flatlick Run |
| Greater Manassas S. D. | 0.700 | Bull Run |
| Lorton Reformatory | 0.410 | Giles Run |
| Marumsco | 1.000 | Marumsco Creek |
| Featherstone, Va. | 0.300 | Farm Creek |
| Marine Corps Schools (Quantico, Va.) | 1.400 | Potomac Estuary |
| Naval Weapons Laboratory (Dahlgren, Va.) | 0.350 | Upper Machodoc Creek |

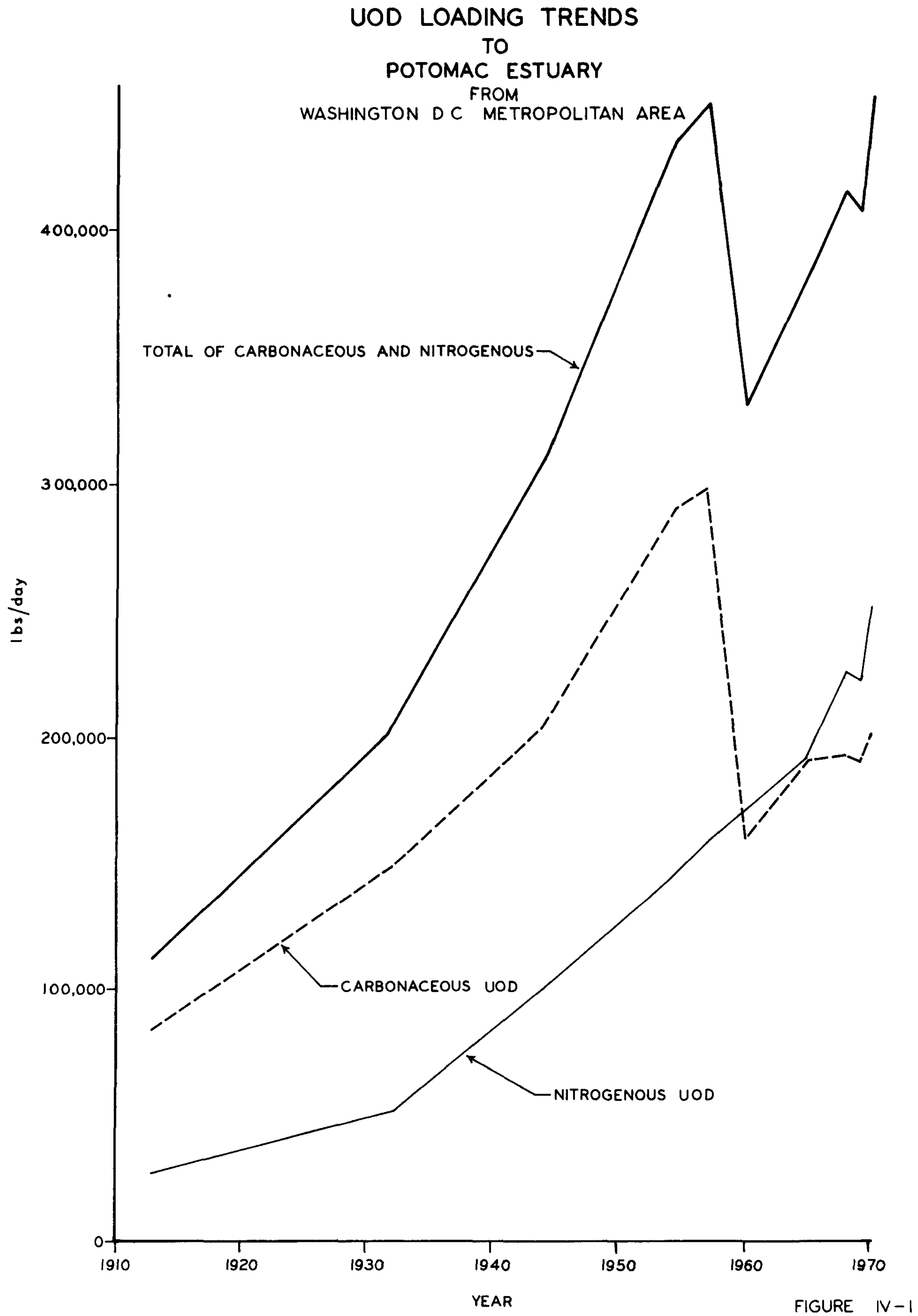

UOD LOADING TRENDS
TO
POTOMAC ESTUARY
FROM
WASHINGTON D C METROPOLITAN AREA
TOTAL OF CARBONACEOUS AND NITROGENOUS
CARBONACEOUS UOD
NITROGENOUS UOD
lbs/day
400,000
300,000
200,000
100,000
0
1910
1920
1930
1940
1950
1960
1970
YEAR

FIGURE IV-1

Compared to the upper reach, which has a population served of approximately 2.51 million, the middle and lower reaches serve a population of approximately 50,000. Most of the discharges in this area are into tributary or embayment waters.

## B. POTOMAC RIVER WATER QUALITY ABOVE GREAT FALLS

Detailed analyses of the freshwater inflow from the upper Potomac River Basin at Great Falls were conducted during 1969 and 1970. During the period of February 1969 to February 1970, the following were the average measured concentrations of $BOD_5$ and nutrients:

| Parameter | Concentration (mg/l) |
|---|---|
| $BOD_5$ | 2.60 |
| TKN as N | 0.61 |
| $NO_2 + NO_3$ as N | 1.00 |
| T. Phosphorus as P | 0.13 |

The observed data, as shown in Figure IV-2, show the wide range of nutrient concentrations for the period of June 1969 to July 1970. The river discharge was considerably higher during the 6 months of 1970 than for the last 7 months of 1969. This resulted in higher $NO_2 + NO_3$ concentrations. Concentrations of TKN and phosphorus appeared to decrease during the higher flow periods except during periods of intense runoff [5].

The contributions from the upper basin in lbs/day during the period of February 1969 through February 1970 are presented in Table IV-3. For the 13-month period, the average daily contributions of nutrients were tabulated and are given below:

| Parameter | Contribution (lbs/day) |
|---|---|
| T. Phosphorus as P | 4,580 |
| Inorganic Phosphorus as P | 2,650 |
| TKN as N | 22,410 |
| $NH_3$ as N | 4,590 |
| $NO_2 + NO_3$ as N | 36,700 |

## NUTRIENT CONCENTRATIONS
### POTOMAC RIVER AT GREAT FALLS

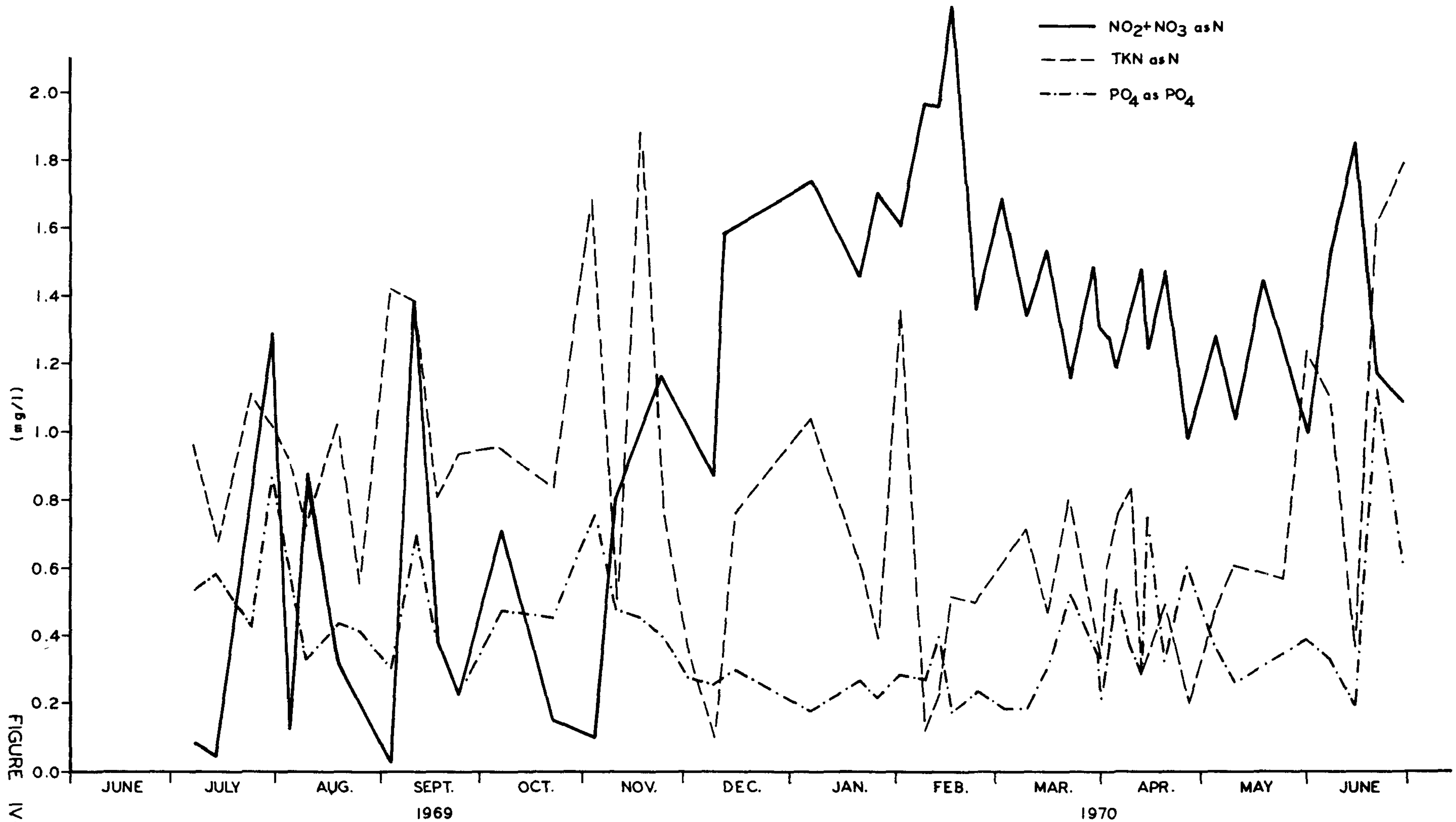



FIGURE IV-2

Table IV-3

UPPER POTOMAC RIVER BASIN CONTRIBUTIONS
(Above Great Falls)
February 1969 through February 1970

| Month | Flow (cfs) | T. Phosphorus as P (lbs/day) | Inorganic Phosphorus as P (lbs/day) | TKN as N (lbs/day) | $NH_3$ as N (lbs/day) | $NO_2 + NO_3$ as N (lbs/day) |
|---|---|---|---|---|---|---|
| February | 6,700 | 4,495 | 2,070 | 22,180 | 4,670 | 23,080 |
| March | 8,400 | 5,500 | 3,270 | 26,360 | 5,300 | 45,370 |
| April | 7,000 | 4,740 | 2,120 | 22,700 | 5,080 | 21,750 |
| May | 3,900 | 2,730 | 900 | 11,680 | 3,750 | 7,910 |
| June | 2,200 | 1,560 | 430 | 7,630 | 2,070 | 2,890 |
| July | 2,400 | 1,700 | 540 | 8,460 | 2,190 | 4,970 |
| August | 8,000 | 5,310 | 2,700 | 26,260 | 5,290 | 32,030 |
| September | 4,300 | 2,920 | 1,050 | 14,680 | 3,370 | 10,040 |
| October | 2,300 | 1,680 | 420 | 8,200 | 2,240 | 3,160 |
| November | 3,600 | 2,540 | 810 | 11,800 | 3,070 | 6,980 |
| December | 7,900 | 5,230 | 2,980 | 25,890 | 5,100 | 39,400 |
| January | 11,900 | 7,830 | 5,600 | 38,870 | 6,950 | 86,980 |
| February | 21,400 | 13,360 | 11,550 | 66,610 | 10,590 | 191,910 |
| **Average** | 6,900 | 4,580 | 2,650 | 22,410 | 4,590 | 36,700 |

A regression analysis of the river discharge and contribution loadings was made. Utilizing the flow duration curve for the Potomac River near Washington and the regression equation between river discharge and loadings, the contribution of phosphorus, nitrogen, and $BOD_5$ was determined for three frequency periods: 5%, 50%, and 95% of the time (Table IV-4). Based on this analysis, 50 percent of the time, which corresponds to a median river discharge of 6,470 cfs, the nutrient loadings into the Potomac from the upper basin are as follows:

| Parameter | Median Loading (lbs/day) |
|---|---|
| $BOD_5$ | 89,390 |
| TKN as N | 16,850 |
| $NO_2 + NO_3$ as N | 19,830 |
| Phosphorus as P | 4,350 |
| Total Carbon as C | 480,000 |

Data for the 5-percent duration or 34,000 cfs, as also given in Table IV-4, show higher loading rates and thus higher total loadings. Conversely, for the 95-percent duration of the 1200 cfs discharge rate, the loading rates are lower as are the loadings. For water quality control purposes, the 50- and 95-percent duration times are more applicable since they occur under critical summer conditions.

* Frequency percent is percentage of time in which a given parameter is equalled or exceeded

Table IV-4

NUTRIENT AND BOD CONTRIBUTIONS FROM THE UPPER POTOMAC RIVER BASIN
ABOVE GREAT FALLS, MARYLAND
(Drainage Area = 11,460 sq. mi.)

| Frequency* of Yield | Associated River Discharge | T. Phosphorus as P | | $NO_2 + NO_3$ as N | | TKN as N | | $BOD_5$ | |
|---|---|---|---|---|---|---|---|---|---|
| | cfs | lbs/day/sq mi | lbs/day | lbs/day sq mi | lbs/day | lbs/day/sq mi | lbs/day | lbs/day/sq mi | lbs/day |
| 5 | 34,600 | 1.68 | 19,250 | 24.22 | 277,560 | 8.60 | 98,560 | 27.6 | 316,300 |
| 50 | 6,470 | 0.38 | 4,350 | 1.73 | 19,830 | 1.47 | 16,850 | 7.8 | 89,390 |
| 95 | 1,200 | 0.08 | 920 | 0.11 | 1,260 | 0.43 | 4,930 | 1.7 | 19,490 |

* The percent of time of which a given frequency of yield in lbs/day/sq mi was equalled or exceeded

C. SUBURBAN AND URBAN RUNOFF

An analysis similar to that used for the Potomac at Great Falls was applied to data on Rock Creek and the Anacostia River. Based on these regression studies and flow duration curves, yield rates in terms of lbs/day/sq mi were determined as given in Table IV-5. These rates were used for the suburban areas in Virginia and Maryland.

For the District of Columbia, data on stormwater and urban runoff were obtained from a study of Washington overflows [6]. The rates and flow frequency percentages based upon the Rock Creek and the Anacostia River drainage areas were used.

The median loadings contributed from urban and suburban areas to the upper Potomac Estuary are tabulated below:

| Parameter | Loadings (lbs/day) |
|---|---|
| $BOD_5$ | 12,500 |
| TKN as N | 2,560 |
| $NO_2 + NO_3$ | 1,510 |
| T. Phosphorus as P | 850 |

The total loadings (lbs/day) of BOD and nutrients from suburban and urban runoff were fairly small when compared to those from the upper Potomac Basin. However, yield rates (lbs/day/sq mi) for the urban and suburban area, except for nitrites and nitrates, were significantly higher (Table IV-5). This indicates that as population in an area increases, the BOD, phosphorus, and TKN loadings from urban runoff will probably also increase.

Table IV-5

URBAN AND SUBURBAN RUNOFF CONTRIBUTIONS TO UPPER POTOMAC ESTUARY

(Great Falls to Indian Head)

| | Area | Duration* Yield Rate | T. Phosphorus as P | | $NO_2 + NO_3$ as N | | TKN | | $BOD_5$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | sq mi | | lbs/day/sq mi | lbs/day | lbs/day/sq mi | lbs/day | lbs/day/sq mi | lbs/day | lbs/day/sq mi | lbs/day |
| Maryland | 352 | 5% | 3.30 | 1,200 | 15.65 | 5,500 | 30.40 | 10,700 | 64.0 | 22,500 |
| | 352 | 50% | 1.00 | 350 | 1.71 | 600 | 3.20 | 1,100 | 9.6 | 3,400 |
| | 352 | 95% | 0.10 | 35 | 0.20 | 70 | 0.60 | 210 | 1.2 | 420 |
| Virginia | 300 | 5% | 3.30 | 1,000 | 15.65 | 4,700 | 30.40 | 9,100 | 64.0 | 19,200 |
| | 300 | 50% | 1.00 | 300 | 1.71 | 510 | 3.20 | 960 | 9.6 | 2,900 |
| | 300 | 95% | 0.10 | 30 | 0.20 | 60 | 0.60 | 180 | 1.2 | 360 |
| District of Columbia | 62 | 5% | 17.74 | 1,100 | 27.42 | 1,700 | 41.90 | 2,600 | 62.9 | 3,900 |
| | 62 | 50% | 3.23 | 200 | 6.45 | 400 | 8.10 | 500 | 10.0 | 6,200 |
| | 62 | 95% | 0.40 | 25 | 0.40 | 50 | 1.50 | 90 | 4.8 | 300 |
| Total | 714 | 5% | 4.62 | 3,300 | 16.66 | 11,900 | 31.37 | 22,400 | 63.86 | 45,600 |
| | 714 | 50% | 1.20 | 850 | 2.11 | 1,510 | 3.58 | 2,560 | 17.50 | 12,500 |
| | 714 | 95% | 0.12 | 90 | 0.25 | 180 | 0.67 | 480 | 1.51 | 1,080 |

* The percent of time of which a given duration of yield in lbs/day/sq mi was equaled or exceeded

## D. SUMMARY AND COMPARISON OF NUTRIENTS, BOD, AND CARBON CONTRIBUTIONS

For the 50- and 95-percent flow durations, the largest source of BOD and nutrients is from wastewater discharges in the Washington area. As summarized below, under low-flow conditions, wastewater discharges contributed over 55 percent of all four parameters.

| Parameter | 95% Low-Flow Condition Potomac R. Flow = 1200 cfs | | 50% Median-Flow Condition Potomac R. Flow = 6470 cfs | |
|---|---|---|---|---|
| | Total From all Sources (lbs/day) | Percentage From Wastewater (%) | Total From all Sources (lbs/day) | Percentage From Wastewater (%) |
| T. Oxygen Demand | 515,800 | 88 | 733,000 | 62 |
| T. Carbon | 380,000 | 55 | 720,000 | 29 |
| T. Nitrogen | 66,900 | 90 | 100,000 | 60 |
| T. Phosphorus | 25,000 | 96 | 29,300 | 82 |
| $BOD_5$ | 161,580 | 87 | 242,900 | 58 |

Even under median-flow conditions, the contribution of total oxygen demand, total nitrogen, and total phosphorus is largest from the wastewater treatment facilities. At the 5-percent frequency or for a Potomac flow of 34,600 cfs, only in the case of phosphorus (52%) is the largest percentage from wastewater discharges (see Table IV-6).

Table IV-6
SUMMARY OF CONTRIBUTIONS OF NUTRIENTS, BOD, AND CARBON

| Loading* Duration | Parameter | Upper Potomac River Basin | | Urban and Suburban Runoff | | Wastewater Treatment Facility Discharge | | Total |
|---|---|---|---|---|---|---|---|---|
| | | lbs/day | % of Total | lbs/day | % of Total | lbs/day | % of Total | lbs/day |
| 5% | $BOD_5$ | 316,300 | 62.89 | 45,600 | 9.07 | 141,000 | 28.04 | 502,900 |
| | Total Oxygen Demand | 2,030,000 | 76.46 | 169,000 | 6.36 | 456,000 | 17.18 | 2,655,000 |
| | Total Carbon | 1,400,000 | 82.50 | 87,000 | 5.23 | 210,000 | 12.37 | 1,697,000 |
| | Total Nitrogen | 376,000 | 79.99 | 34,300 | 7.29 | 60,000 | 12.75 | 470,300 |
| | Total Phosphorus | 19,300 | 41.41 | 3,300 | 7.08 | 24,000 | 51.51 | 46,600 |
| 50% | $BOD_5$ | 89,400 | 36.81 | 12,500 | 5.15 | 141,000 | 58.04 | 242,900 |
| | Total Oxygen Demand | 247,000 | 33.70 | 30,000 | 4.09 | 456,000 | 62.21 | 733,000 |
| | Total Carbon | 480,000 | 66.67 | 30,000 | 4.17 | 210,000 | 29.16 | 720,000 |
| | Total Nitrogen | 36,000 | 35.97 | 4,070 | 4.07 | 60,000 | 59.96 | 100,070 |
| | Total Phosphorus | 4,400 | 15.04 | 850 | 2.91 | 24,000 | 82.05 | 29,250 |
| 95% | $BOD_5$ | 19,500 | 12.07 | 1,080 | 0.67 | 141,000 | 87.26 | 161,580 |
| | Total Oxygen Demand | 56,000 | 10.86 | 3,800 | 0.74 | 456,000 | 88.40 | 515,800 |
| | Total Carbon | 160,000 | 42.11 | 10,000 | 2.63 | 210,000 | 55.26 | 380,000 |
| | Total Nitrogen | 6,200 | 9.27 | 660 | 0.99 | 60,000 | 89.74 | 66,860 |
| | Total Phosphorus | 920 | 3.68 | 90 | 0.36 | 24,000 | 95.96 | 25,010 |

* The percent of time for which a given loading is equaled or exceeded. The 5%, 50%, and 95% corresponds to a freshwater flow into the estuary of 34,600 cfs, 6,470 cfs, and 1,200 cfs, respectively.

# CHAPTER V

## WATER QUALITY CONDITIONS AND TRENDS

The water quality problems resulting from discharge of municipal wastewater into the Potomac Estuary are not new. The first three conclusions of a study conducted in 1913 [7], which are as applicable today as they were then, are listed below:

1. "That at no point above Washington is the water of the Potomac River safe for use as a public water supply without reasonable treatment.

2. "That portions of the main or Georgetown Channel, between the Chain Bridge and the junction of the main channel with Anacostia River and Washington Channel, are so heavily polluted that the water is unsafe for bathing purposes. The water from this section supplies the Tidal Basin.

3. "That the conditions of that area in Anacostia River in the neighborhood of the sewage-pumping station and at the junction of the three channels is bad during hot weather, at times constituting a nuisance; but that, when the improvements now planned or under construction are completed, these conditions should no longer exist."

Not only has the water quality problem as stated above persisted, conditions have deteriorated considerably.

A. BACTERIAL DENSITIES

Bacterial densities in the Potomac Estuary have been determined routinely since 1938. Total coliform counts in the Potomac at Three Sisters Island have remained fairly constant for the past 20 years at about 2,000 MPN/100 ml during the summer months (Figure V-1). In contrast, total coliform densities in the estuary have increased to over 2,000,000 in 1966 and then decreased to less than 7,000 in 1970 near the Blue Plains Sewage Treatment Plant. The reduction in recent years can be attributed in part to an increase in overall wastewater treatment efficiency including chlorination, and to higher river flows.

During 1969, continuous year-around chlorination of final effluents was initiated at all major plants. This appears to be the most significant single factor in the reduction of bacterial densities in the estuary near Washington. As shown in Figure V-2, there has been a corresponding reduction in fecal coliform counts under similar flow and temperature conditions in August 1968 and August 1970.

The highest fecal coliform densities in 1968 were found between River Mile 10 and 15 in the vicinity of the major wastewater discharges. In August 1970, the highest densities were found at River Mile 7 in the vicinity of Hains Point. At times, 10 to 20 mgd of untreated sewage is discharged into the estuary as a result of inadequate sewerage and treatment plant capacity at Blue Plains. Urban runoff from the Anacostia River and Rock Creek basins also add to the fecal coliform problem.

TOTAL COLIFORM ORGANISMS
UPPER POTOMAC ESTUARY
1938-1970 SUMMER AVERAGES

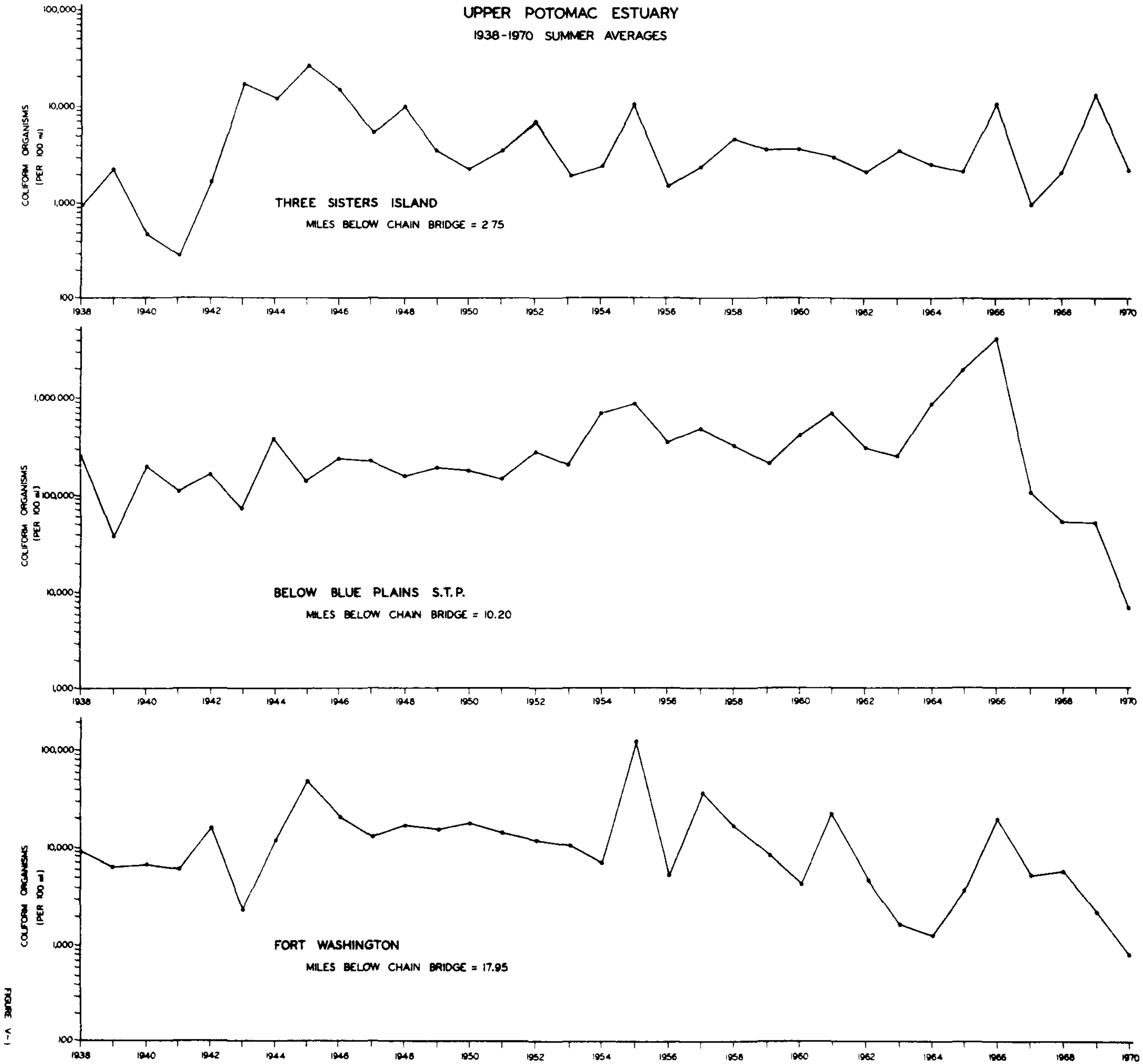



FIGURE V-1

# FECAL COLIFORM DENSITIES
## UPPER POTOMAC ESTUARY

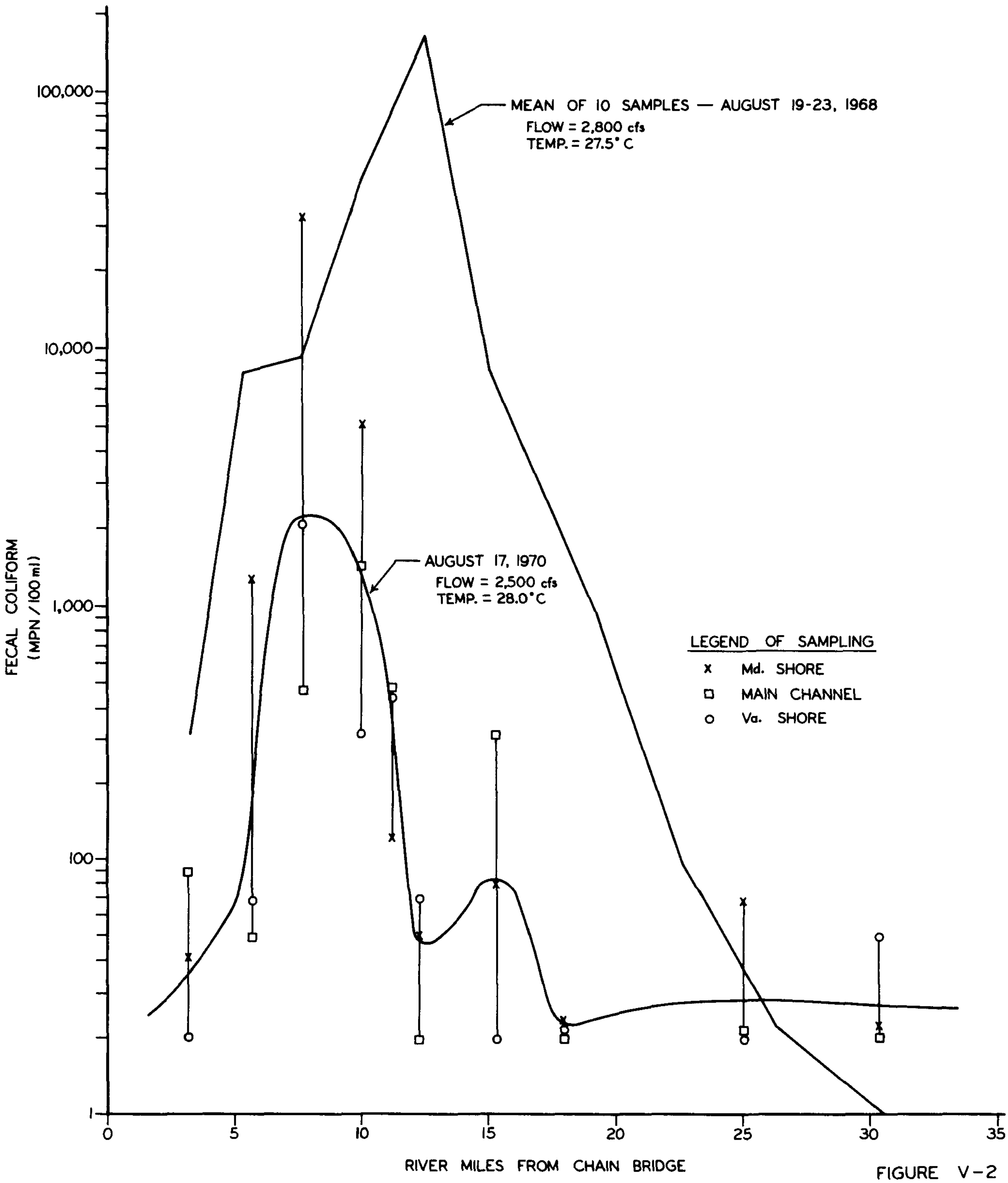



FIGURE V-2

At the Fort Washington monitoring station, total coliform densities during the summer months have remained fairly constant except for recent downtrends (see Figure V-1). These downtrends can also be attributed to recent chlorination of treatment plant effluents.

B. DISSOLVED OXYGEN

Dissolved oxygen (DO) concentrations in the upper Potomac Estuary have also been routinely monitored since 1938. As shown in Figure V-3, there has been a continuous downward trend in DO in the Potomac Estuary near and below the wastewater discharges.

A significant increase in DO occurred in the early 1960's near the Blue Plains outfall. However, with the population increase of the past decade and little or no increase in treatment plant capacities, DO in the Blue Plains vicinity during the summer months is now approaching the levels of the late 1950's.

With increased loadings to existing waste treatment plants and additional facilities being located farther downstream, the number of miles affected by wastewater effluents has increased. As presented in Figure V-3, the minimum 28-day DO concentrations at Fort Washington have decreased from approximately 5.0 mg/l to less than 4.0 mg/l since 1938. Currently, about 20 miles of the estuary has a DO concentration of less than 5.0 mg/l (the water quality standard for that reach of the Potomac) during low-flow periods.

The DO concentration at any given location in the estuary is a function of many factors including biological activity, freshwater inflow, temperature, wastewater loadings, and tidal stage. On four sampling cruises made during the summer months of 1969, the locations and readings of the minimum concentration of DO varied as shown in Figure V-4. Minimum dissolved oxygen readings of less than 2.0 mg/l were recorded on all four cruises, even when the freshwater inflow was as high as 8,890 cfs. Increases in freshwater inflows caused the point of minimum DO to move downstream as evidenced when the DO profiles for June 30 and August 14 are compared.

Data for the Potomac Estuary at the Woodrow Wilson Bridge (Figures V-5 and V-6) show the typical annual variation in DO. During the summer of 1965, DO concentrations ranged from 0.5 to 3.5 mg/l with an average of 2.0 mg/l. DO during the summer months of 1966 ranged from 0.5 to 3.0 mg/l with an average of 1.5 mg/l. For the months of September through December 1965, the DO concentrations remained depressed as a result of low-flow conditions. During December 1965, the DO was approximately 5.5 mg/l even when the water temperature was less than 10°C.

The DO concentration for a given time and location can also vary over the cross-section of the estuary. In the Piscataway embayment, DO varied from 4.0 to 12.0 mg/l during a sampling cruise made on June 27, 1970. At the same time, the main channel of the Potomac Estuary showed a fairly uniform DO (about 4.0 mg/l) as a result of tidal mixing (see Figure V-7). The higher DO concentrations in the embayment were attributed to the photosynthetic production by dense algal growths. During hours of darkness, the DO dropped to less than 8.0 mg/l in the embayment while it remained around 4.0 mg/l in the main Potomac.

## DISSOLVED OXYGEN CONCENTRATION
UPPER POTOMAC ESTUARY
1938 - 1970

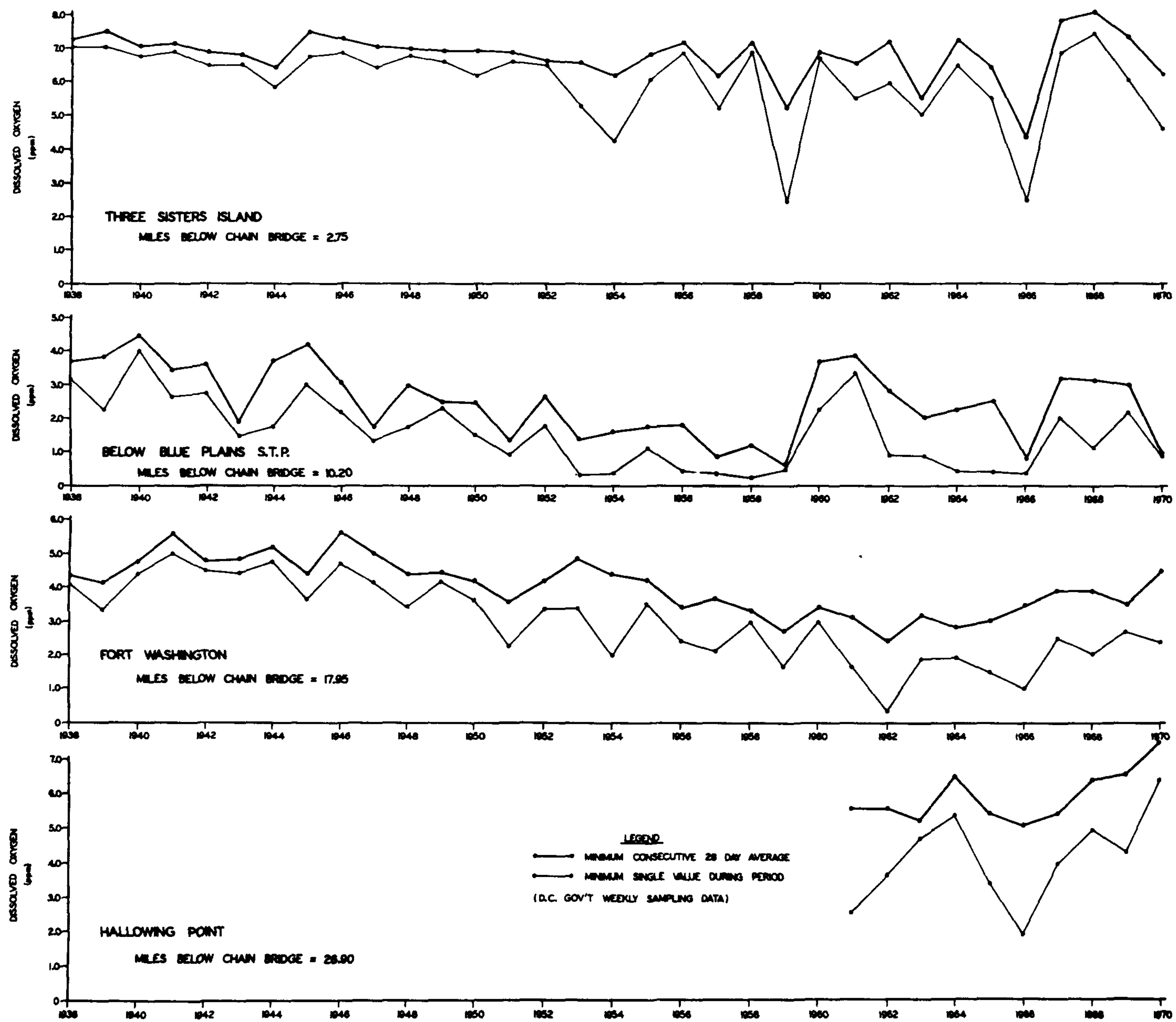



FIGURE V-3

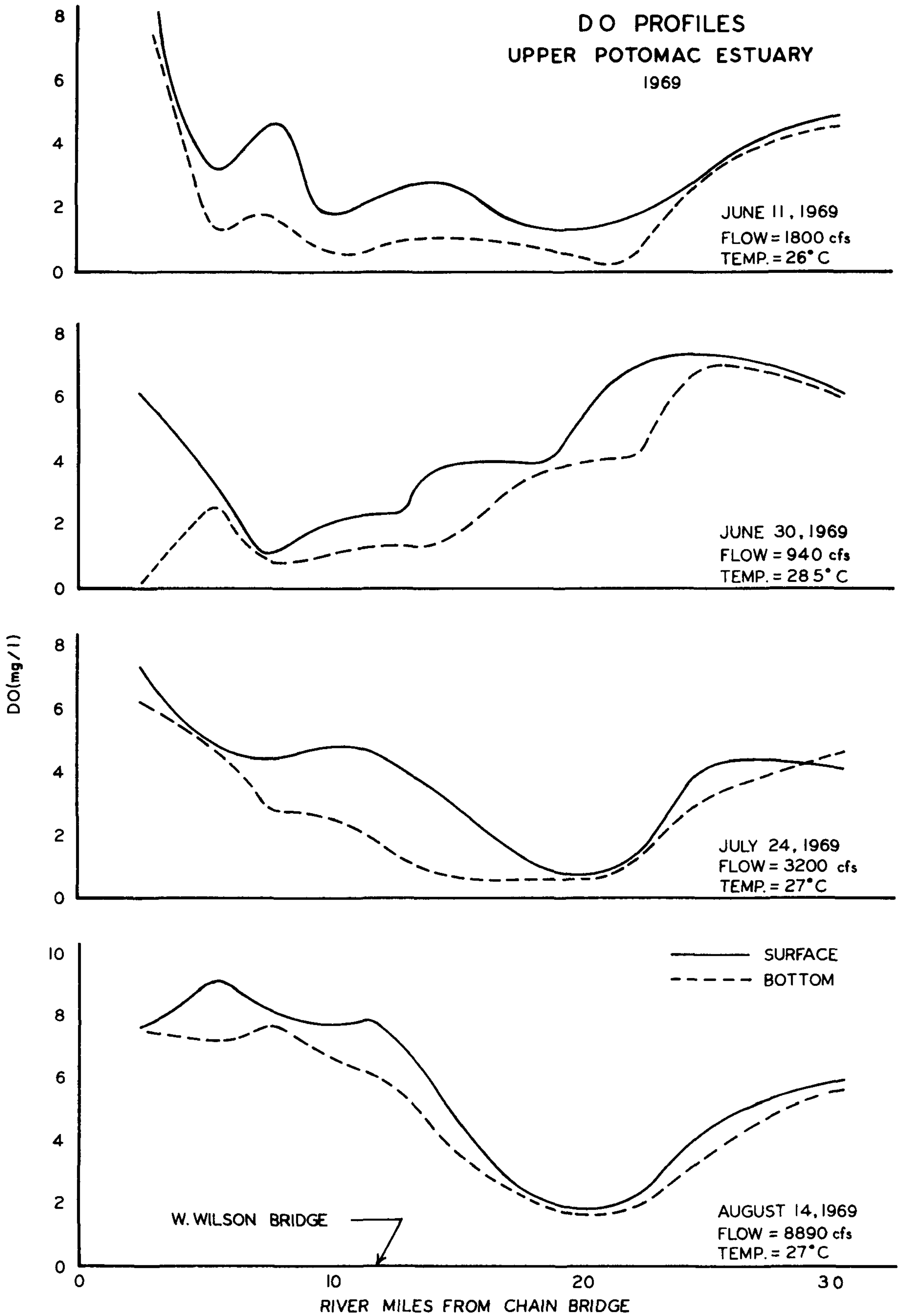

D O PROFILES
UPPER POTOMAC ESTUARY
1969
JUNE 11, 1969
FLOW = 1800 cfs
TEMP. = 26° C
JUNE 30, 1969
FLOW = 940 cfs
TEMP. = 28.5° C
JULY 24, 1969
FLOW = 3200 cfs
TEMP. = 27°C
AUGUST 14, 1969
FLOW = 8890 cfs
TEMP. = 27°C
SURFACE
BOTTOM
W. WILSON BRIDGE
DO(mg/l)
RIVER MILES FROM CHAIN BRIDGE
0
10
20
30

FIGURE V-4

# DISSOLVED OXYGEN CONCENTRATION

## POTOMAC ESTUARY at WOODROW WILSON BRIDGE

## 1965

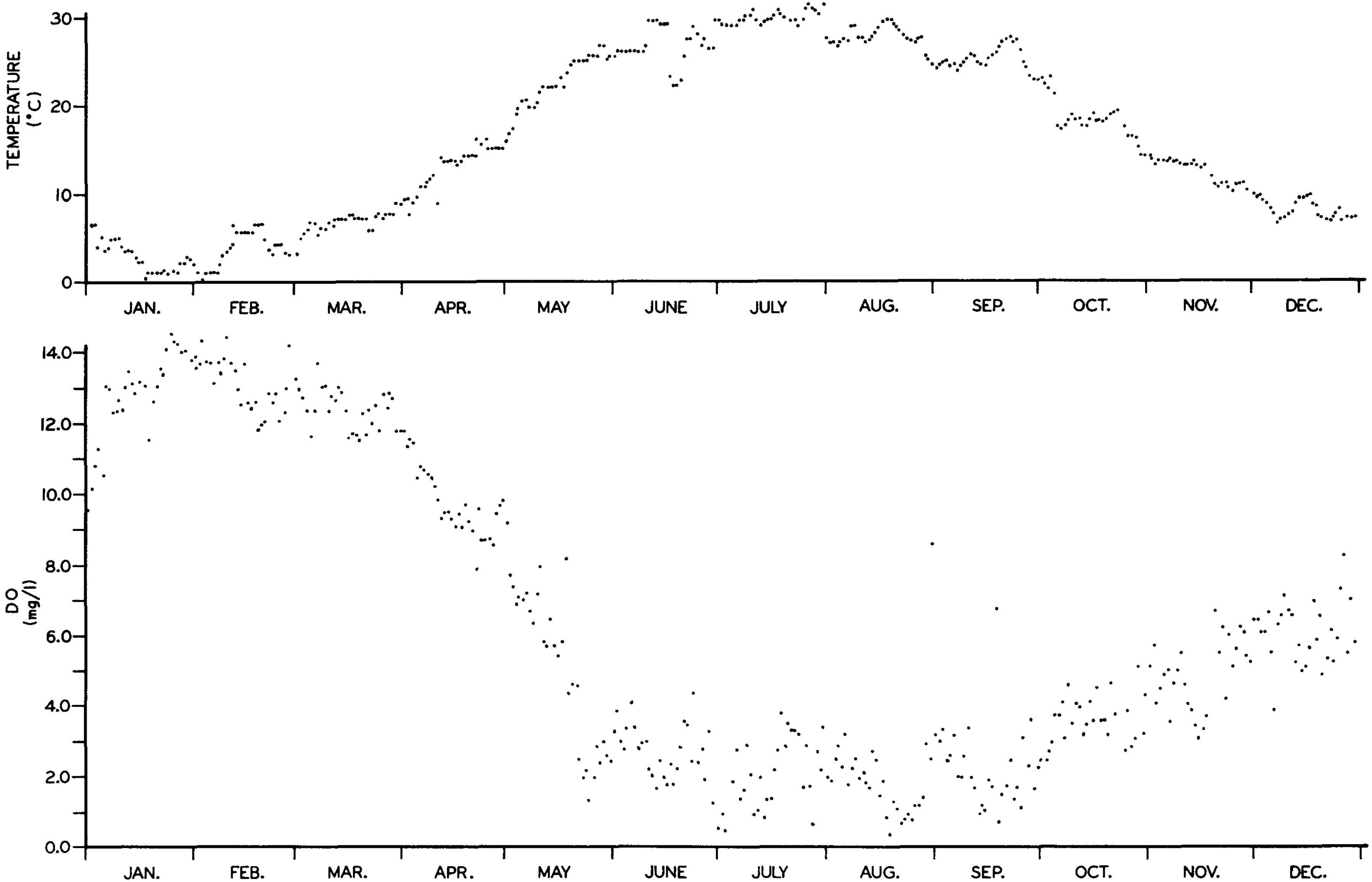



FIGURE V-5

# DISSOLVED OXYGEN CONCENTRATION

## POTOMAC ESTUARY at WOODROW WILSON BRIDGE

## 1966

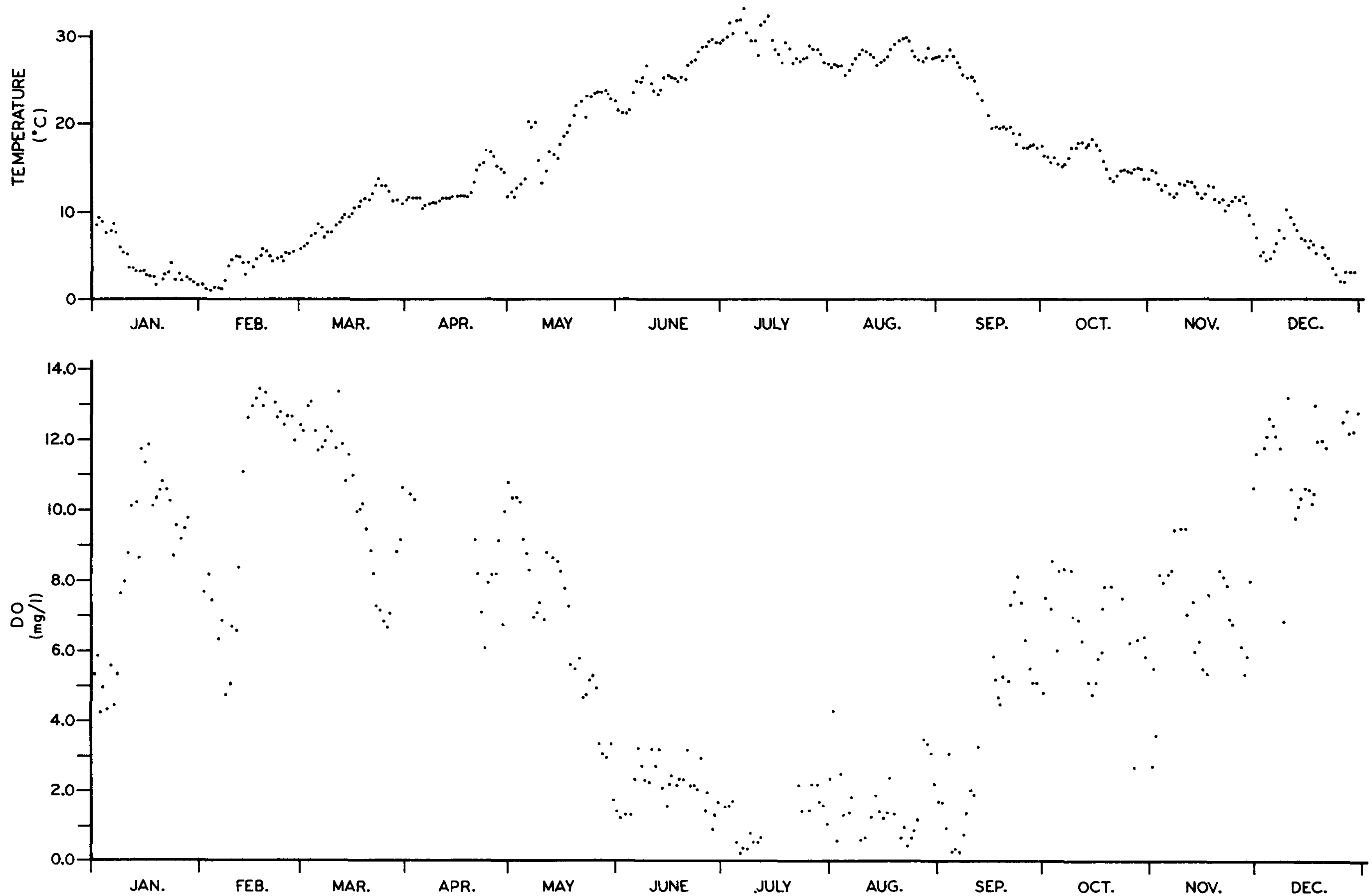



FIGURE V-6

## DO CONTOUR (mg/l)

### PISCATAWAY EMBAYMENT – POTOMAC ESTUARY

JUNE 22, 1970

12:00 A.M.

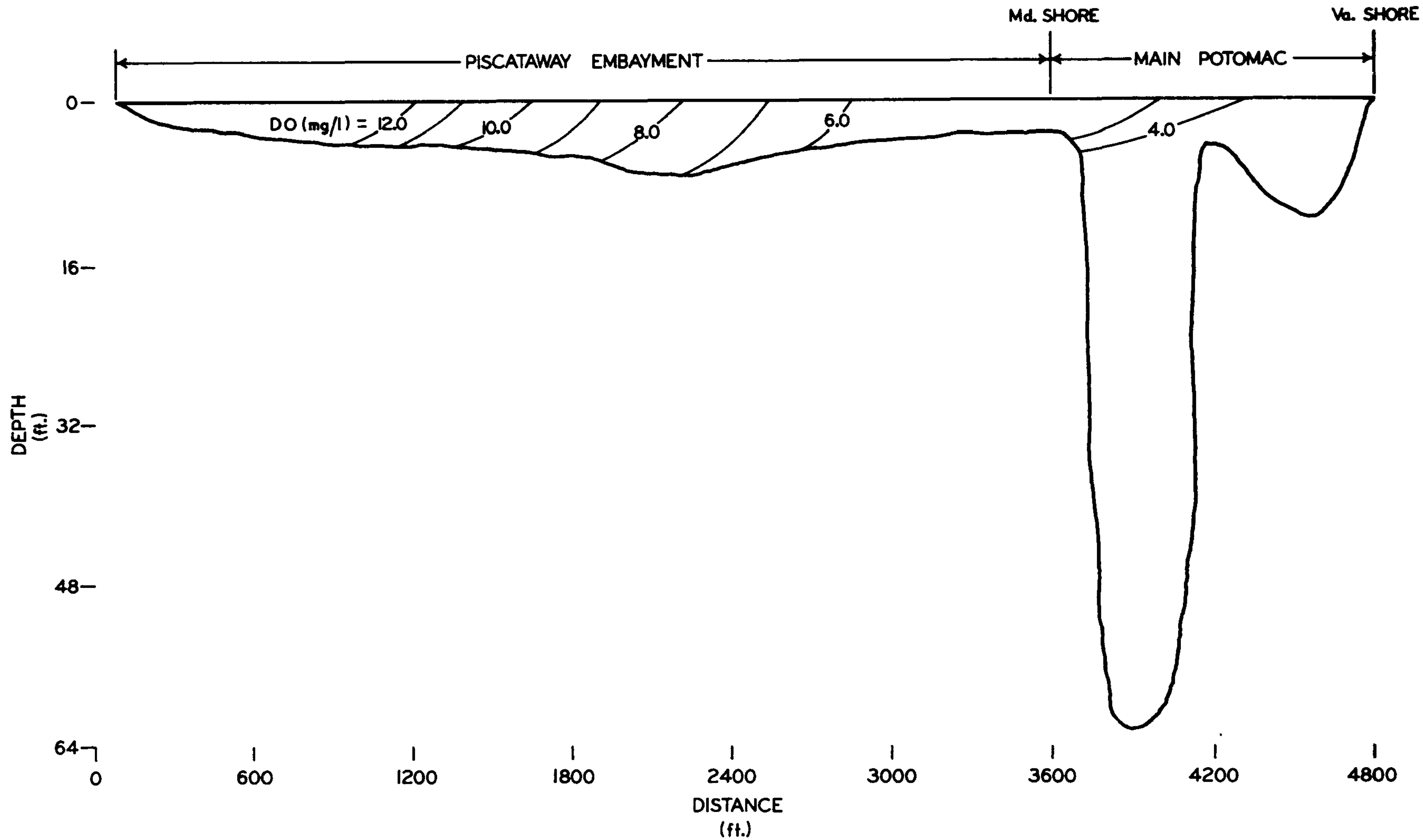



FIGURE V-7

C. SILT AND DEBRIS

The upper Potomac Estuary has changed drastically during the past hundred years. At one time, water covered what is now the corner of Seventeenth Street and Constitution Avenue. Potomac Park and Hains Point did not exist. Tidewaters covered the present site of National Airport and Bolling Field. The Anacostia River was a broad stream with extensive mud flats. Many of the tidal flats of the upper Potomac were formed by sediments and have been transformed by dredged material into the present Washington area waterfronts.

The silt in the Potomac Estuary can be attributed to three sources:

a. Above Great Falls, mainly forested;

b. Washington metropolitan area, mainly urban;

c. Coastal area, mainly rural.

For the water years 1961 through 1968, the average sediment yield of the upper Potomac above Great Falls was 1.98 billion lbs/year (Table V-1). The highest percentage of the annual contribution occurred during either February or March with the maximum month values ranging from 51 percent to 90 percent of the total annual load.

The Northwest Branch of the Anacostia River near Colesville, Maryland with a drainage area of 21.1 square miles showed an annual yield ranging from 1.0 to 1.6 million lbs/sq mile with an average of 1.34 million lbs/sq mi/yr (Table V-2). This is about seven times greater than that from the upper basin which averages about 0.190 million lbs/sq mi/yr.

Table V-1

SEDIMENT DATA
Potomac River Basin Below Confluence of Monocacy River

| Year | Total for Year (1000 lbs) | Maximum Month | % of Annual for Maximum Month | Annual Yield (1000 lbs/sq mi) |
|---|---|---|---|---|
| 1961 | 2,516,600 | February | 65.7 | 240 |
| 1962 | 1,997,600 | March | 64.2 | 190 |
| 1963 | 2,379,000 | March | 89.8 | 227 |
| 1964 | 2,052,000 | March | 51.6 | 196 |
| 1965 | 1,504,000 | March | 54.3 | 143 |
| 1966 | 1,175,000 | February | 50.8 | 112 |
| 1967 | 2,562,000 | March | 84.0 | 244 |
| 1968 | 1,684,000 | | | 159 |
| Average | 1,984,000 | | | 190 |

* Sediment data based on a summation of Potomac River at Point of Rocks and Monocacy River at Jug Bridge. Total drainage above the sampling station is equal to 10,468 square miles.

Table V-2

SEDIMENT DATA
Northwest Branch Anacostia River near Colesville, Maryland
(Drainage Area = 21.1 sq mi)

| Year | Total for Year (1000 lbs) | Annual Yield (1000 lbs/sq mile) |
|---|---|---|
| 1963 | 33,600 | 1,590 |
| 1964 | 23,200 | 1,090 |
| 1965 | 32,800 | 1,540 |
| 1966 | 28,800 | 1,360 |
| 1967 | 30,000 | 1,420 |
| 1968 | 21,100 | 1,000 |
| Average | 28,300 | 1,341 |

Applying the Anacostia station average (1.34 million lbs/sq mi/yr) to the entire Washington metropolitan area and a yield rate of 0.20 million lbs/sq mile to the lower coastal area, an estimate of the silt loading to the entire Potomac River is as follows:

| Area | Yield (1000 lbs/sq mi/yr) | Drainage Area (sq mi) | Average Annual Loading (1000 lbs/yr) |
|---|---|---|---|
| Upper Potomac (above Great Falls) | 190 | 11,640 | 2,200,000 |
| Washington Area | 1,340 | 714 | 957,000 |
| Lower Coastal Area | 200 | 2,326 | 465,000 |
| Total | 246* | 14,670 | 3,622,000 |

*Average Annual Yield

The upper basin is the greatest source of sediments.

In addition to the obvious silting of navigation channels, sediments have other relationships to water quality management problems, some which are favorable and some unfavorable. During periods of high flow and suspended sediment load, the Potomac contains correspondingly greater quantities of organic carbon, nitrogen and phosphorus. The suspended and adsorbed pollutants are deposited as the silt settles, primarily in the upper 20 miles of the Potomac Estuary. During high runoff periods, the upper 10 to 20 miles is chocolate brown in color and aesthetically objectionable. Since the high silt loadings usually occur during the spring months when fish are spawning in the estuary, the silt may cover freshly laid eggs, thus reducing the effective spawning area in the upper estuary.

While silt transports a considerable amount of adsorbed nutrients during high-river flows, the overall effect is to reduce the nutrient concentration in the estuary, especially phosphorus. Sampling before and after a period of extremely high runoff in March 1967, as reported by CTSL [8], confirmed this observation. Silt also tends to cover much of the organic matter deposited from wastewater discharges. This covering generally reduces the availability of nutrients and oxygen demanding material from bottom deposits.

It was observed by CTSL on numerous occasions that suspended sediments contribute to algal control in the upper estuary. During the summer months, runoff resulting from heavy rainfall usually causes high turbidity in the upper estuary which restricts light penetration in the water and reduces algal growth even though all other environmental conditions may be favorable.

During the low-flow periods of 1966 and 1970, a reduction in turbidity in the upper estuary along with other favorable environmental condtions caused a significant increase in nuisance algal blooms near and above Woodrow Wilson Bridge [52]. These nuisance blooms can be expected to become more frequent as the silt control program becomes more effective unless there is a simultaneous adequate removal of nutrients from wastewater effluents.

During periods of high runoff, large quantities of debris enter the estuary from the upper basin as well as from the metropolitan area.

Debris from the upper basin is typically trees, brush, leaves, and miscellaneous trash, and is usually partially decomposed. Debris from the metropolitan area not only enters the estuary from local streams but also from storm sewers and often contains paper, vegetable and fruit peelings, styrofoam cups, etc. It appears that better solid-waste management practices would decrease the amount of local debris entering the estuary.

The effect of the increased silt and debris organic loadings on the oxygen resources of the estuary has not been well defined. Based upon DO studies made during a period of heavy precipitation, it appeared that increased flows and the resulting dilution minimized any immediate effect on the oxygen budget. Most of the organic matter carried into the estuary by silt and debris settles and contributes to the benthic oxygen demand. CTSL studies in the Potomac Estuary indicated that oxygen uptake from benthic deposits was about twice as large in areas with treated waste sludge deposits than in other areas of the upper estuary (Figure V-8). Analysis of sediments for chemical oxygen demand (COD), as presented in Figure V-9, shows a fairly close relationship between COD and benthic demand. From COD and uptake data, it appears that the effect of sludge deposits and other suspended solids from wastewater on the oxygen resources is much greater than the effect from the organic solids in silt and debris.

## CHEMICAL OXYGEN DEMAND OF SEDIMENTS

POTOMAC ESTUARY

MEAN VALUES 1966-67

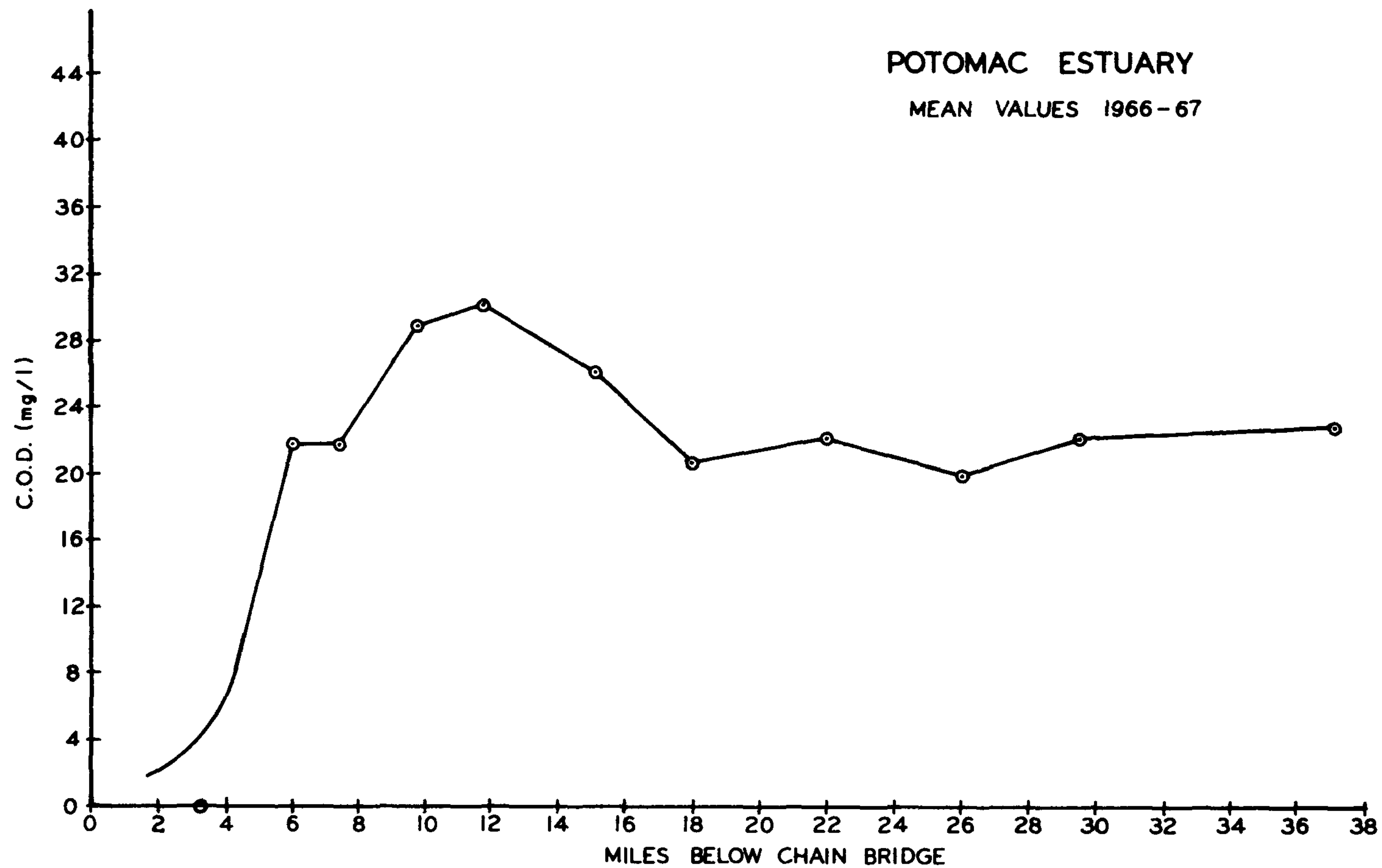



FIGURE V-9

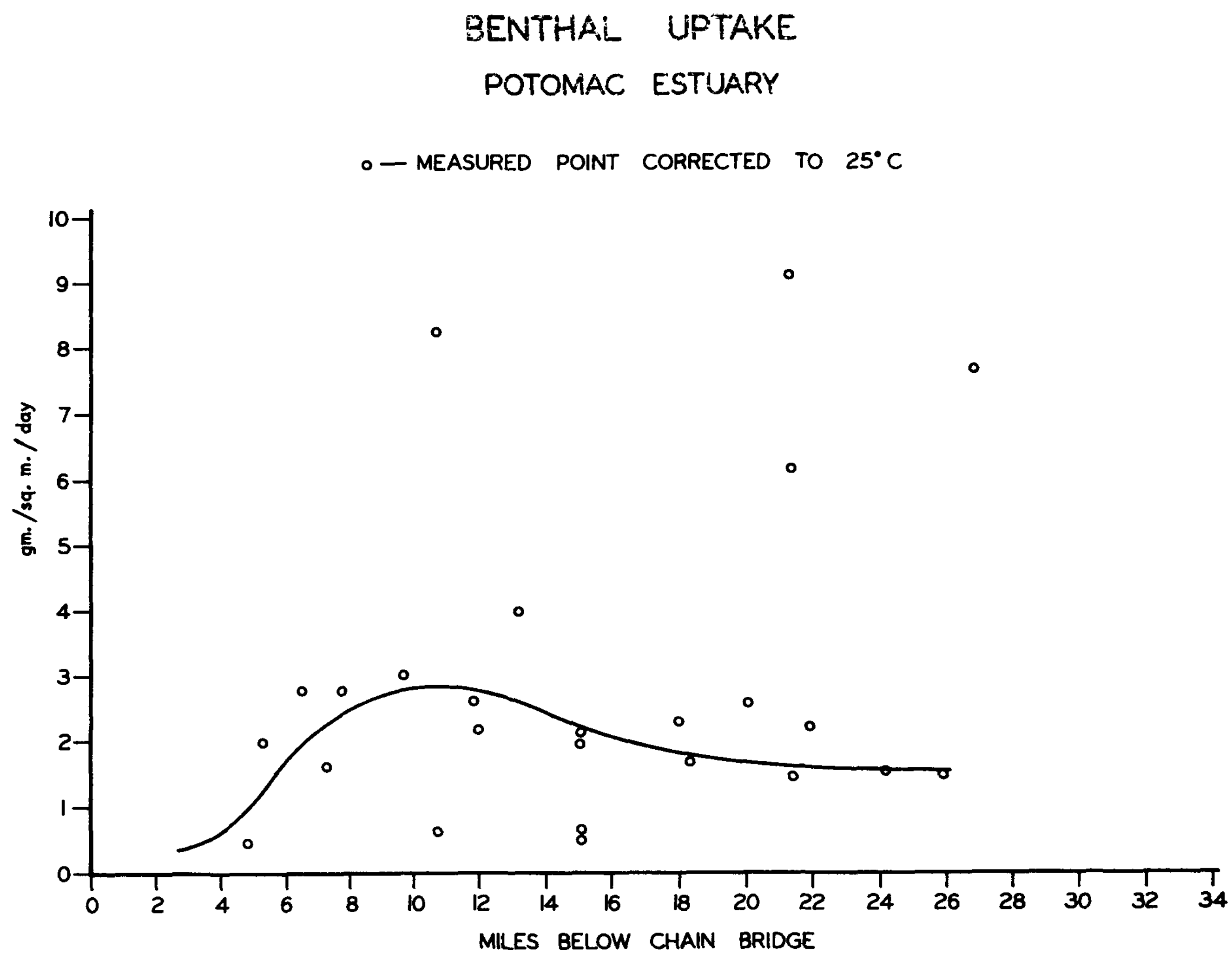

BENTHAL UPTAKE
POTOMAC ESTUARY
o — MEASURED POINT CORRECTED TO 25°C
gm./sq. m./day
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
MILES BELOW CHAIN BRIDGE

FIGURE V-8

## D. NUTRIENTS AND ALGAL GROWTH

As discussed previously in this report, the major source of nitrogen and phosphorus in the upper Potomac Estuary is from the wastewater discharges in the Washington area. Total phosphorus has increased about 22-fold, from 1,100 lbs/day in 1913 to 24,000 lbs/day in 1970, with total nitrogen loadings increasing from 6,400 to 60,000 lbs/day. A greater increase for phosphorus reflects not only an increase in population but also the increased use of detergents. The current carbon loadings are about 100,000 lbs/day, approximately the same as they were in the mid-1940's. The decrease in organic carbon in the early 1960's was a result of the completion of present treatment facilities at Blue Plains.

### 1. Nutrient Concentrations in the Potomac Estuary

The concentrations and forms of phosphorus and nitrogen in the Potomac Estuary are a function of wastewater loadings, temperature, freshwater inflow, and biological activity. As shown in Figure V-10, the inorganic phosphorus varied considerably for the six stations sampled from March 1969 through September 1970. The concentration at Hains Point, located at the upper end of the tidal excursion of the major wastewater discharges, was fairly uniform averaging about 0.3 mg/l. At Woodrow Wilson Bridge, located below the Blue Plains wastewater discharge, the inorganic phosphorus increased appreciably with concentrations over 2.5 mg/l during periods of low flow such as those that occurred in July to October 1969 and September 1970. The

## INORGANIC PHOSPHATE CONCENTRATION as $PO_4$
### POTOMAC ESTUARY
### 1969 - 1970

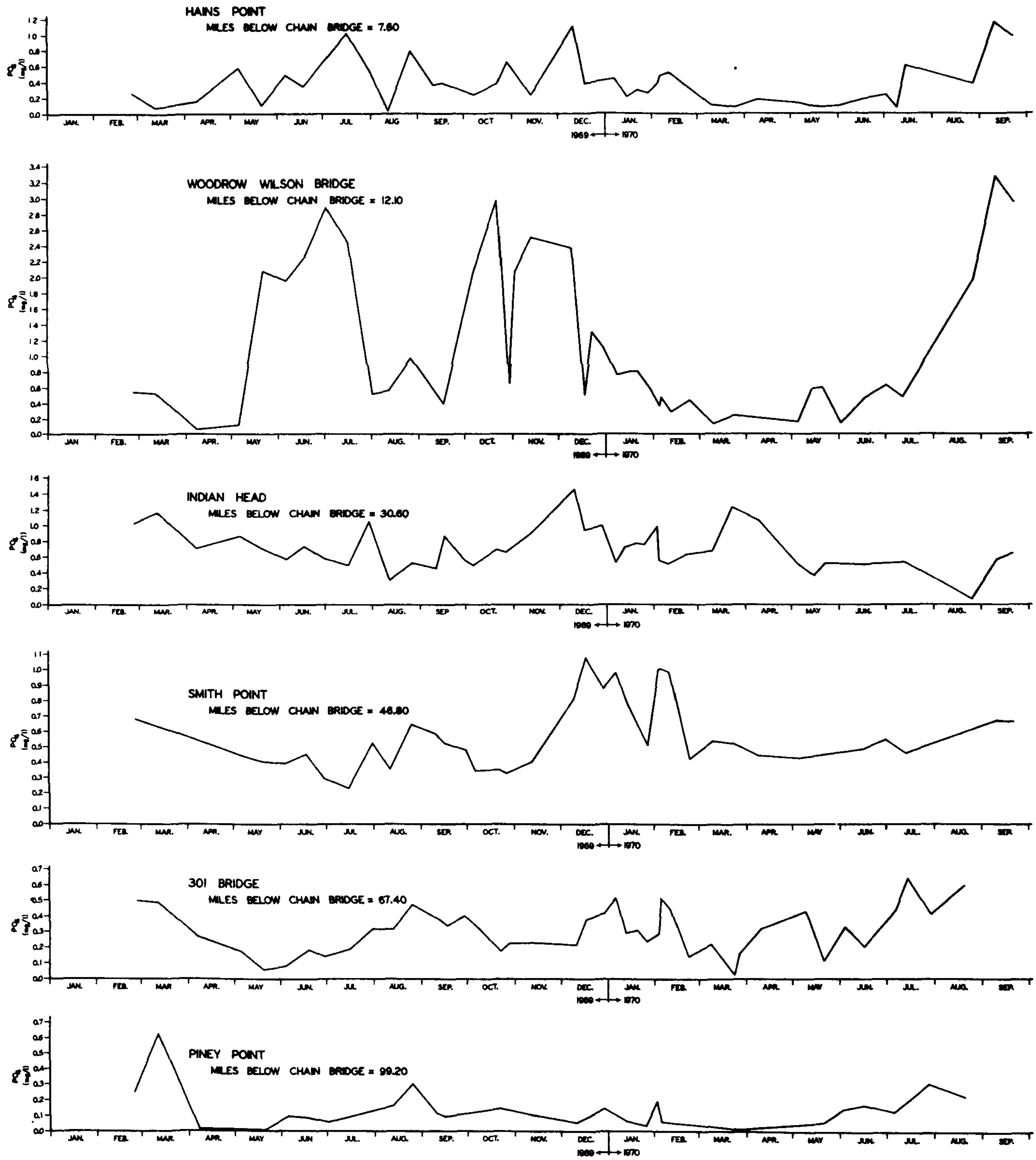



FIGURE V-10

remaining four downstream stations had concentrations progressively smaller.

It was observed that much of the phosphorus is deposited into the upper estuary even during high flows such as those in August 1969 and April 1970. During periods of high freshwater inflow, the sediment appears to adsorb more phosphorus than it releases. This is discussed in greater detail later.

The total phosphorus concentration closely parallels that of inorganic phosphorus. In the upper reach, the ratio of total phosphorus to inorganic phosphorus ranges from 1.1 to 1.5. The ratio is higher in the middle reach normally varying from 1.5 to 2.0 with the lower reach having a range from approximately 2.0 to 2.5.

The concentration of nitrite ($NO_2$) and nitrate ($NO_3$) nitrogen at Hains Point and Woodrow Wilson Bridge varies almost inversely to that of phosphorus (Figure V-11). The $NO_2 + NO_3$ concentration was highest in July and August 1969 and during the spring months of 1970. During these months, both high-flow periods, the phosphorus was lowest (Figure V-10). The increase of $NO_2 + NO_3$ at Indian Head as compared to Woodrow Wilson Bridge in May-June 1969, September-November 1969, and July 1970 was a result of the conversion of ammonia from the wastewater treatment plant discharges to $NO_3$. The extremely low concentration of $NO_2 + NO_3$ in the summer months at Smith Point was caused by uptake by algal cells [52]. During winter months algal utilization is lower [52], thus the concentrations of nitrates are high, as in January and April 1970. At Piney Point, concentrations of $NO_2 + NO_3$ are usually less than 0.1 mg/1.

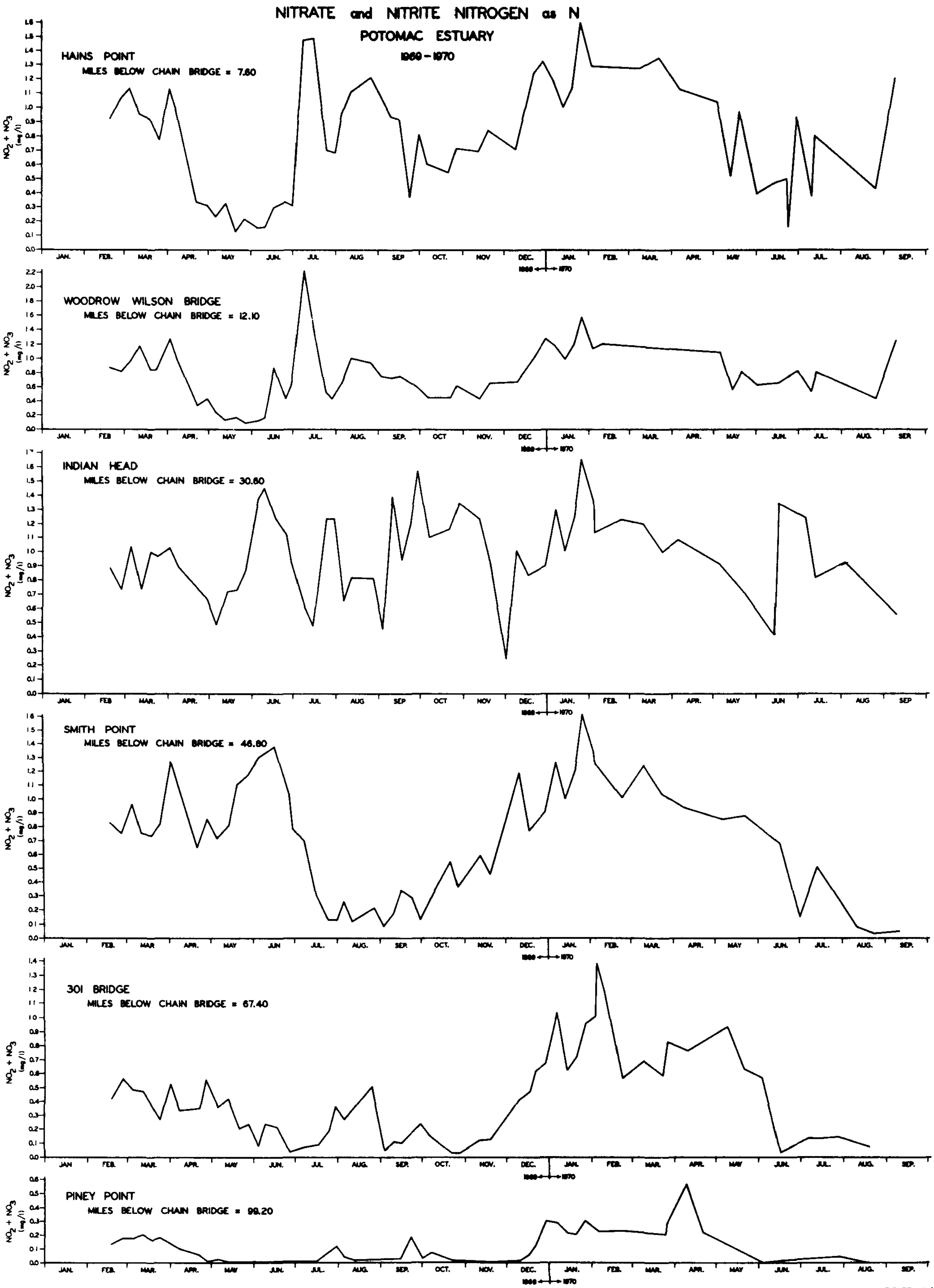

NITRATE and NITRITE NITROGEN as N
POTOMAC ESTUARY
1969 - 1970
HAINS POINT
MILES BELOW CHAIN BRIDGE = 7.60
WOODROW WILSON BRIDGE
MILES BELOW CHAIN BRIDGE = 12.10
INDIAN HEAD
MILES BELOW CHAIN BRIDGE = 30.60
SMITH POINT
MILES BELOW CHAIN BRIDGE = 46.80
301 BRIDGE
MILES BELOW CHAIN BRIDGE = 67.40
PINEY POINT
MILES BELOW CHAIN BRIDGE = 99.20
NO2 + NO3 (mg/l)
JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP.
1969 ← → 1970

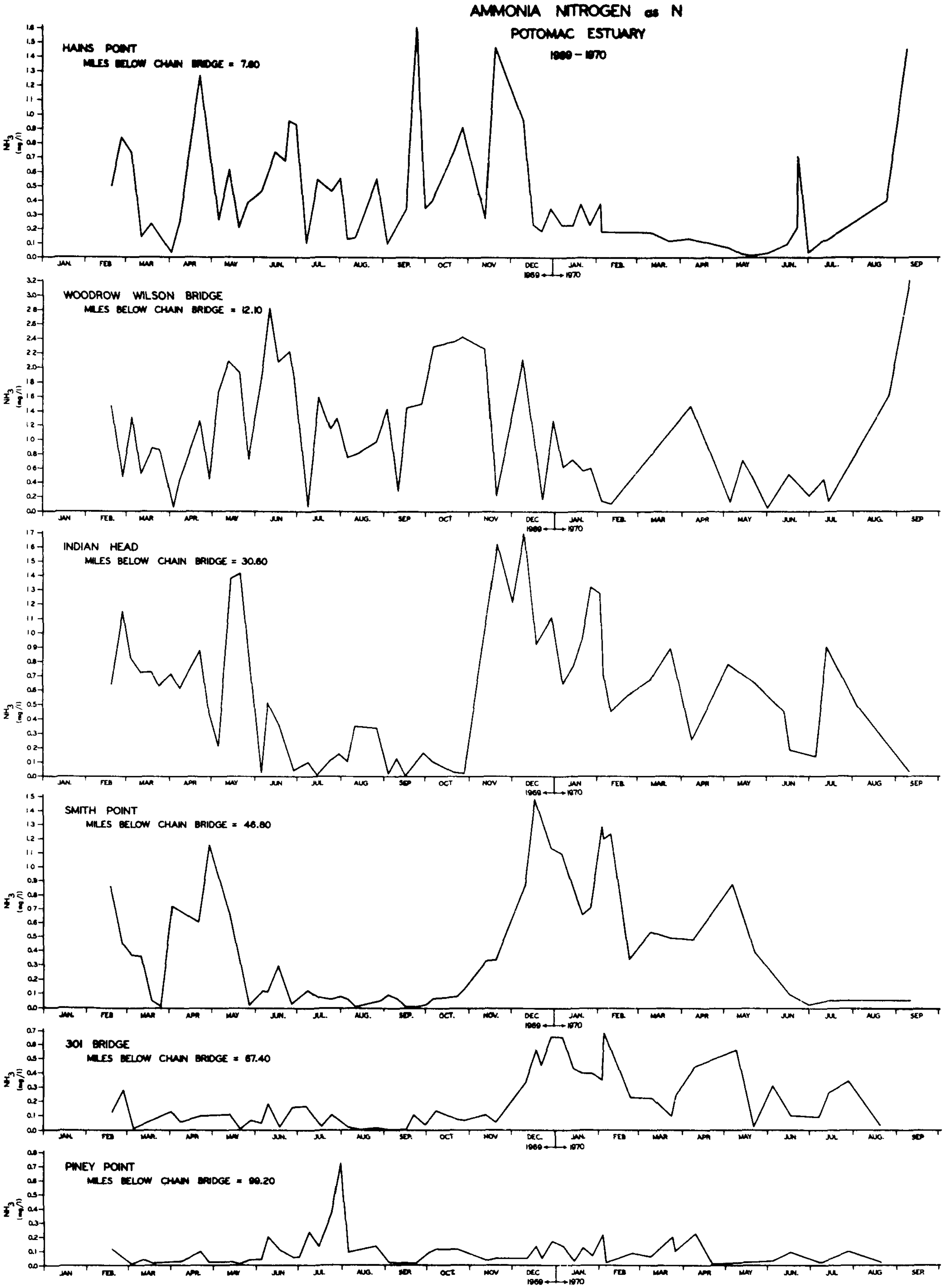
FIGURE V-11

As shown in Figure V-12, the concentration of ammonia nitrogen is also affected by flow and temperature conditions. Although large quantities of ammonia are discharged from wastewater treatment facilities into the Potomac near Woodrow Wilson Bridge, the ammonia at Indian Head during the summer months is low because of nitrification.

During the summer and early fall months, the average ranges of pH, alkalinity, and free dissolved $CO_2$ (measured by titration) for the five stations in the upper and middle reaches were:

| Location | pH (units) | Alkalinity (mg/l as $CaCO_3$ | Free Dissolved $CO_2$ (mg/l) |
|---|---|---|---|
| Chain Bridge | 7.5 - 8.0 | 80 - 100 | 2 - 4 |
| W. Wilson Bridge | 7.0 - 7.5 | 90 - 110 | 8 - 12 |
| Indian Head | 7.2 - 8.0 | 70 - 90 | 6 - 10 |
| Maryland Point | 7.5 - 8.2 | 60 - 85 | 2 - 8 |
| Rte. 301 Bridge | 7.5 - 8.0 | 65 - 85 | 7 - 8 |

In the vicinity of the Woodrow Wilson Bridge, there is an increase in both alkalinity and $CO_2$ with a corresponding decrease in pH attributed to wastewater discharges. There is a decrease in both alkalinity and $CO_2$ with a corresponding increase in pH at the Indian Head and Maryland Point stations which are due to algal growths. In the lower estuary, the alkalinity and $CO_2$ increases while pH decreases. The algal standing crops are considerably smaller in this reach.



AMMONIA NITROGEN as N
POTOMAC ESTUARY
1969 – 1970
HAINS POINT
MILES BELOW CHAIN BRIDGE = 7.80
WOODROW WILSON BRIDGE
MILES BELOW CHAIN BRIDGE = 12.10
INDIAN HEAD
MILES BELOW CHAIN BRIDGE = 30.60
SMITH POINT
MILES BELOW CHAIN BRIDGE = 46.80
301 BRIDGE
MILES BELOW CHAIN BRIDGE = 67.40
PINEY POINT
MILES BELOW CHAIN BRIDGE = 99.20
NH3 (mg/l)
JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP.
1969 ←→ 1970


FIGURE V-12

## 2. Mathematical Models for Nutrient Transport

Mathematical models for predicting the movement and transport of phosphorus and nitrogen have been developed by CTSL. A detailed report of the modeling of nutrient transport is in preparation. Some of the model's predictions for phosphorus are shown in Figures V-13 and V-14 and for nitrogen in Figures V-15 and V-16.

The effects of temperature on nutrient transport, deposition, and utilization by the biota were determined by CTSL. The rates of phosphorus loss, ammonia utilization, and nitrate algal uptake as a function of temperature are shown in Figures V-17, V-18, and V-19, respectively.

These models, which considered the effects of temperature on the algal productivity rates, were used to investigate the role of nutrients in eutrophication. The models were also used to establish maximum allowable nutrient loadings by zones as presented later in this report.

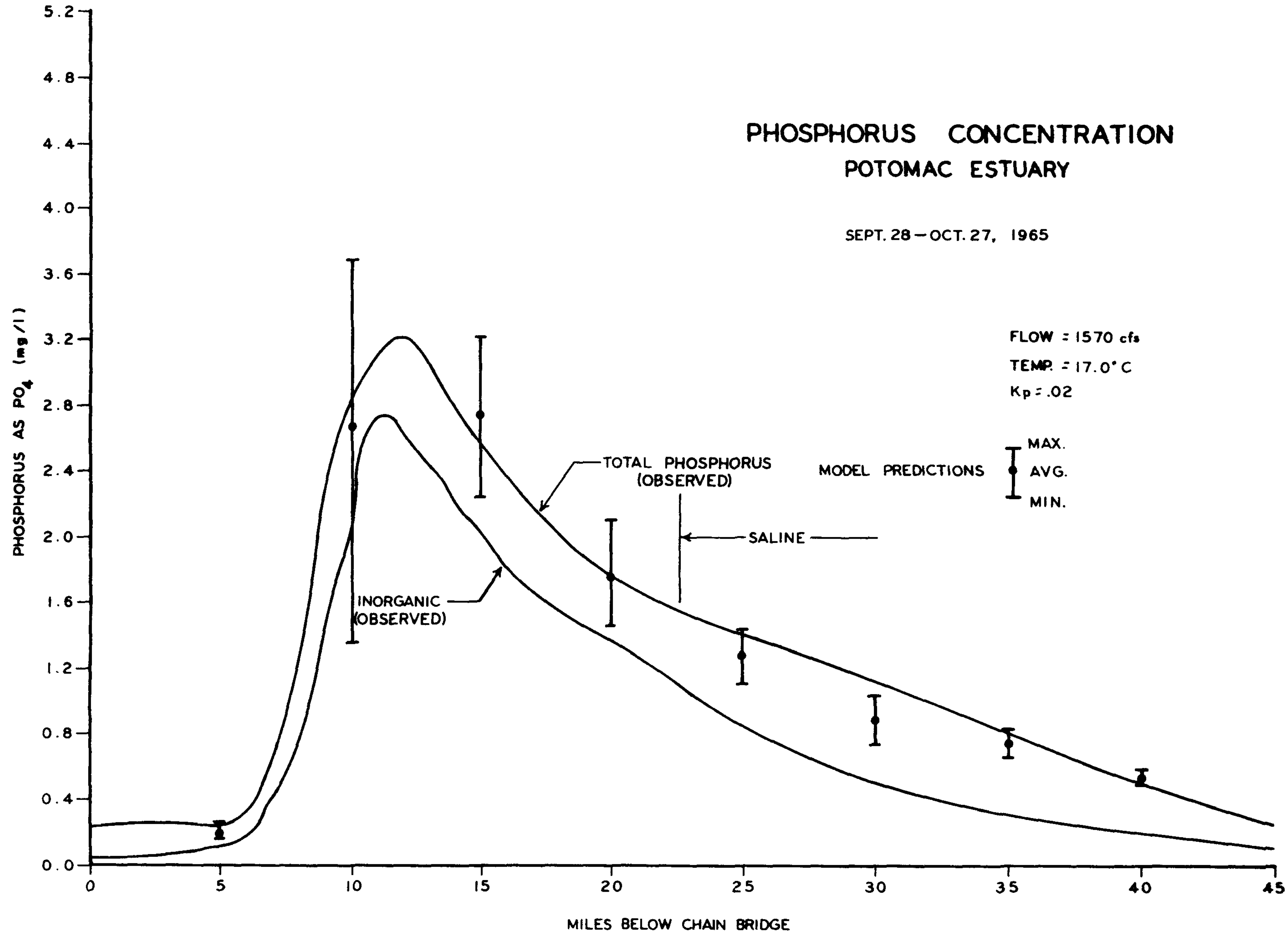

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
SEPT. 28 – OCT. 27, 1965
FLOW = 1570 cfs
TEMP. = 17.0°C
Kp = .02
MODEL PREDICTIONS
MAX.
AVG.
MIN.
TOTAL PHOSPHORUS (OBSERVED)
INORGANIC (OBSERVED)
SALINE
PHOSPHORUS AS PO4 (mg/l)
MILES BELOW CHAIN BRIDGE
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40
45

FIGURE V-13

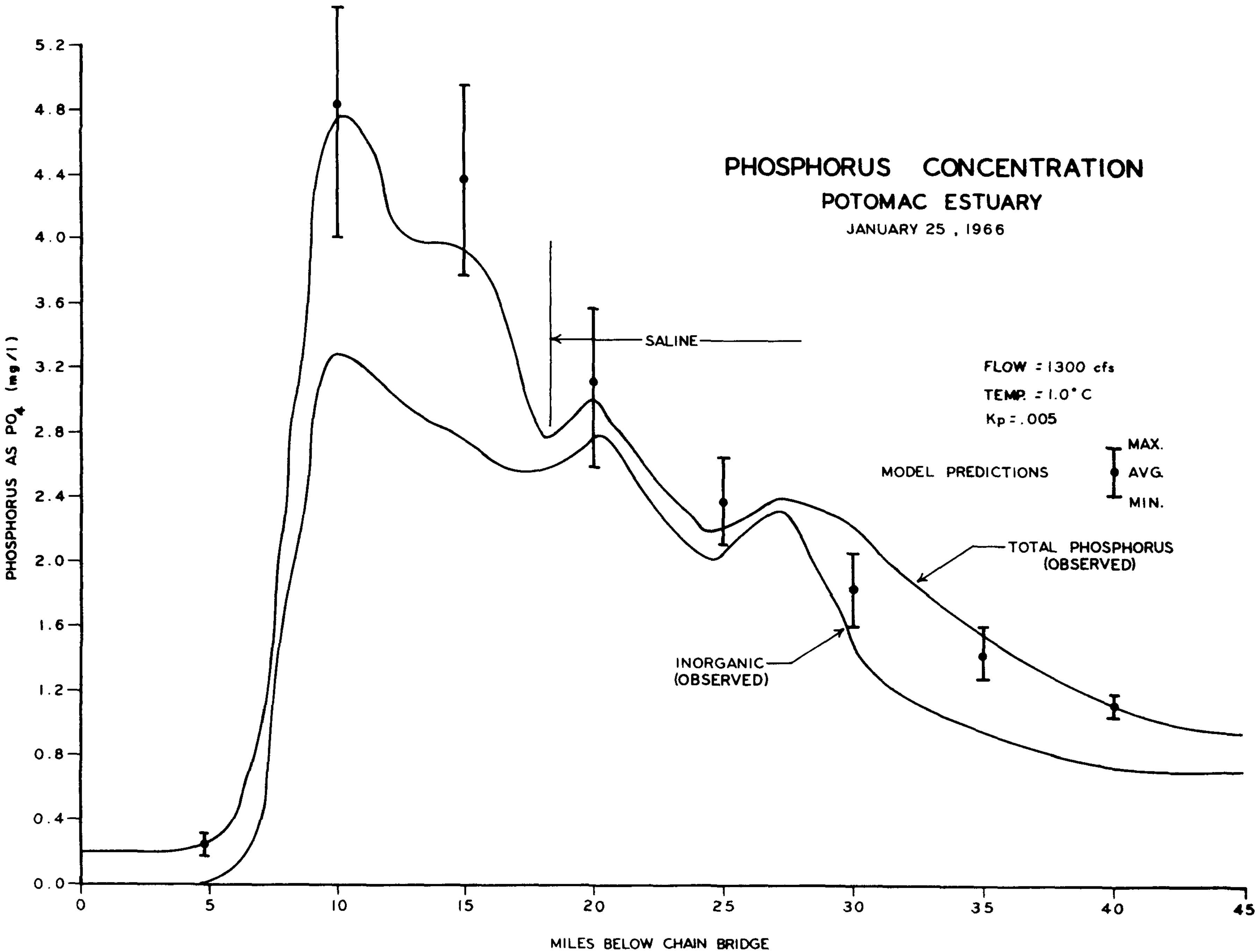

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
JANUARY 25, 1966
FLOW = 1300 cfs
TEMP. = 1.0° C
Kp = .005
MODEL PREDICTIONS
MAX.
AVG.
MIN.
SALINE
TOTAL PHOSPHORUS (OBSERVED)
INORGANIC (OBSERVED)
PHOSPHORUS AS PO4 (mg/l)
MILES BELOW CHAIN BRIDGE
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
0
5
10
15
20
25
30
35
40
45

FIGURE V-14

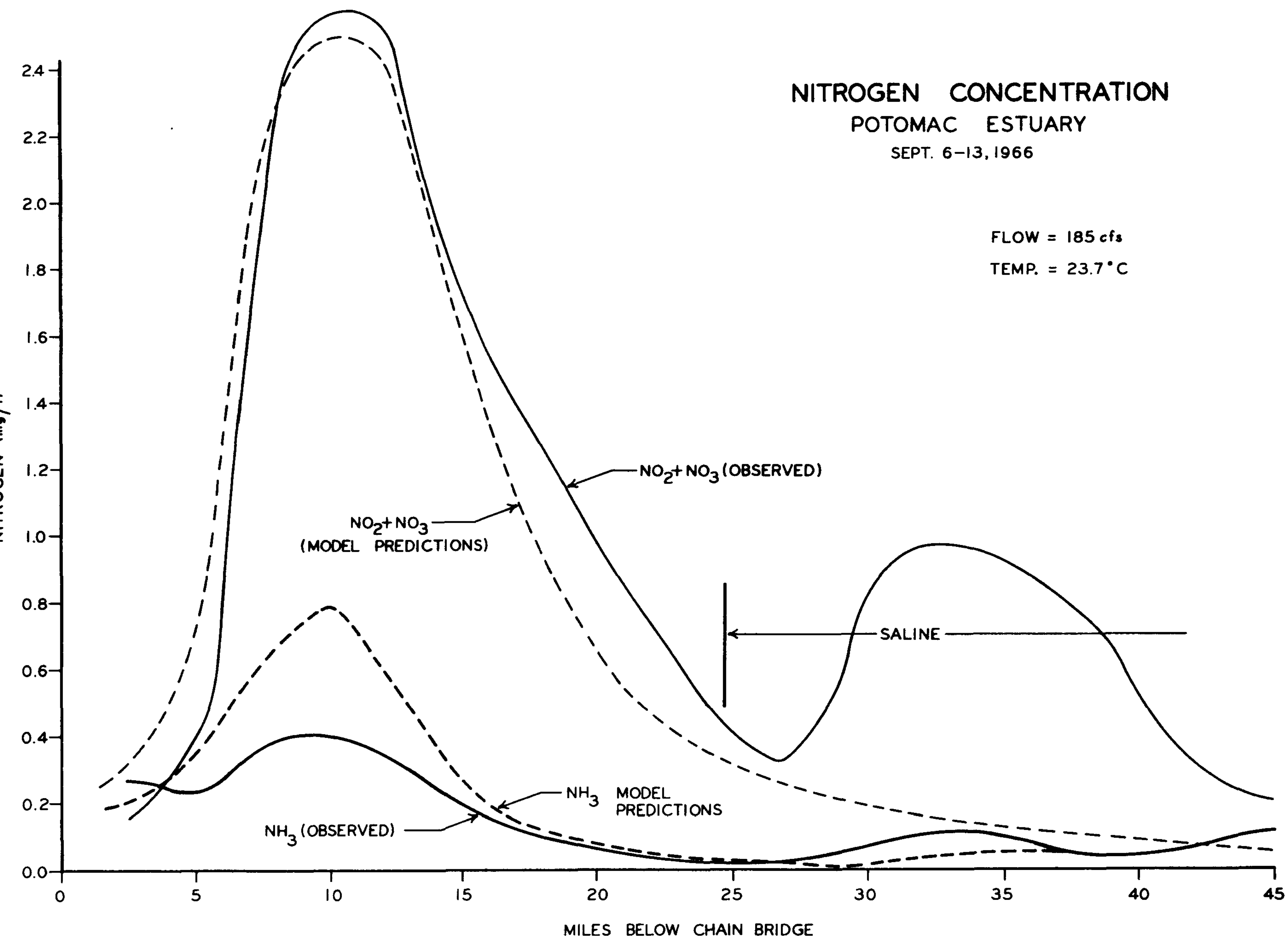
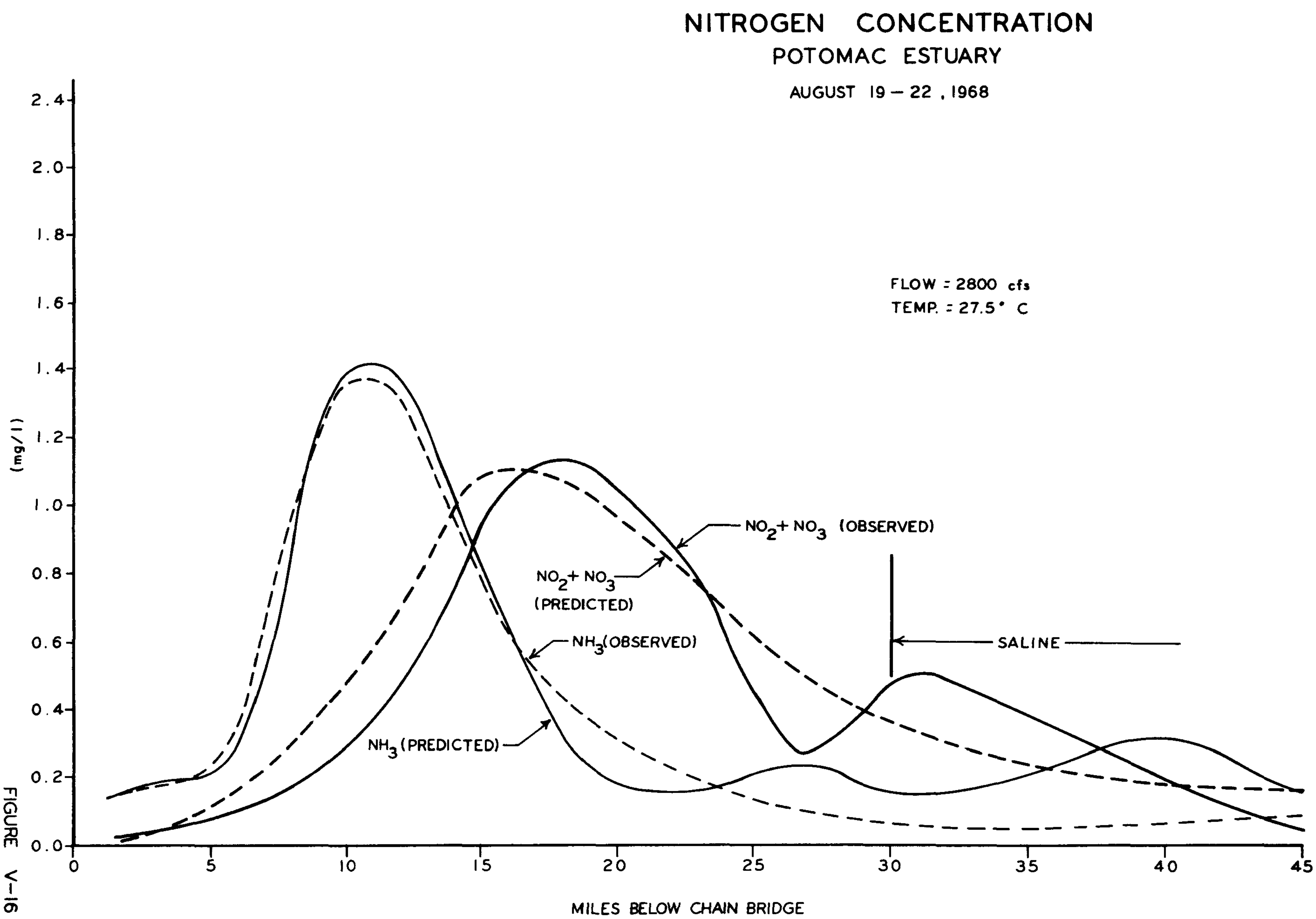

NITROGEN CONCENTRATION
POTOMAC ESTUARY
SEPT. 6–13, 1966
FLOW = 185 cfs
TEMP. = 23.7°C
NITROGEN (mg/l)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE
$NO_2 + NO_3$ (OBSERVED)
$NO_2 + NO_3$ (MODEL PREDICTIONS)
SALINE
$NH_3$ MODEL PREDICTIONS
$NH_3$ (OBSERVED)

FIGURE V-15


NITROGEN CONCENTRATION
POTOMAC ESTUARY
AUGUST 19 – 22 , 1968
FLOW = 2800 cfs
TEMP. = 27.5° C
(mg/l)
2.4
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE
$NO_2 + NO_3$ (OBSERVED)
$NO_2 + NO_3$ (PREDICTED)
$NH_3$ (OBSERVED)
$NH_3$ (PREDICTED)
SALINE
FIGURE V-16

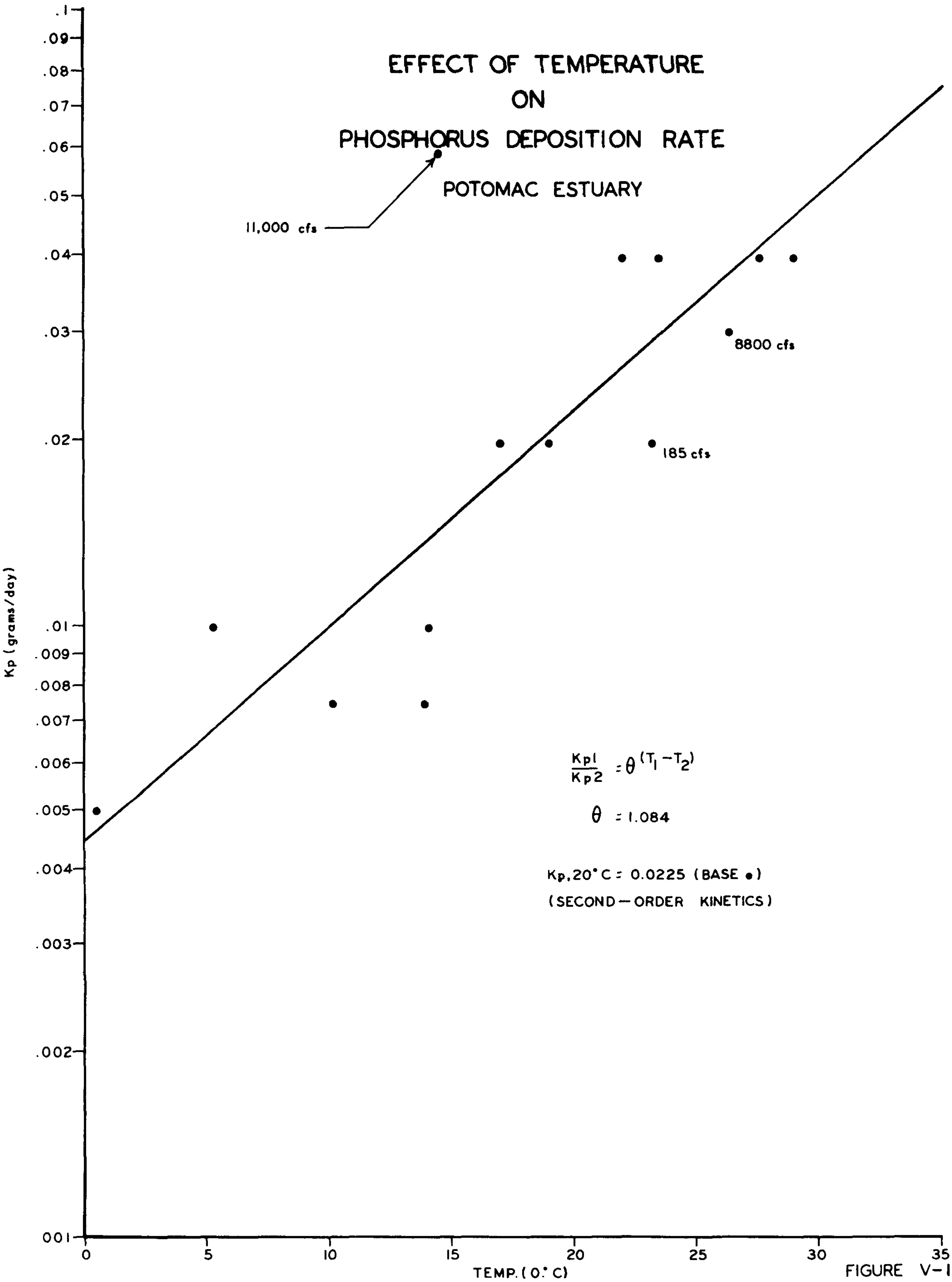

EFFECT OF TEMPERATURE
ON
PHOSPHORUS DEPOSITION RATE
POTOMAC ESTUARY
11,000 cfs
8800 cfs
185 cfs
Kp (grams/day)
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
.009
.008
.007
.006
.005
.004
.003
.002
.001
0
5
10
15
20
25
30
35
TEMP. (0.° C)
$\frac{Kp1}{Kp2} = \theta^{(T_1 - T_2)}$
$\theta = 1.084$
Kp, 20° C = 0.0225 (BASE e)
(SECOND – ORDER KINETICS)

FIGURE V-17

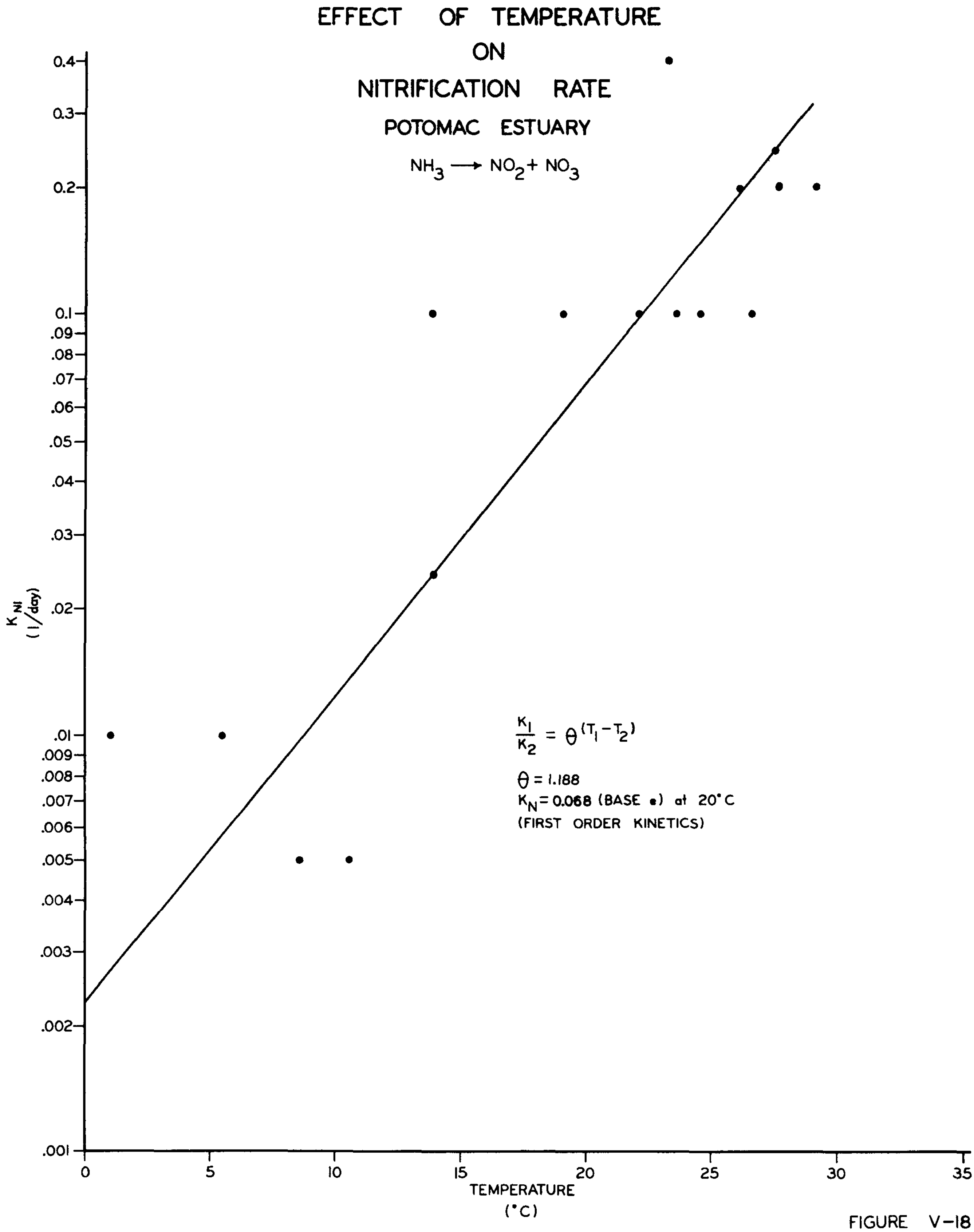
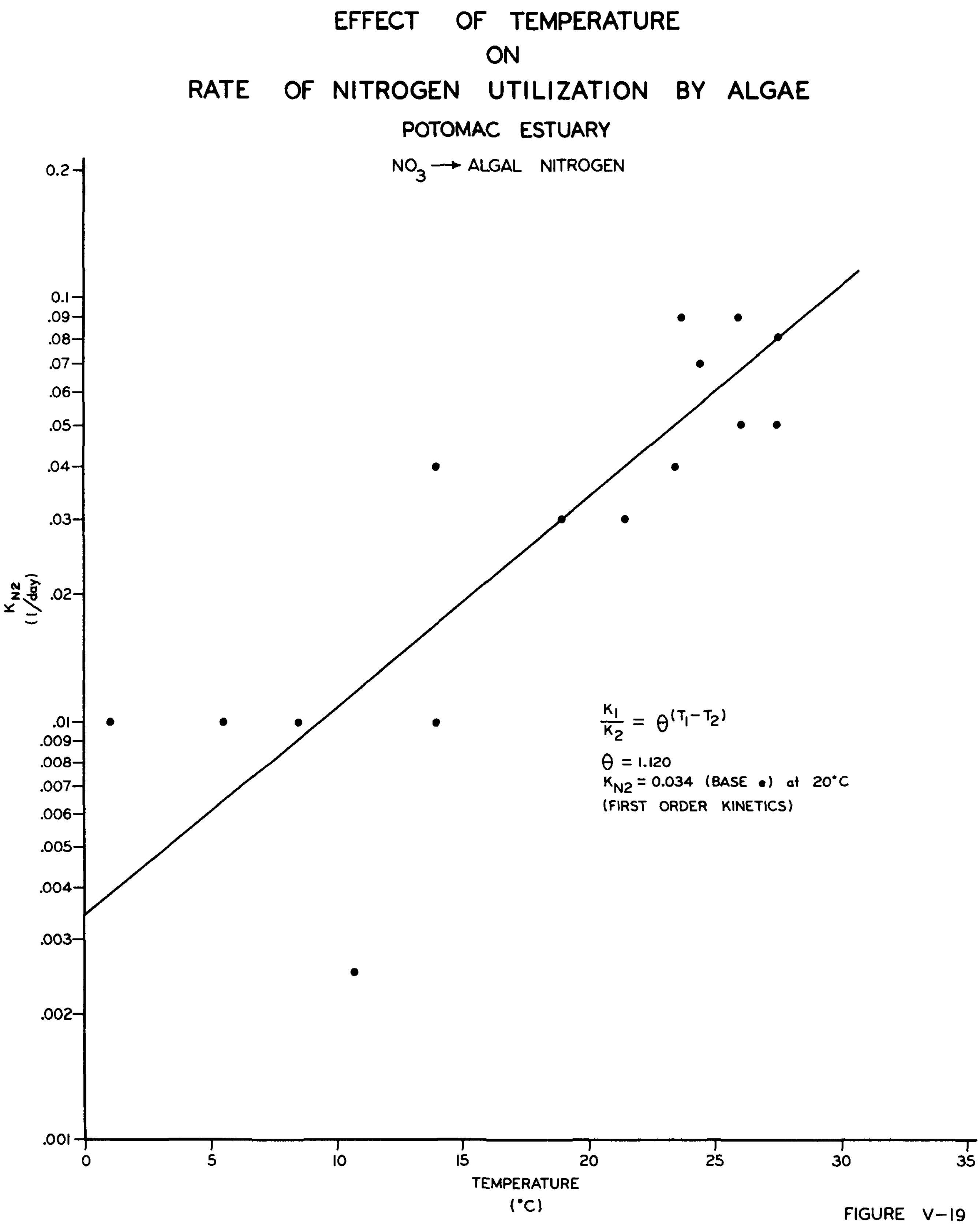

EFFECT OF TEMPERATURE
ON
NITRIFICATION RATE
POTOMAC ESTUARY
NH3 → NO2 + NO3
K1/K2 = θ^(T1 − T2)
θ = 1.188
KN = 0.068 (BASE •) at 20°C
(FIRST ORDER KINETICS)
KNI (1/day)
TEMPERATURE
(°C)
0.4
0.3
0.2
0.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
.009
.008
.007
.006
.005
.004
.003
.002
.001
0
5
10
15
20
25
30
35

FIGURE V-18



EFFECT OF TEMPERATURE
ON
RATE OF NITROGEN UTILIZATION BY ALGAE
POTOMAC ESTUARY
NO3 → ALGAL NITROGEN
KN2 (1/day)
0.2
0.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
.009
.008
.007
.006
.005
.004
.003
.002
.001
K1/K2 = θ^(T1-T2)
θ = 1.120
KN2 = 0.034 (BASE •) at 20°C
(FIRST ORDER KINETICS)
0
5
10
15
20
25
30
35
TEMPERATURE
(°C)


FIGURE V-19

3. Ecological Trends as Related to Nutrient Loadings

The Potomac tidal system is saline in the lower reach with the middle reach brackish and the upper reach fresh water. These differences in salinity as well as nutrient enrichment by wastewater discharges have a pronounced effect on the ecology of the estuary. Under summer and fall conditions, large populations of blue-green algae (a pollution tolerant phytoplankton), mainly *Anacystis* sp. are prevalent in the freshwater portion of the estuary. Large standing crops of this alga occur, especially during periods of low flow, forming green mats of cells. The blue-green algae are apparently not readily grazed by the higher trophic forms and therefore are often considered a "dead end" of the normal food chain.

In the saline portion of the Potomac Estuary, the algal populations are not as dense as in the freshwater portion. Nevertheless, at times large populations of marine phytoplankton, primarily the algae *Gymnodinium* sp. and *Amphidinium* sp., occur producing massive growths known as "red tides."

The effect of the increases in nutrient loadings from wastewater since 1913 on the dominant plant forms in the upper estuary has been dramatic (Figure V-20). Several nutrients and other growth factors have been implicated as stimulating this, with nitrogen and phosphorus showing promise of being the most manageable.

The historical plant life cycles in the upper Potomac Estuary can be inferred from several studies. Cumming [7] surveyed the estuary in 1913-1914 and noted the absence of plant life near the

WASTEWATER NUTRIENT ENRICHMENT TRENDS AND ECOLOGICAL EFFECTS

UPPER POTOMAC TIDAL RIVER SYSTEM

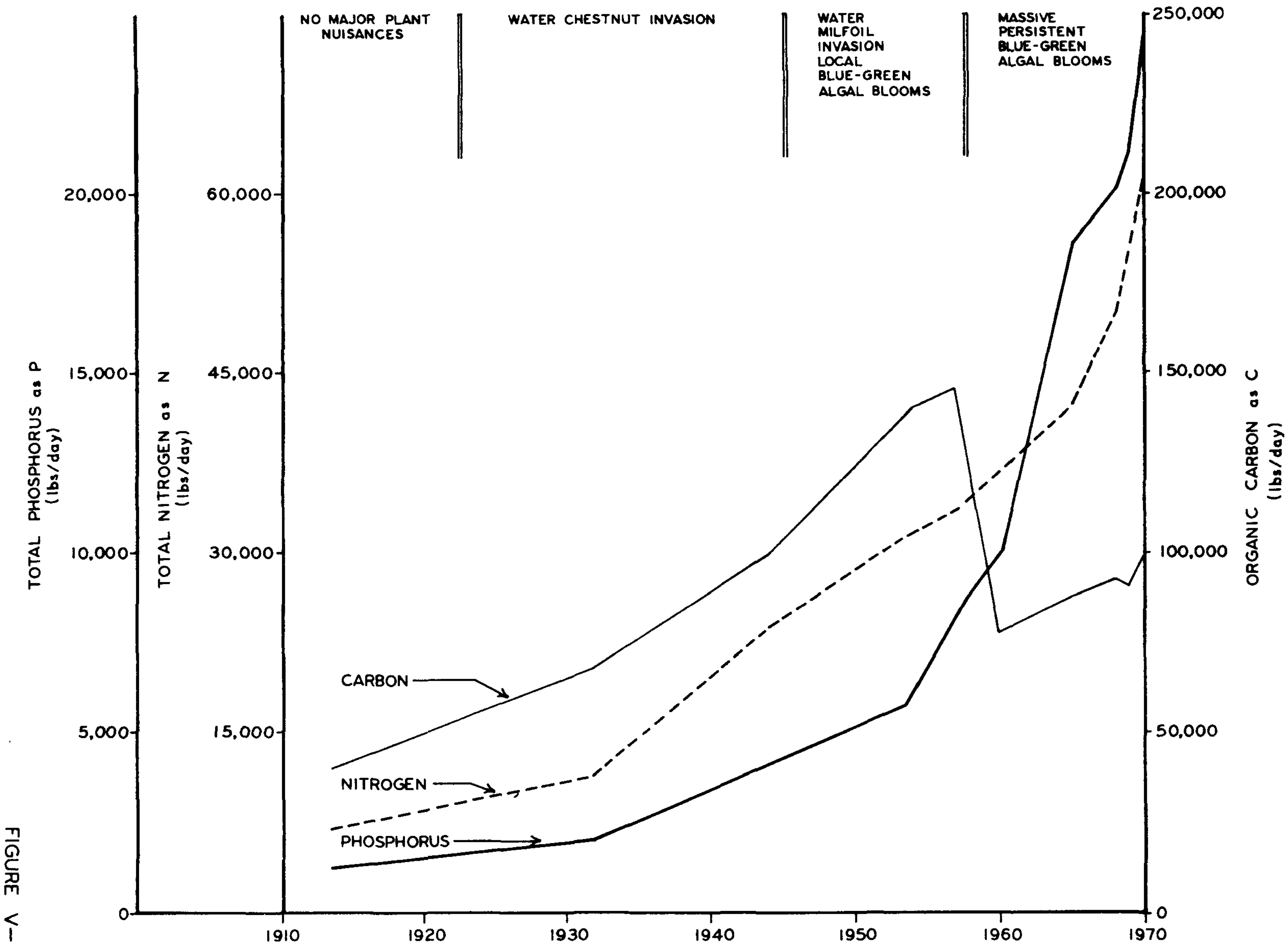



FIGURE V-20

major waste outfalls with "normal" amounts of rooted aquatic plants on the flats or shoal areas below the urban area. No nuisance levels of rooted aquatic plants or phytoplankton blooms were noted.

In the 1920's, an infestation of water chestnut appeared in the waters of the Chesapeake Bay including the Potomac Estuary. This infestation was controlled by mechanical removal [9].

In September and October 1952, another survey of the reaches near the metropolitan area made by Bartsch [10] revealed that vegetation in the area was virtually nonexistent. No dense phytoplankton blooms were reported although the study did not include the downstream areas where they were subsequently found.

In August and September 1959, a survey of the area was made by Stotts and Longwell [11]. Blooms of the nuisance blue-green alga Anacystis were reported in the Anacostia and Potomac Rivers near Washington.

In 1958 a rooted aquatic plant, water milfoil, developed in the Potomac Estuary and created nuisance conditions. The growth increased to major proportions by 1963, especially in the embayments from Indian Head downstream [12].

These dense strands of rooted aquatic plants, which rapidly invaded the system, dramatically disappeared in 1965 and 1966. The decrease was presumably due to a natural virus [13].

Subsequent and continuing observations by CTSL have confirmed persistent massive summer blooms of the blue-green alga Anacystis in nuisance concentrations of greater than 50 ug/l from the metropolitan area downstream at least as far as Maryland Point [14]. Chlorophyll a determinations (a gross measure of algal standing crop) in the upper reach and in the middle and lower reaches of the Potomac Estuary are presented in Figures V-21 and V-22 respectively.

Chlorophyll a at Indian Head and Smith Point for 1965-1966 and 1969-1970, as presented in Figures V-21 and V-22 respectively, indicate that algal populations have not only increased in density but have become more persistent over the annual cycle. At both stations, higher values of chlorophyll were measured during the 1969-1970 sampling cruises. The occurrence of a spring bloom of diatoms was observed in 1969 and 1970. This had not been observed during the 1965-1966 cruises.

These biological observations over the years appear to indicate a species succession. The initial response to a relatively light overenrichment [9] was the growth of water chestnut which when removed allowed the increasing nutrient load to be taken up into the rooted aquatic plant, water milfoil (Myriophyllum spicatum). The die-off of water milfoil then allowed the nutrients to be competitively selected by the blue-green alga Anacystis. Since Anacystis is apparently not utilized in the normal food chain, huge mats and masses accumulate, die off, and decay.

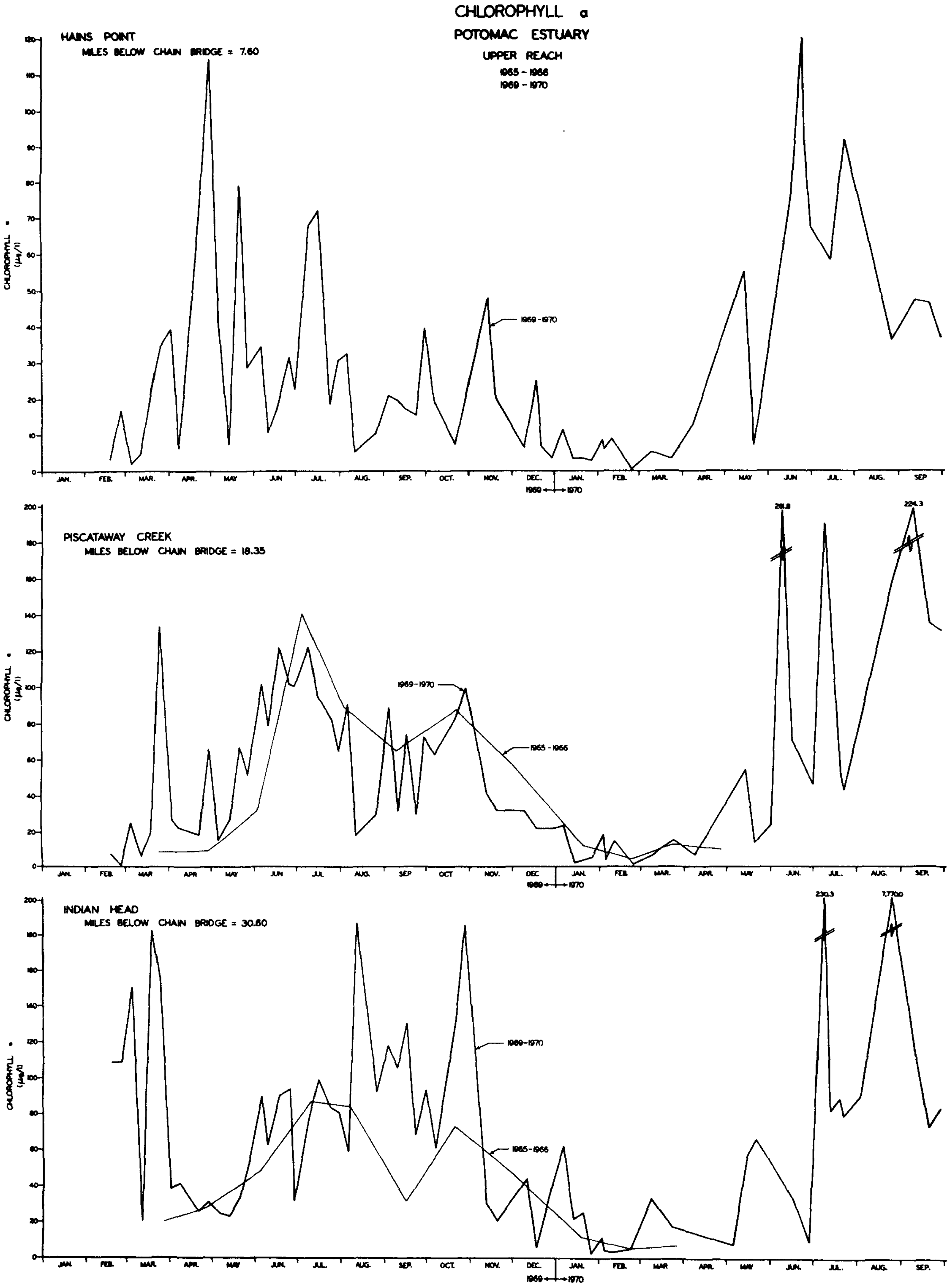

CHLOROPHYLL a
POTOMAC ESTUARY
UPPER REACH
1965 - 1966
1969 - 1970
HAINS POINT
MILES BELOW CHAIN BRIDGE = 7.60
CHLOROPHYLL a (μg/l)
1969-1970
JAN. FEB. MAR. APR. MAY JUN JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN JUL. AUG. SEP.
1969 ← → 1970
PISCATAWAY CREEK
MILES BELOW CHAIN BRIDGE = 18.35
281.8
224.3
1969-1970
1965-1966
INDIAN HEAD
MILES BELOW CHAIN BRIDGE = 30.60
230.3
1969-1970
1965-1966

FIGURE V-21

# CHLOROPHYLL a
## POTOMAC ESTUARY
### MIDDLE and LOWER REACH
1965 - 1966
1969 - 1970

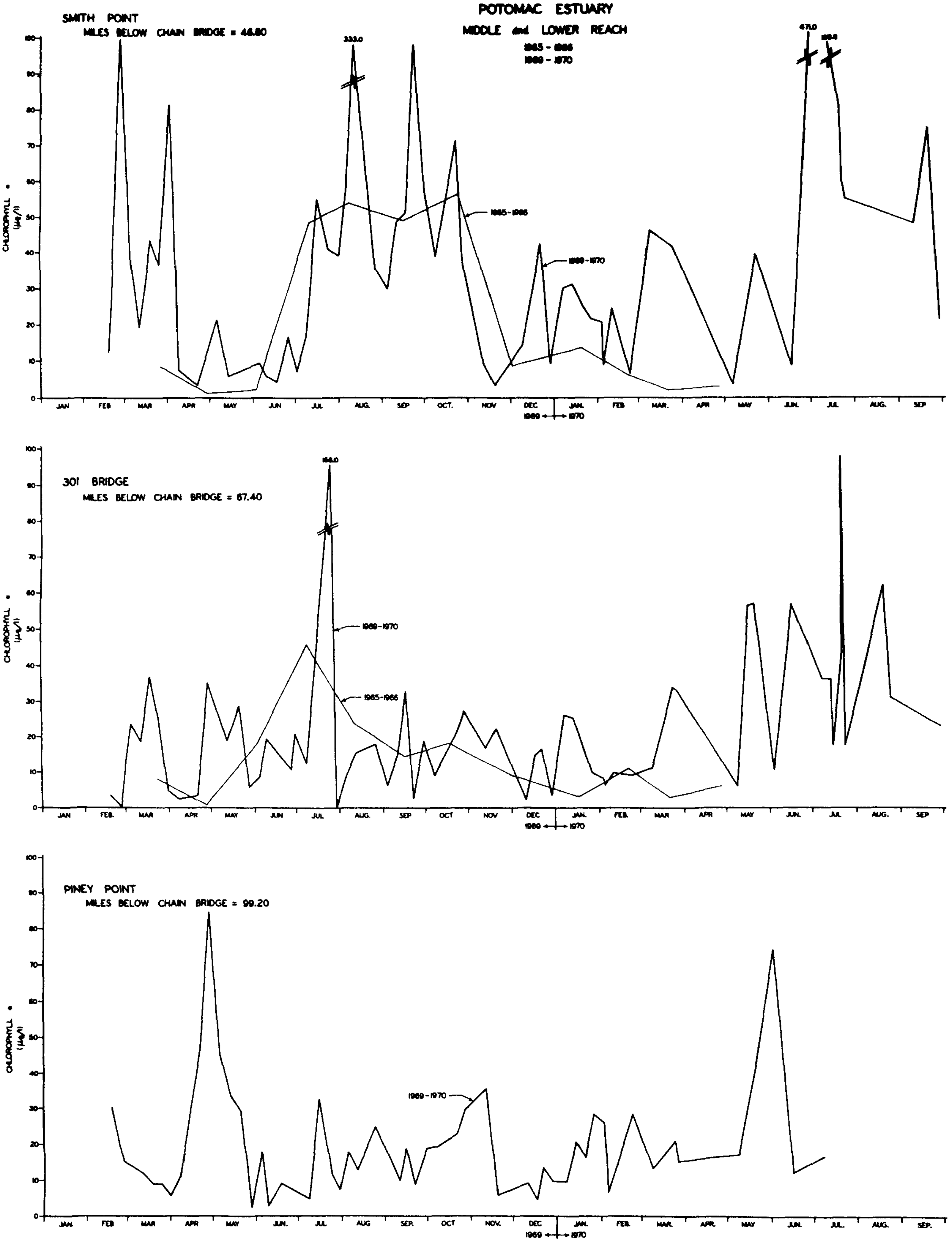



FIGURE V-22

From the above considerations, it would appear that nuisance conditions did not develop linearly with an increase in nutrients. Instead, the increase in nutrients appeared to favor the growth and thus the domination by a given species. As nutrients increased further, the species in turn was rapidly replaced by another dominant form. For example, water chestnut was replaced by water milfoil which in turn was replaced by Anacystis.

Figure V-20 indicates that the massive blue-green algal blooms were associated with large phosphorus and nitrogen loading increases in the upper reaches of the Potomac River tidal system. The massive algal blooms have persisted since the early 1960's even though the amount of organic carbon from wastewater discharges has been reduced by almost 50 percent.

Laboratory and controlled field pond studies by Mulligan [15] have shown similar results. Ponds receiving low-nutrient additions (phosphorus and nitrogen) contained submerged aquatic weeds. Continuous blooms of algae appeared in the ponds having high nitrogen and phosphorus concentrations. An important observation in Mulligan's studies was that when the water quality was returned to its original state by reduction of nutrient concentrations, the ecosystem also reverted to its previous state. This observation was also supported by studies of Edmondson [16] on Lake Washington and Hasler on the Madison, Wisconsin lakes [17].

## E. EFFECTS OF EUTROPHICATION ON WATER QUALITY

The effects of nutrient enrichment and the resulting algal growths are fourfold: (1) an increase in organic oxygen demanding load, (2) an increase or decrease in dissolved oxygen caused by algal photosynthesis or respiration, (3) the creation of nuisance and aesthetically objectionable conditions, and (4) the possible toxic effects on other plants and aquatic life. Each of the effects is discussed separately below:

### 1. Increase in Organic Oxygen Demanding Load

Algal cells convert inorganic carbon and nitrogen into organic compounds and result in an appreciable oxygen demanding load after their death. For example, under summer conditions, all of the 60,000 lbs/day of nitrogen discharged into the estuary from wastewater treatment facilities is converted into algal cells. The combined ultimate oxygen demand of nitrogen and carbon from these cells is approximately 490,000 lbs/day. This load, though dispersed over the entire upper estuary, is nevertheless greater than the total oxygen demand by all wastewater discharges into the upper estuary.

Laboratory studies on rate kinetics of the oxidation of algal cells at temperatures of 28°C to 30°C indicated that the reaction rates for the oxygen demanding process vary from 0.16 to 1.25 per day. The increase in organic oxygen demanding loads is often concentrated in the embayments or along the shores as a result of wind action. These concentrations of decaying algae produce noxious odors.

2. Algal Oxygen Production and Respiration

As shown in Figure V-7, the DO concentration in the Piscataway embayment was 12 mg/l which was about 4 mg/l above saturation capacity at the observed water temperature. This increase in DO above saturation capacity is due to oxygen produced by algal cells. The total oxygen production of a community as a result of the photosynthetic activity is a function of algal biomass and population composition, light intensity, and temperature. In the upper and middle Potomac Estuary, light penetration is usually limited to the upper 2 to 4 feet of the water column.

Bacterial and algal respiration occur simultaneously with the oxygen production process. Since the upper estuary is well mixed, this respiration process occurs over the entire water column. During the months of June and July 1970, oxygen production and respiration rate studies were made in the upper and middle Potomac Estuary as presented in Table V-3. A special respiration study was conducted on July 29, 1970, which indicated that .0010 mg $O_2$/hr/ug of chlorophyll respiration could be attributed to algae with the remainder due to bacterial and other oxidation processes.

With a euphotic zone of 2 feet, an average oxygen production of .010 mg $O_2$/hr/ug of chlorophyll for 12 hours/day, an average respiration of .0010 mg $O_2$/hr/ug of chlorophyll for 24 hours/day, and an average chlorophyll concentration of 100 ug/l, the oxygen balance for various water columns is given in Table V-4. The data indicate that for a

Table V-3

OXYGEN PRODUCTION AND RESPIRATION RATE SURVEY
Upper and Middle Potomac Estuary
1970

| Date | Water Temp. (°C) | Chlorophyll a Range (ug/l) | Light Intensity Range (foot candles) | Oxygen Production mg/hr/ug of Chlorophyll a | Respiration mg/hr/ug of Chlorophyll a |
|---|---|---|---|---|---|
| 6-22 | 26 | 40-110 | 250-300 | .0073 | .0023 |
| 6-23 | 27 | 70-120 | 200-300 | .0084 | .0011 |
| 6-24 | 27 | 54-110 | 200-300 | .0087 | .0024 |
| 6-25 | 27 | 50- 60 | 200-300 | .0121 | .0033 |
| 7-20 | 28 | 30-100 | 250-400 | .0130 | .0022 |
| 7-21 | 27 | 30-143 | 200-300 | .0130 | .0016 |
| 7-22 | 26 | 30-140 | 100-200 | .0146 | .0017 |
| 7-27 | 28 | - | - | .0060 | .0010 |

Table V-4

OXYGEN PRODUCTION-RESPIRATION BALANCES

Chlorophyll a = 100 ug/l
Oxygen Production = .010 mg/hr/ug chlorophyll for 12 hours/day
Respiration = .0010 mg/hr/ug chlorophyll for 24 hours/day

Euphotic Zone of 2.0 feet

| Water Column (depth) | Increase in Oxygen Averaged over Entire Water Column due to Photosynthesis (mg/l/day) | Decrease in Oxygen due to Respiration | Net (mg/l/day) |
|---|---|---|---|
| 4 | 6.0 | 2.4 | 3.6 |
| 8 | 3.0 | 2.4 | 0.6 |
| 12 | 2.0 | 2.4 | -0.4 |
| 16 | 1.5 | 2.4 | -0.9 |
| 20 | 1.2 | 2.4 | -1.2 |

Euphotic Zone of 4.0 feet

| Water Column (depth) | Increase in Oxygen Averaged over Entire Water Column due to Photosynthesis (mg/l/day) | Decrease in Oxygen due to Respiration | Net (mg/l/day) |
|---|---|---|---|
| 4 | 12.0 | 2.4 | +9.6 |
| 8 | 6.0 | 2.4 | +3.6 |
| 12 | 4.0 | 2.4 | +1.6 |
| 16 | 3.0 | 2.4 | +0.6 |
| 20 | 2.4 | 2.4 | 0.0 |

water depth greater than 10 feet, respiration would be larger than production, thus resulting in a negative net balance on the oxygen resources of the system.

If the euphotic zone were increased to 4 feet, there would be a net oxygen production for water columns of 24 feet or less. Conversely, if the depth of the euphotic zone were 1 foot, there would be a net oxygen production for water approximately 6 feet and less in depth.

The DO budget in the Potomac Estuary is affected by algal production and respiration as shown in Figure V-23. The net result of oxygen production and demand by algal respiration and decay is a reduction of the oxygen resources. This DO depression is approximately 2.0 mg/l in the estuary and can be attributed to algal respiration and decay. The net oxygen production concept has been incorporated into the DO budget model for the Potomac Estuary.

DO CONCENTRATIONS
POTOMAC ESTUARY
AUGUST 19—22, 1968

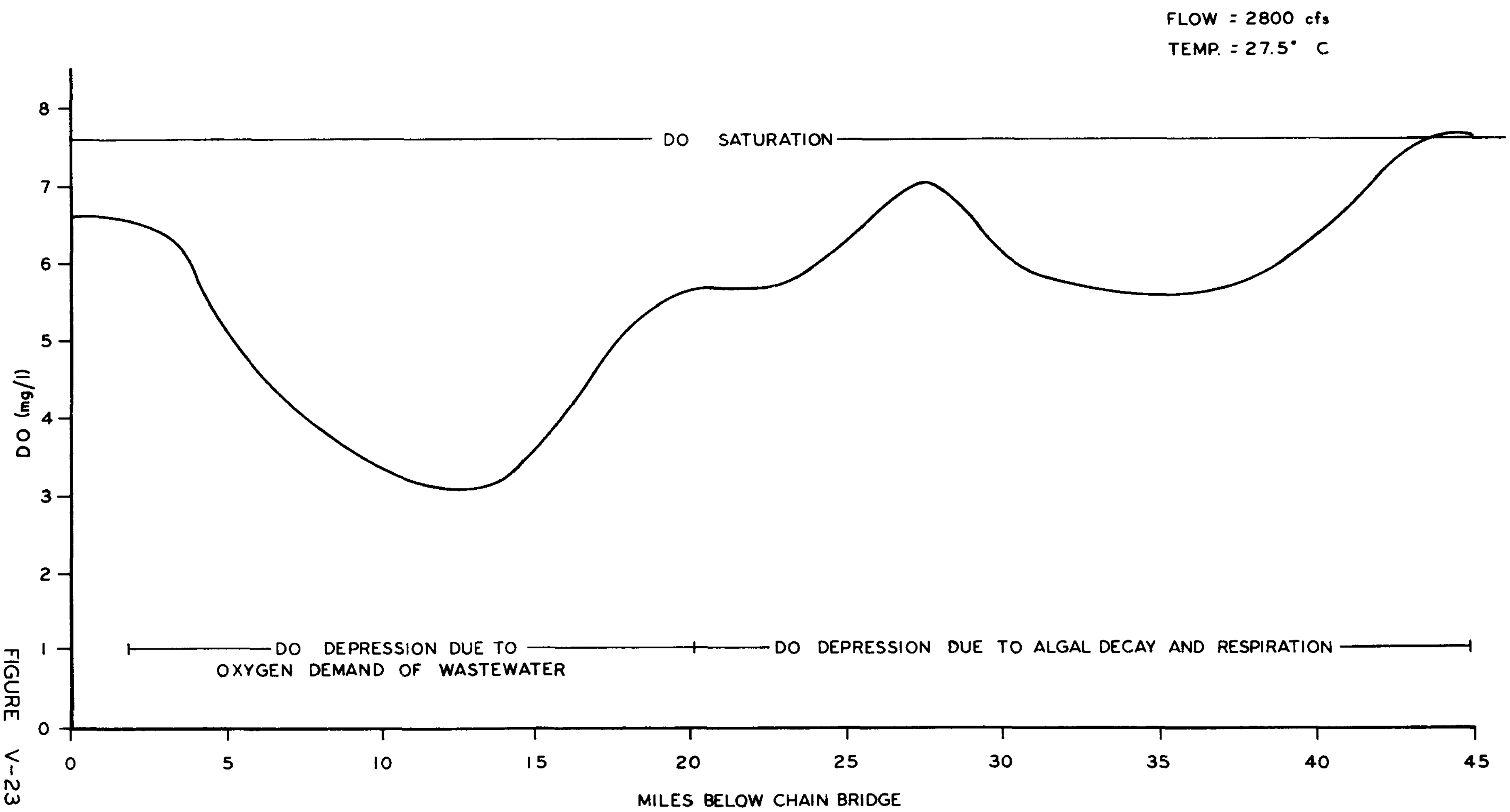



FIGURE V-23

3. Unfavorable Physical and Aesthetic Characteristics of Algal Blooms

When algal blooms become extensive, large mats are formed causing what appears to be a coating of green paint on the water surface. In embayments such as Gunston Cove, Piscataway and Dogue Creeks, these mats usually concentrate in the vicinity of marinas not only coating the hulls of boats but also emitting an obnoxious odor when the cells die and decay.

Along the Potomac shorelines, rows of algal mats are often formed by wind action. These windrows of algae render the shoreline unsuitable for swimming and recreation.

In September 1970, after a period of low flows, the algal blooms became quite prominent in the area of Woodrow Wilson Bridge. After a week of temperatures in the 90's Fahrenheit, an algal mat developed in the Tidal Basin. The dense growth of algae was physically removed to minimize the obnoxious odors emanating from the decaying mats. This was the first known occurrence of a heavy algal bloom in the Tidal Basin.

4. Algal Toxicity

It has been postulated that some algal species cause gastric disturbances in human beings who ingest infested water. Under certain conditions, several species of blue-green algae produce toxic organic compounds that can kill fish, birds, and domestic animals [21]. Of the 10 such known genera, three (Anabaena, Oscillatoria, and Anacystis) grow profusely in the upper Potomac Estuary.

At the present time, the effects of toxins from blue-green algae on other forms of life in the waters of the Potomac Estuary are not well established. In the summer of 1970, the blue crab harvest in an area of heavy algal blooms was reduced because of undesirable tastes and odors. It was also reported that several people became ill after eating crabs from this area. Crabbing in the lower Potomac, where there are no blue-green algal blooms, was not affected. It is postulated that the objectionable taste and odor of the crabs was related to the blue-green algae.

If the estuary is to be used as a water supply source, the possibility of the effect of toxins from blue-green algae must be considered. The genera currently found in the Potomac have known species which are toxin producers and as mentioned previously are also known to affect the taste and odor of seafood.

# CHAPTER VI

# DISSOLVED OXYGEN ENHANCEMENT

## A. STUDY APPROACH

The concentration of dissolved oxygen in the upper estuary is a function of environmental conditions, biological population and activity, and concentration and composition of organic matter in the system. A schematic diagram shown in Figure VI-1, originally presented by Torpey [18], demonstrates the interrelationships of the oxidation of carbonaceous and nitrogenous components of organic matter by bacteria, and photosynthetic activity by phytoplankton, and dissolved oxygen.

The three biological systems having the greatest effect on the DO are the bacteria which oxidize the carbonaceous matter, the bacteria which oxidize the nitrogenous matter, and the phytoplankton which grow as a result of nutrient enrichment. In the upper Potomac Estuary, these three biological systems can and do occur simultaneously in the same area. The predominance of one or all of the three systems depends not only on the source of organic matter (wastewater effluents) but also on such environmental factors as temperature, light penetration, and freshwater inflow.

A DO budget has been incorporated into the FWQA Dynamic Quality Model consisting of the following five linkages:

(1) Oxidation of carbonaceous matter,

(2) Oxidation of nitrogenous matter (ammonia and organic),

A SCHEMATIC DIAGRAM OF
DISSOLVED OXYGEN INTERRELATIONSHIPS
FOR THE THREE
MAJOR BIOLOGICAL SYSTEMS

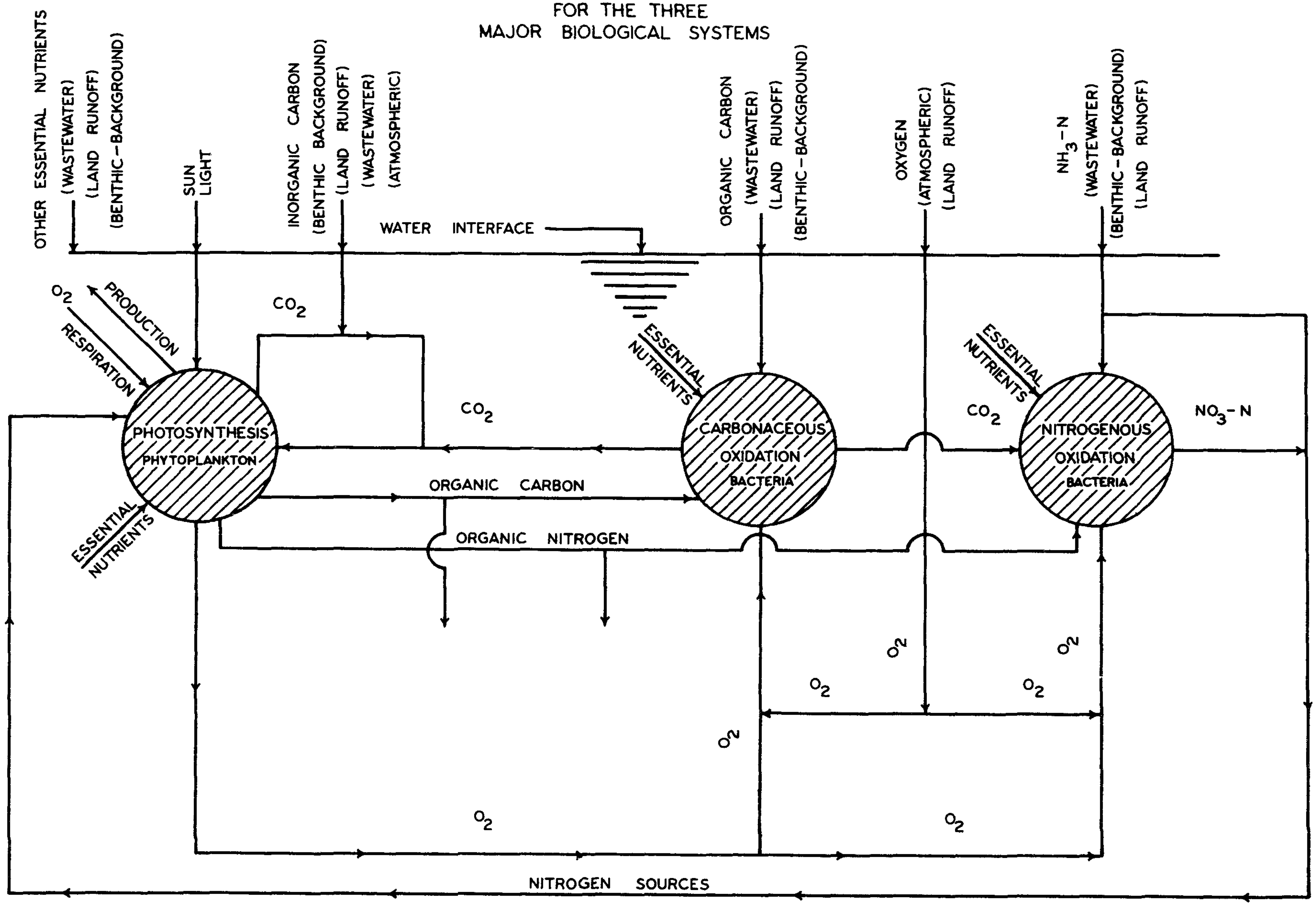



FIGURE VI-1

(3) Oxygen production and respiration of simulated algal standing crops based upon nitrate utilization by the cells,

(4) Benthic demand, and

(5) Reaeration from the atmosphere.

The model, which is described in a CTSL report currently in preparation, has been verified for flow ranges from 212 to 8800 cfs. The average observed and predicted DO concentrations for the periods of September 22, 1968, and August 12-19, 1969, as shown in Figures VI-2 and VI-3 respectively, demonstrate that the model can predict DO responses over a wide range of freshwater inflows.

The basic coefficients used in the DO budget model are:

| Process | Rate (base e) at 20°C | Temperature Coefficient $\theta^{(T_1 - T_{20})}$ |
|---|---|---|
| Carbonaceous oxidation | 0.170 | 1.047 |
| Nitrogenous oxidation | 0.068 | 1.188 |
| Algal utilization of nitrogen | 0.034 | 1.120 |
| Reaeration from the atmosphere | * | 1.021 |

The remaining processes in the DO budget are given below:

Algal oxygen production rate = 0.012 mg $O_2$/hr/ug chlorophyll a

Algal respiration rate = 0.0008 mg $O_2$/hr/ug chlorophyll a

Euphotic zone = 2 feet deep

Respiration depth = full depth of water column

Algal oxygen production period = 12 hours

Algal respiration period = 24 hours

Benthic demand rate = 1.0 gr $O_2$/day sq mi

* The model calculates reaeration as a function of depth and velocity using any one of three formulations.

## DO CONCENTRATIONS
### POTOMAC ESTUARY
### SEPT. 22, 1968

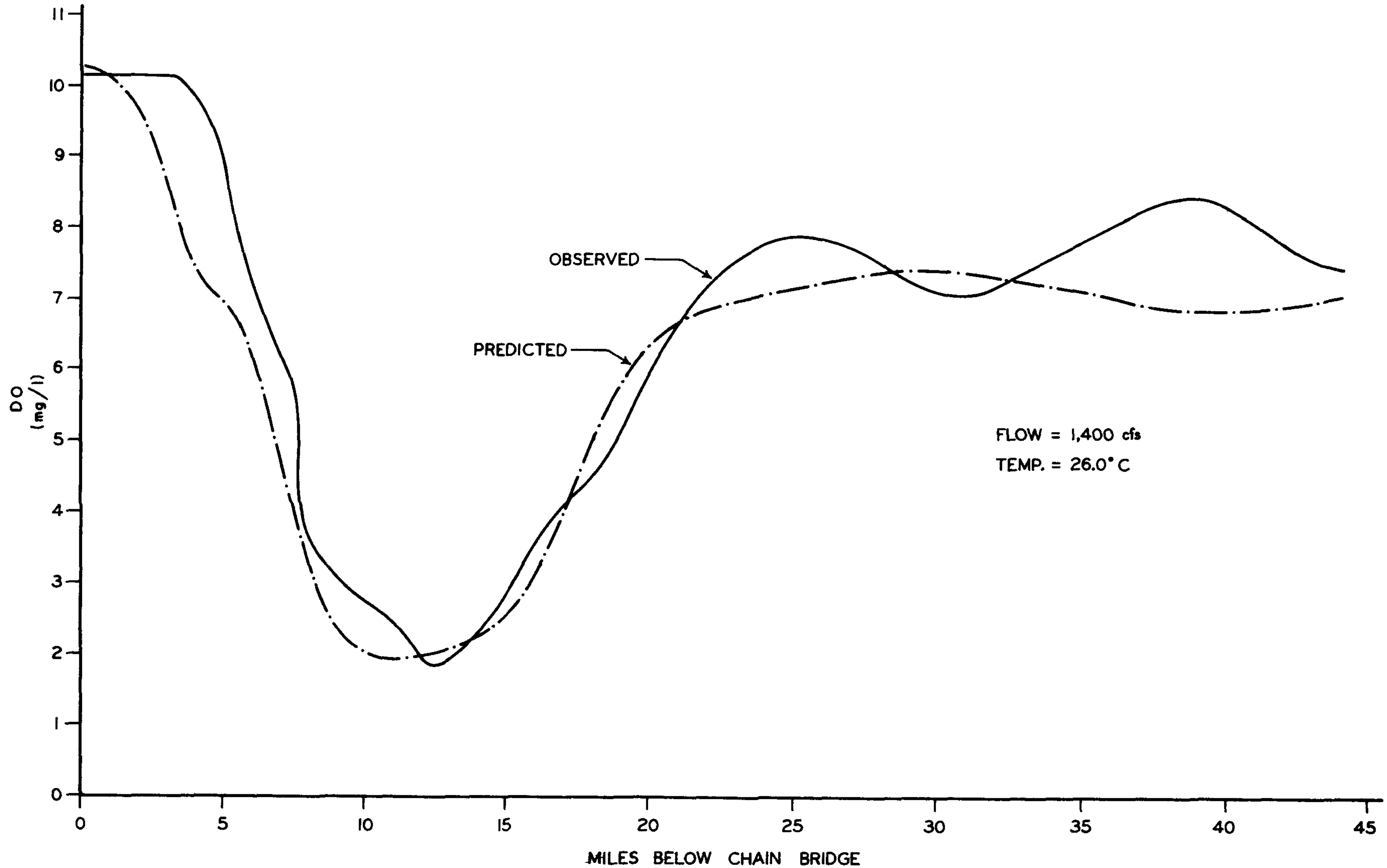



FIGURE VI-2

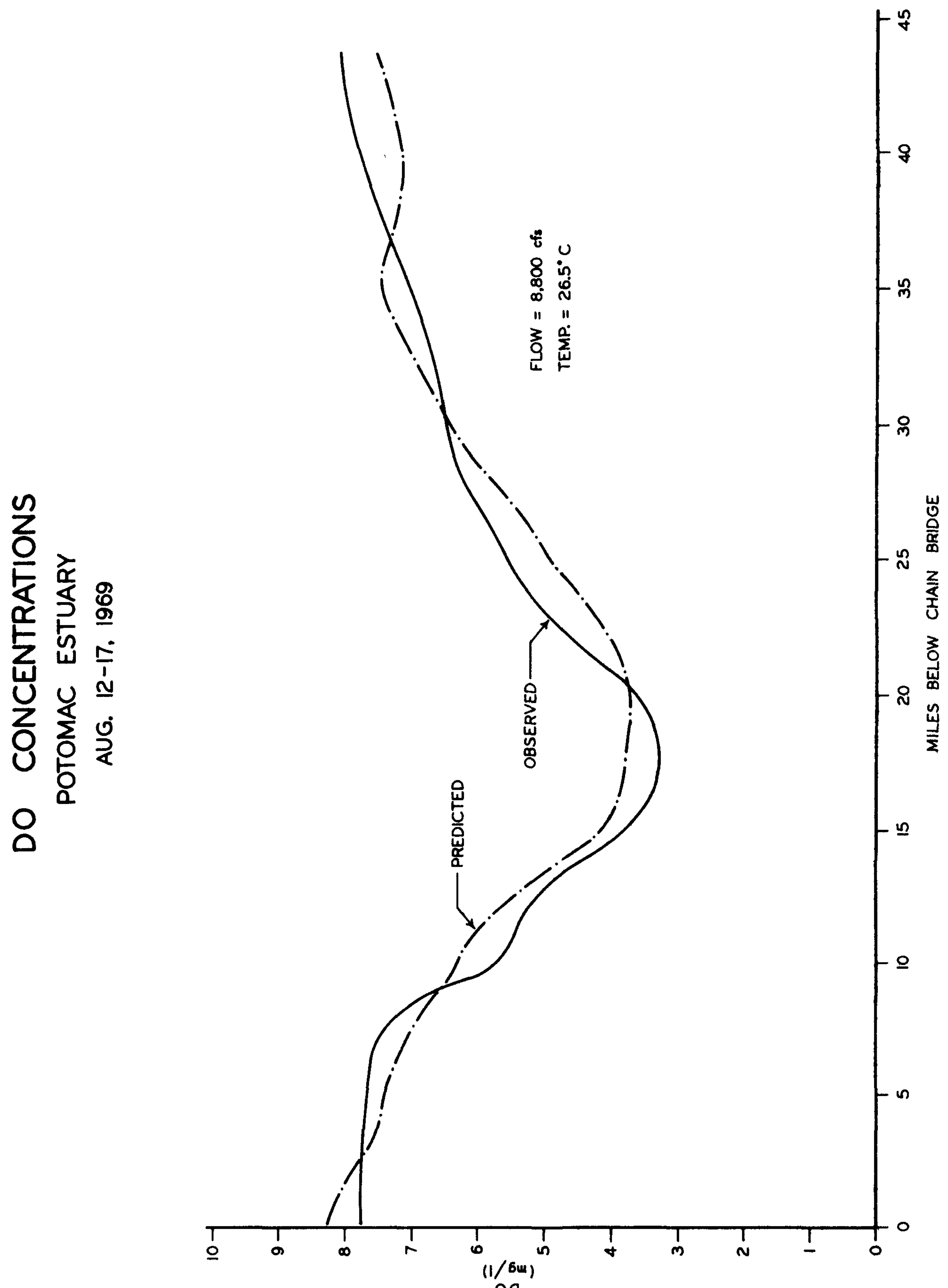

DO CONCENTRATIONS
POTOMAC ESTUARY
AUG. 12-17, 1969
FLOW = 8,800 cfs
TEMP. = 26.5°C
PREDICTED
OBSERVED
DO
(mg/l)
MILES BELOW CHAIN BRIDGE
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45

FIGURE VI-3

Details of the effect of these parameters on the DO budget will also be given in the CTSL report now in preparation.

The major area of depressed oxygen during low-flow periods is from Hains Point to about Gunston Cove. In this area, the major source of the oxygen depression is from wastewater effluent. The total daily oxygen demanding loads from these discharges are as follows:

Carbonaceous = 200,000 lbs/day

Nitrogenous = 250,000 lbs/day

Under these flow conditions, approximately 65,000 lbs/day of carbonaceous and nitrogenous oxygen demand enter the upper estuary from land runoff. From the above, it can be concluded that the current nitrogenous demand has the greatest effect on the oxygen resources of the estuary with carbonaceous demand being slightly lower.

However, the rate at which the demand (carbonaceous and nitrogenous) is exerted varies significantly depending upon temperature. At a 28°C temperature, the demand rates are equal at 0.34 day (base e); while at 15°C, the carbonaceous demand rate is 0.18 with the nitrogenous demand dropping to 0.03. See Figure V-18 for nitrification rates.

Simulation runs with the model indicate that while nitrification continues to occur at temperatures of 15°C or lower, it plays a minor role in the overall DO budget of the upper Potomac Estuary.

For 22 years of record, mean monthly water temperatures in the upper estuary have been determined as given below:

| | | | |
|---|---|---|---|
| January | 2.5°C | July | 28.1°C |
| February | 3.3°C | August | 27.8°C |
| March | 7.8°C | September | 24.7°C |
| April | 14.0°C | October | 18.4°C |
| May | 20.4°C | November | 11.5°C |
| June | 25.9°C | December | 4.8°C |

Based upon the above tabulation and the study discussed above, it appears that nitrification control for DO enhancement is required only for the months of April through October. This is developed further in Chapter XII.

## B. DO CRITERIA

Water quality standards for dissolved oxygen have been adopted by the States of Maryland and Virginia and by the District of Columbia.

For the waters of the Potomac, the standards are as given below:

| Jurisdiction | Average DO (mg/l) | Minimum DO (mg/l) |
|---|---|---|
| District of Columbia* | 5.0 (Daily) | 4.0 |
| State of Maryland | 5.0 (Monthly) | 4.0 |
| State of Virginia | 5.0 (Daily) | 4.0 |

* Except between the Rochambeau Memorial and Prince Georges County (Maryland) line where the average is 4.0 and the minimum DO is 3.0.

These DO standards were used as criteria in this study.

# CHAPTER VII

## ALGAL GROWTH RESPONSE TO NUTRIENT CONTROL

Reductions in the standing crop (biomass) of algae in the Potomac Estuary can be achieved by management, singly or in combinations, of carbon, nitrogen, and phosphorus content. The decision as to which nutrient or nutrients to control may depend upon several factors especially the four listed below:

1. Level of algal reduction required to minimize the effect on water quality such as DO and recreational water use,

2. Maximum nutrient concentration allowable to maintain a maximum permissible algal standing crop,

3. Controllability and mobility of a given nutrient, and

4. The overall water quality objectives, such as DO enhancement, eutrophication reversal, or reduction of potentially toxic matter including heavy metals.

The four factors listed above were used not only to establish the nutrient criteria but also to develop the overall wastewater management program for the Potomac Estuary.

A. EUTROPHICATION CONTROL OBJECTIVES

For purposes of water quality management, the upper Potomac Estuary may be considered eutrophic when undesired standing crops become the predominant plant life as is now occurring with the nuisance blue-green alga species. The major objectives for controlling the blue-green algal standing crop in the upper estuary are fourfold:

1. To reduce the dissolved oxygen (DO) depression caused by respiration and the decay of algal growths especially in waters over 10 feet in depth. At times, DO depressions of more than 3.0 mg/l below saturation occur even during daylight hours.

2. To minimize the increase of ultimate oxygen demand (UOD) resulting from the conversion by algal cells of inorganic carbon and nitrogen from wastewater to oxidizable organic compounds. Currently, more UOD is added to the upper Potomac Estuary in the summer months as a result of algal growth than from wastewater discharges.

3. To enhance the aesthetic conditions in the upper estuary. Large green mats develop during the months of June through October and create objectionable odors, clog marinas, cover beaches and shorelines, and in general reduce the potential of the estuary for recreational purposes such as fishing, boating, and water skiing.

4. To reduce any potential toxin problem and objectionable taste and odor problems related to excessive blue-green algal crops if the upper estuary is to be used as a supplemental water supply.

To aid in defining an algal standing crop limit, a subjective analysis using chlorophyll concentrations was developed incorporating conditions having possible effects on water quality. Four major restraints to desired water uses are offered in this analysis (Table VII-1) including the required reduction in the chlorophyll standing crop for each of the parameters.

The desired maximum limit of 0.5 mg/l DO below saturation was selected by CTSL to allow for assimilation of waste discharges and naturally occurring oxygen demanding pollutants. To minimize the effects of increased organic loads and sludge deposits caused by algal growths, an upper limit of 5.0 mg/l of total oxygen demand is proposed.

Of the four restraints, the most stringent reduction percentage is for control of growths to prevent nuisance conditions. From the above analysis, a 75 to 90 percent reduction in chlorophyll concentration will be required in the Potomac Estuary, or chlorophyll levels of approximately 25 ug/l.

Table VII-1

SUBJECTIVE ANALYSIS OF ALGAL CONTROL REQUIREMENTS

| Water Quality or Water Use Restraints | Indications of Restraints | Magnitude of Current Restraints* | Desired Maximum Limit | Required Percentage Reduction of Current Standing Crop |
|---|---|---|---|---|
| DO Depression Caused by Decay and Respiration | mg/1 of DO Below Saturation | 1.5 to 3.0 mg/1 | 0.5 mg/1 | 65-85 |
| Increase in Total Oxygen Demanding Load | mg/1 of Increase in Ultimate BOD | 15 to 30 mg/1 | 5.0 mg/1 | 65-80 |
| Recreational & Aesthetic Nuisance Conditions | Chlorophyll Concentration | > 100 ug/1 | 25 ug/1** | 75-90 |
| Toxins, Taste, & Odor | Undefined | Not Determined | Not Determined | Not Determined |

* Under nuisance bloom conditions, chlorophyll a concentrations are greater than 100 ug/1

** Average over entire water column

## B. NUTRIENT REQUIREMENTS TO PREVENT EXCESSIVE STANDING CROPS OF BLUE-GREEN ALGAE

Various investigators studying algal growth requirements have discussed the concentrations of nitrogen and phosphorus needed to stimulate algal blooms. In a recent study of the Occoquan Reservoir, located on a tributary of the Potomac Estuary, Sawyer [19] recommended limits of inorganic nitrogen and inorganic phosphorus of 0.35 and 0.02 mg/l, respectively. This reservoir has blue-green algal blooms under summer conditions attributed to wastewater effluents discharged into tributaries flowing into the reservoir. Mackenthun [20] cites data indicating upper limits of inorganic nitrogen at 0.3 mg/l and inorganic phosphorus at 0.01 mg/l at the start of the growing season to prevent blooms. FWQA's Committee on Water Quality Criteria recommends an upper limit of 0.05 mg/l of total phosphorus for estuarine waters [21]. No recommendations for inorganic nitrogen were made other than that the ratio of nitrogen to phosphorus should not be radically changed from that naturally occurring.

Pritchard [22], studying the Chesapeake Bay and its tributaries, suggests that if total phosphorus concentrations in estuarine waters are less than 0.03 mg/l, biologically healthy conditions will be maintained. Jaworski _et al_ [14], reviewing historical data for the upper Potomac Estuary, suggest that if the concentration of inorganic phosphorus and inorganic nitrogen were at 0.1 and 0.3 mg/l respectively, algal blooms of approximately 50 ug/l of chlorophyll _a_ would result. A chlorophyll _a_ concentration of 50 ug/l or over was considered indicative of excessive algae. Studies of the James River Estuary, a sister estuary to the Potomac, by Brehmer and Haltiwanger [23] indicate that nitrogen appears to be the rate limiting nutrient.

Recently, the management of carbon in controlling algal blooms has been suggested by Kuentzel [24] and Lange [25]. Studies by Kerr et al [26] also suggest that inorganic carbon is apparently directly responsible for increased algal populations in waters they have studied. The Kerr studies indicate that the addition of nitrogen and phosphorus indirectly increases algal growth by stimulating growth of large heterotrophic populations. No concentration criteria for either nitrogen, phosphorus, or carbon were suggested to prevent excessive algal blooms.

In addition to the review of data cited above and other numerous articles not reported, six considerations were used to develop the nutrient requirements for the Potomac Estuary. The six were

1. Algal composition analyses,
2. Analysis of the nutrient data on an annual cycle and profile basis,
3. Nutrient bioassay,
4. Nutrient and algal mathematical modeling,
5. Comparison with an estuary currently not eutrophic, and
6. Review of historical nutrient and ecological trends in the Potomac Estuary.

A comprehensive approach to algal growth control was taken to include all three reaches of the estuary: the fresh water, the brackish, and the saline portions. In a study undertaken by Carpenter, Pritchard, and Whaley, oxygen concentrations of less than 1.0 mg/l were found in the area of the lower reach of the Potomac [27]. Comparable areas of the Chesapeake Bay, in terms of salinity and vertical stratification, did not show depletions to less than 1.0 mg/l. In terms of plankton counts and chlorophyll, their study indicated that the lower reach of the Potomac was more eutrophic than comparable waters of the Chesapeake Bay.

1. Algal Composition Analysis

In a previous chapter, the need to control algal growth was established. The three major nutrients in blue-green algal cells are carbon, nitrogen, and phosphorus. The chemical composition by weight of Anacystis, which is the most common algae in the Potomac as reported by Lawrence [21], is presented below:

| | |
|---|---|
| Carbon | 46.46% |
| Nitrogen | 8.08% |
| Phosphorus | 0.68% |

Elemental analysis of the blue-green algae in the Potomac was made during the summer months of 1970 [53] and the data on carbon, nitrogen, and phosphorus ratios in terms of micrograms of chlorophyll a and grams of suspended solids are presented in Table VII-2. These data indicate that water with an algal bloom of 100 ug/l chlorophyll a contains the following:

| Parameter | Concentration |
|---|---|
| S. Solids | 14.2 mg/l |
| Carbon | 4.5 mg/l |
| Nitrogen | 1.0 mg/l |
| Phosphorus | 0.1 mg/l (0.3 mg/l as $PO_4$) |

Assuming that all nutrients can be utilized by the algal cells, an algal bloom with a concentration of 100 ug/l of chlorophyll a requires a minimum of 4.5 mg/l of carbon, 1.0 mg/l of nitrogen, and 0.10 mg/l of phosphorus (0.30 mg/l of $PO_4$) in the supporting water.

Table VII-2

ALGAL COMPOSITION STUDY
Upper Potomac Estuary
1970

| Date | Sampling Location on Potomac | Carbon Ratio: mg carbon / ug chloro* | Carbon Ratio: mg carbon / mg S.S.** | Nitrogen Ratio: mg N / ug chloro | Nitrogen Ratio: mg N / mg S.S. | T. Phosphorus Ratio: mg $PO_4$ / ug chloro | T. Phosphorus Ratio: Mg $PO_4$ / mg S.S. |
|---|---|---|---|---|---|---|---|
| 7-20 | Indian Head | .068 | .379 | .012 | .066 | .003 | .016 |
| 7-20 | Smith Point | .064 | .366 | .009 | .062 | .002 | .016 |
| 7-24 | Maryland Point | .058 | .433 | .006 | .048 | .002 | .015 |
| 8-24 | Sandy Point (Mallows Bay) | - | - | .008 | - | .004 | - |
| 8-26 | Sandy Point (Mallows Bay 1) | .044 | - | .018 | .033 | .006 | .011 |
| 8-26 | Sandy Point (Mallows Bay 2) | .025 | .199 | .012 | .095 | .003 | .022 |
| 8-26 | Indian Head #1 | .037 | - | .009 | - | .002 | - |
| 8-26 | Indian Head #2 | .025 | .279 | .012 | .132 | .003 | .037 |
| 10-06 | Indian Head | .055 | - | .009 | - | .002 | - |
| 10-06 | Possum Point | .044 | - | .006 | - | .002 | - |
| | AVERAGE | .045 | .331 | .010 | .073 | .003 | .019 |

*Chloro = Chlorophyll a

**S.S. = Suspended Solids

***To convert $PO_4$ in mg/l to P in mg/l divide by 3.07

For the Potomac Estuary, which can be considered a slow-moving continuous culture system during the summer, a carbon concentration equal to or less than 1.1 mg/l, 0.25 mg/l of nitrogen, and 0.08 mg/l (0.027 mg/l as P) of phosphate would be theoretically required to maintain a 25 ug/l chlorophyll a level (or one quarter of the nutrient content in a bloom of 100 ug/l). These should be considered maximum concentrations since no recycling is assumed.

2. Analysis of Data on an Annual Cycle and Longitudinal Profile Basis

Using the disappearance of a specific nutrient both seasonally and along longitudinal profiles, insight can be gained as to the possibility of this nutrient becoming algal growth rate limiting. This assumes that other environmental factors do not restrict growth.

Figure V-10 in Chapter V shows that there was over 0.2 mg/l of available phosphorus as $PO_4$ in the critical reaches above Route 301 Bridge where there is substantial algal growth. From Indian Head to Smith Point, the area of pronounced algal growth, there was over 0.4 mg/l of inorganic phosphorus in the waters even under maximum bloom conditions. These data indicate that in the upper and middle reaches of the Potomac, phosphorus is in excess of 0.30 mg/l as $PO_4$ and thus not rate limiting. In the lower reach around Piney Point, the inorganic phosphorus was often as high as 0.1 mg/l and thus phosphorus could be limiting for this reach.

When the $NH_3$ and $NO_2$ + $NO_3$ concentrations shown in Figures V-11 and V-12 are reviewed, it is evident that in the later summer months practically all of the inorganic nitrogen had disappeared in the reach between the Smith Point and Route 301 Bridge stations by late July 1969 and by mid-August 1970. This depletion occurred even though the summers of 1969 and 1970 had relatively high flows. Based upon the disappearance of inorganic nitrogen, it appears that nitrogen becomes the major factor in limiting algal growth in the middle reach of the estuary.

To determine if carbon was limiting algal growth in the bloom area of the Potomac, total and organic carbon analyses were made during September 1970. (Flows during August and September 1970 were low with air temperatures reaching 95°F during the last week of September.) Dense algal blooms extended from Hains Point to Smith Point. Carbon concentrations obtained during a sampling cruise on September 20, 1970, were as follows:

| Station | Organic Carbon (mg/l) | Inorganic Carbon (mg/l) |
|---|---|---|
| Hains Point | 7.2 | 12.2 |
| Wilson Bridge | 10.5 | 15.4 |
| Piscataway | 10.5 | 8.6 |
| Indian Head | 10.5 | 15.0 |
| Smith Point | 8.5 | 7.7 |
| Route 301 Bridge | 6.1 | 6.1 |

The above data, which were obtained during the mid-day hours of September 20, 1970, indicate that there were large quantities of inorganic carbon available for algal growth. As reported earlier, with the free carbon dioxide in the water ranging between 6.0 and 10.0 at the point of maximum growth (Indian Head), it appears that there is an excess of inorganic carbon available for algal growths.

A review of nutrient data for the summer of 1965 yielded similar results. As can be seen in Figure VII-1, there was complete utilization of nitrate nitrogen between March and August by biota in the Potomac

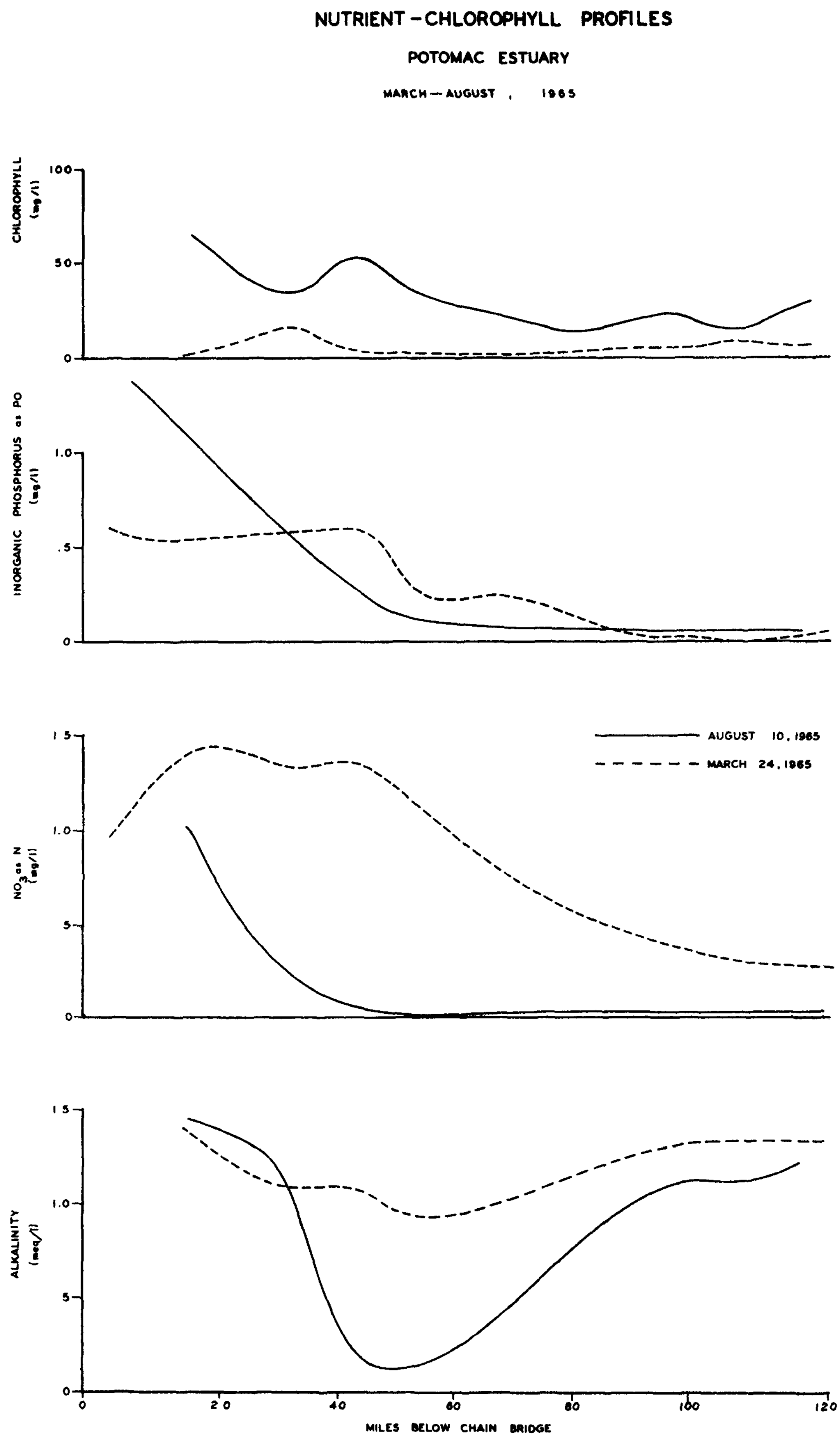

NUTRIENT-CHLOROPHYLL PROFILES
POTOMAC ESTUARY
MARCH—AUGUST, 1965
CHLOROPHYLL (mg/l)
100
50
0
INORGANIC PHOSPHORUS as PO (mg/l)
1.0
.5
0
AUGUST 10, 1965
MARCH 24, 1965
NO3 as N (mg/l)
1.5
1.0
.5
0
ALKALINITY (meq/l)
1.5
1.0
.5
0
0
20
40
60
80
100
120
MILES BELOW CHAIN BRIDGE

FIGURE VII-1

Estuary from River Mile 20 to 60. The utilization of significant quantities of inorganic carbon as indicated by alkalinity was also observed.

The basic difference between these sets of conditions was that the freshwater inflow during June and July 1965 was considerably less than in 1970. The increase in freshwater inflow in 1970 was enough to keep the Potomac high in nitrogen until late August and to maintain a minimum of 5.0 mg/l of carbon throughout the estuary.

From the 1965 data, it can be concluded that: (1) phosphorus is excessive in the upper and middle reaches of the estuary with very low concentrations in the lower reach, (2) inorganic nitrogen has the largest decrease and virtually disappears, with the lower 60 miles of the estuary almost void of nitrogen in August, (3) the significant loss of total alkalinity (a measure of inorganic carbon) occurred in approximately 15-20 miles of the middle portion of the estuary. However, there was a residual of about 3.0 to 5.0 mg/l of inorganic carbon, and (4) based on the above, it appears that nitrogen in the middle reach and possibly both nitrogen and phosphorus in the lower reach was controlling the growth of algae. All three nutrients are in excess in the upper reach with light penetration being the limiting factor of growth.

The 1965 data also demonstrated that another source of inorganic carbon to the Potomac Estuary is recruitment from the Chesapeake Bay.

This source of inorganic carbon appears to be a very important part of the entire carbon balance especially in the middle and lower portion of the estuary. In this area, which as previously indicated is more eutrophic than comparable areas of the Chesapeake Bay, the control of algae may be limited to management of nitrogen and phosphorus.

3. <u>Bioassay Studies</u>

To determine further what nutrients were limiting algal growth in the Potomac, bioassay tests as developed by Fitzgerald [28] [29] were employed. Tests for both phosphorus and nitrogen were conducted in the Potomac from Piscataway Creek to Route 301 Bridge for the period June through October 1970.

Using the rate of ammonia absorption by algal growths, it is possible to determine if the algal cells have surplus nitrogen or if they are nitrogen starved. Tests made during June and early July indicate that ammonia was either released or absorbed at a low rate in the range of $10^{-6}$ mg N/hr/ug chlorophyll a. The cells had adequate nitrogen available for growth as was also indicated by the high nitrate concentration in the water, especially at the upper stations above Indian Head.

Bioassay tests for October 13, 1970, as tabulated below, show a significant increase in ammonia absorption rates between the Piscataway station and the Smith Point station farther downstream.

Table VII-3

NITROGEN BIOASSAY SUMMARY
Potomac Estuary
1970

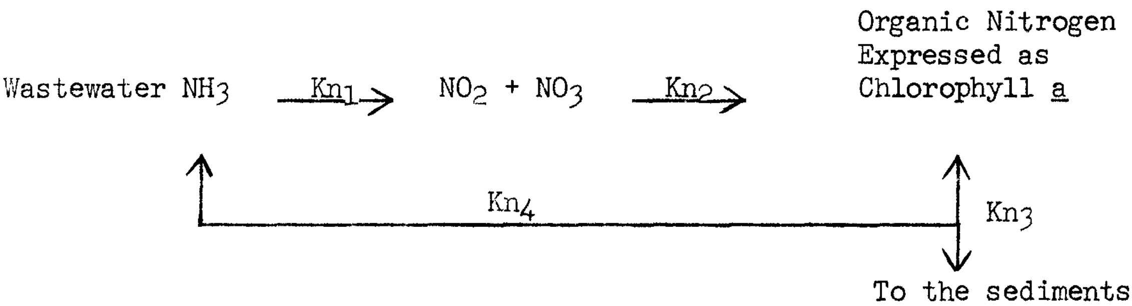
| Station | $NH_3$ In Water (mg/1) | $NO_2$ + $NO_3$ In Water (mg/1) | Ammonia Nitrogen Absorbed (mg N/hr/ug chloro) |
|---|---|---|---|
| Piscataway | .110 | 2.560 | + 6.0 x $10^{-5}$ |
| Indian Head | .150 | .684 | + 6.0 x $10^{-5}$ |
| Possum Point | .001 | .220 | + 2.3 x $10^{-4}$ |
| Smith Point | .001 | .150 | + 1.3 x $10^{-4}$ |

The higher rates of ammonia absorption for Possum and Smith Points and the low concentration of inorganic nitrogen indicate that this reach of the Potomac is becoming nitrogen limited.

Two tests, an extraction and an enzymatic analysis [29], were used to determine if algal growth was phosphorus limited. The phosphorus extraction bioassay studies indicated very little difference between amounts of phosphorus released at the upstream and downstream stations. Tests for alkaline phosphatase, an enzyme indicator of phosphorus starved algal cells, were all negative. These two tests also confirmed the observation, discussed in the previous section, that the phosphorus content in the upper and middle estuary was excessive (over 0.15 mg/l as P).

4. Nutrient and Algal Modeling

Recognizing the possibility that the Potomac becomes nitrogen starved in late summer, an attempt was made to surrogately mathematically model algal growth based on the nitrogen cycle. The model, similar to that proposed by Thomann *et al* [30] is a feedback system as shown below:




This system was incorporated into the dynamic estuary model [41] and was utilized to establish the first-order rates for the feedback system for summer conditions. The established rates (base e) are:

| Kinetic Reaction | Rates | |
|---|---|---|
| $Kn_1$ | .30 - .40 | (per day) |
| $Kn_2$ | .07 - .09 | (per day) |
| $Kn_3$ | .01 - .05 | (per day) |
| $Kn_4$ | (not established) | (per day) |

The first two reactions including the rates $Kn_1$ and $Kn_2$ have been fairly well verified as reported earlier and as shown in the predicted profiles of $NH_3$ and $NO_2 + NO_3$ in Figures V-15 and V-16. The feedback link appears to play a minor part in the system during the earlier summer months.

Predicted profiles using the surrogate algal model, as shown in Figures VII-2 and VII-3, matched the observed data quite closely with respect to location of maximum concentration and general shape of the profile. Other model predictions and a complete description of the model are also currently being prepared by CTSL.

From these mathematical model runs, it appears that the standing crop of the blue-green alga can be predicted using the nitrogen cycle. This further supports the premise that the availability of nitrogen appears to be controlling the standing crop of algae.

Using the model and the August 19-23, 1968, data as shown in Figure VII-2, the reduction of chlorophyll a concentrations to 25 ug/l would result in a maximum $NO_2$ + $NO_3$ concentration of 0.25 mg/l. For the September 6-9, 1966, data as shown in Figure VII-3, an upper limit of 0.38 mg/l of nitrogen would be required to reduce the chlorophyll level to 25.0 ug/l. From the modeling analysis, it appears that if the inorganic nitrogen is between 0.2 and 0.4 mg/l the blooms can be held below the maximum level of 25 ug/l of chlorophyll a.

## CHLOROPHYLL CONCENTRATION
### POTOMAC ESTUARY
AUGUST 19-23, 1968

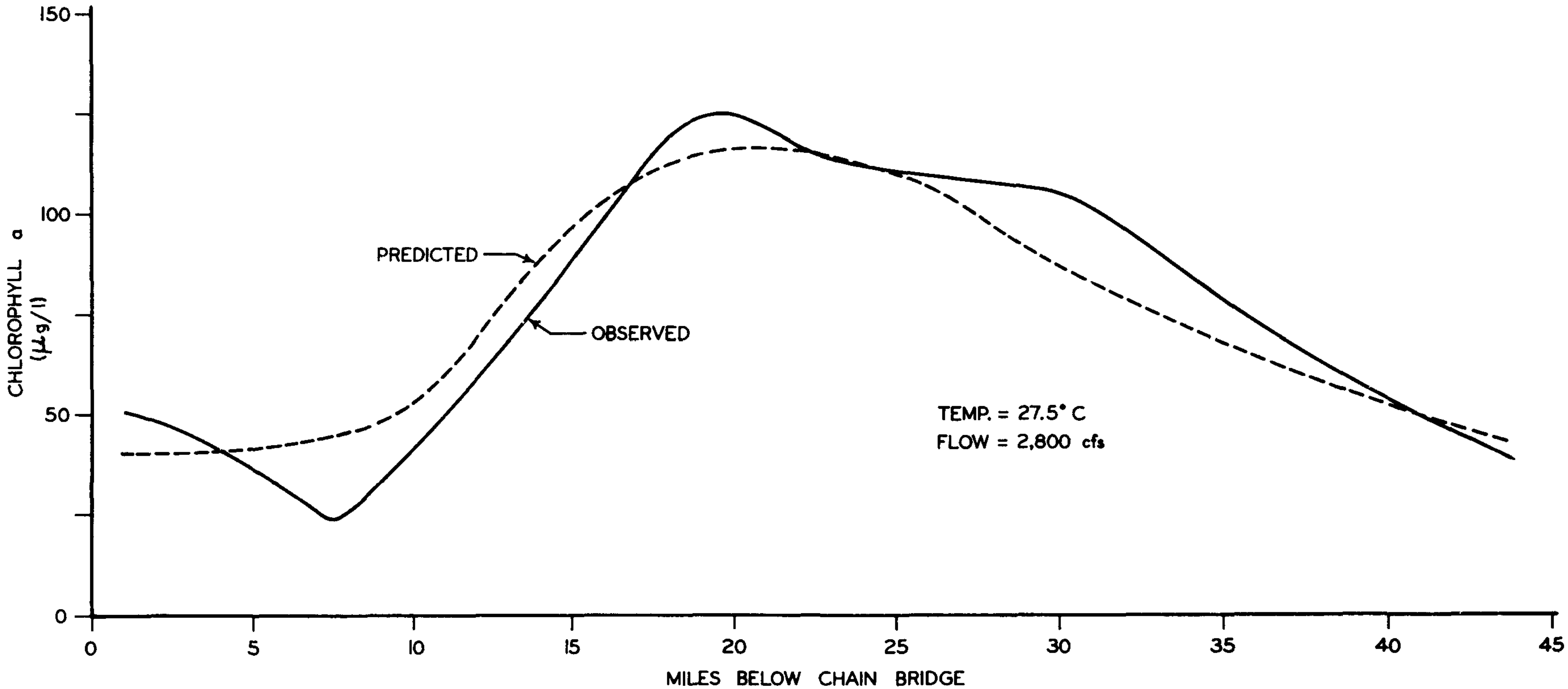



FIGURE VII - 2

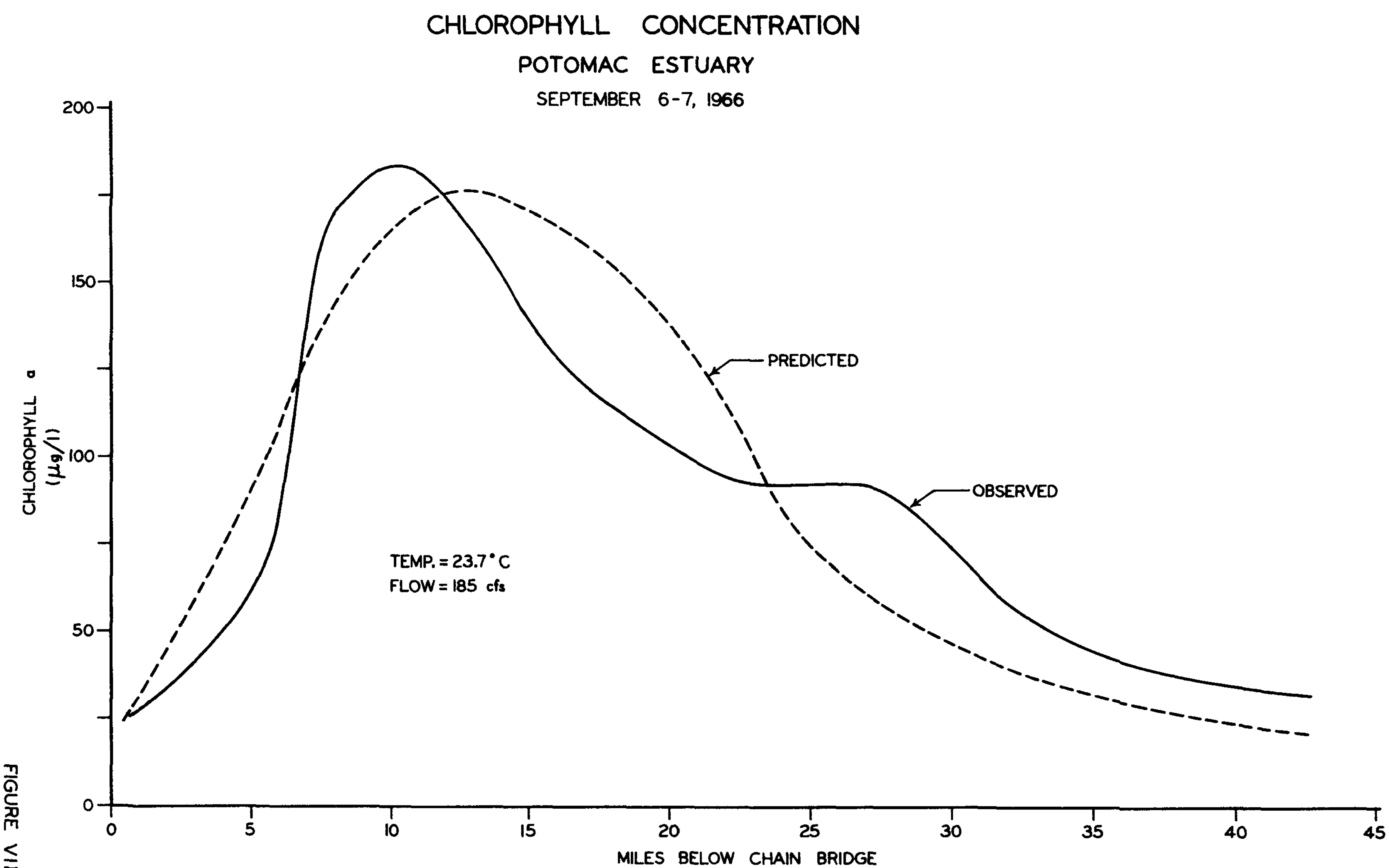

CHLOROPHYLL CONCENTRATION
POTOMAC ESTUARY
SEPTEMBER 6-7, 1966
CHLOROPHYLL a (μg/l)
200
150
100
50
0
PREDICTED
OBSERVED
TEMP. = 23.7° C
FLOW = 185 cfs
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VII-3

5. Comparison With a Less-Stressed Estuary

To investigate further the nutrient requirements for algal growth, seven sampling cruises of the upper 30 miles of the Rappahannock Estuary were made in 1970. As shown in Table VII-4, the estuary contains relatively high concentrations of both organic and inorganic carbon with low nitrates and inorganic phosphates. This is due in part to an industrial discharge which is low in nitrogen and phosphorus but high in organic carbon. The data suggest that if inorganic phosphate is approximately 0.1 to 0.2 mg/l and $NO_2$ + $NO_3$ between 0.1 to 0.3 mg/l, the standing crop of algae will be minimal with a chlorophyll a concentration of less than 40.0 ug/l.

Table VII-4

SUMMARY DATA
Upper Rappahannock Estuary
1970

| Date | Inorganic P as $PO_4$ (mg/l) | $NO_2$ + $NO_3$ (mg/l) | Chloro <u>a</u> (ug/l) | Organic Carbon (mg/l) | Inorganic Carbon (mg/l) |
|---|---|---|---|---|---|
| 6-23 | 0.13 | 0.26 | 32 | 7.3 | No Data |
| 6-30 | 0.18 | 0.12 | 34 | No Data | No Data |
| 7-07 | 0.10 | 0.11 | 40 | No Data | No Data |
| 7-13* | 0.38 | 0.64 | 8 | 7.8 | No Data |
| 7-21 | 0.15 | 0.27 | 70 | 5.0 | 5.0 |
| 7-29 | 0.22 | 0.39 | 17 | 9.7 | 4.8 |
| 8-28 | 0.14 | 0.21 | 39 | 17.9 | No Data |

* High river discharge

6. Review of Historical Nutrient and Ecological Trends in the Potomac Estuary

As reported in Chapter V, there appears to be a definite relationship between the ecological and nutrient enrichment trends in the upper Potomac (Figure V-20). Prior to the 1920's, the phosphorus loading was 1,100 lbs/day or 4 percent of today's loading. Similarly, the nitrogen loading was 6,400 lbs/day or 10 percent of today's wastewater contribution.

The concentration in the upper estuary under summer conditions for the period before 1920 was estimated to be 0.12 to 0.20 mg/l of $PO_4$ with inorganic nitrogen ranging from 0.15 to 0.30 mg/l. With a reversion to these concentrations, not only should there be a significant reduction in the blue-green algal population, but there should also be a general reversal in the ecological community succession.

## C. CONTROLLABILITY OF VARIOUS NUTRIENTS

As discussed previously, the three major sources of nutrients in the upper estuary are ---- (1) wastewater discharges, (2) the upper basin, and (3) Washington urban and suburban drainage.

For the 7 months during which algal growths are most prolific and affected by changes in nutrient contributions, the percentages of phosphorus, nitrogen, and carbon attributable to wastewater discharges are listed below:

| Month | Mean Monthly Flow (cfs) | Percentage Currently from Wastewater Discharges Phosphorus | Nitrogen | Carbon |
|---|---|---|---|---|
| April | 20,000 | 60 | 26 | 17 |
| May | 14,500 | 67 | 36 | 20 |
| June | 8,700 | 76 | 50 | 26 |
| July | 5,500 | 83 | 63 | 33 |
| August | 6,000 | 82 | 61 | 31 |
| September | 4,700 | 84 | 66 | 35 |
| October | 6,300 | 81 | 59 | 29 |

From the above tabulations, it can readily be seen that not only can phosphorus be controlled by removal to the highest degree (percentage removal) at the wastewater treatment facility, but phosphorus can be controlled earliest in the growing season. These two aspects enhance the feasibility of phosphorus management.

While 82 to 96 percent of the phosphorus entering the upper estuary can be controlled by removal at the wastewater treatment facilities during median to low flows [52], an additional reduction of phosphorus concentration occurs during periods of high runoff within the upper estuary itself. As reported by Aalto et al [8], large quantities of phosphorus (over 100,000 lbs/day) enter the upper estuary during high-flow periods at concentrations over 0.5 mg/l (1.5 mg/l as $PO_4$) during the rising portion of the river discharge hydrograph. However, high silt concentrations also accompany high flows. Large amounts of phosphorus are sorbed upon the silt particles and removed from the water system as sedimentation occurs in the upper reach of the estuary.

Although there was some dilution of high phosphorus concentrations, the large sediment load reduced the overall phosphorus concentration by a minimum of 20 percent in the reaches upstream and downstream from the major wastewater sources [52]. This reduction during periods of high flow would tend to add to the controllability of phosphorus as tabulated earlier. The high percentage from wastewater discharges, especially during the early months of the algal growing season and the large losses to the sediments during high-flow periods made phosphorus an ideal nutrient to manage.

The tabulation also indicates that over 60 percent of the nitrogen originates in the wastewater discharges during the critical months of July through October. The previous table does not include nitrogen recruitment from the atmosphere or by either bacterial or algal fixation. Hutchinson [31] reported that about 5 lbs/acre/year of nitrogen is drawn from the atmosphere. Using this rate for the upper 60 miles of the Potomac Estuary, about 1,600 lbs/day of nitrogen is obtained from the atmosphere as compared to over 50,000 lbs/day from wastewater discharges. Thus it can be concluded that nitrogen fixation is a minor source of nitrogen in the Potomac Estuary. Extension of recent data from studies at the University of Wisconsin [53] indicate that approximately 5,000 lbs/day of nitrogen could be fixed by blue-green algae in the upper and middle reaches of the Potomac Estuary. Nevertheless, compared to all other sources, the contribution from the atmosphere including that by nitrogen fixing algae appears to be insignificant. Thus, during the summer months, algal control by management of nitrogen appears to be a feasible alternative to phosphorus control.

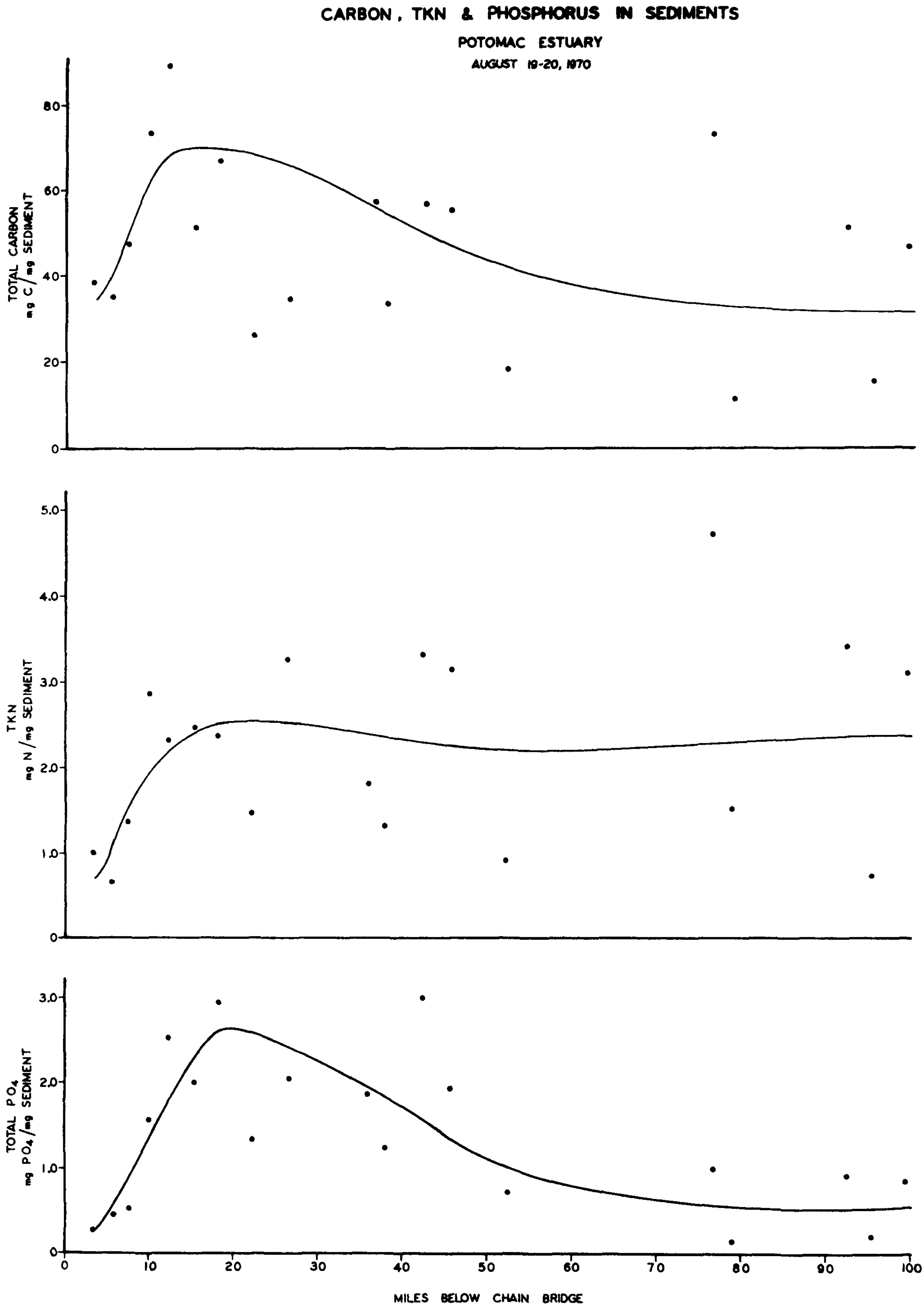
Also in the above tabulation, the maximum percentage of carbon from wastewater is 35 percent. Other major sources not included in this figure are from the atmosphere, bacterial action in water, and bacterial action in the sediments. The quantity of carbon ($CO_2$) exchanged at the air-water interface is a function of the transfer rates, concentration of $CO_2$ in the air, pH of water, and the alkalinity of the water. For the Potomac, the maximum potential $CO_2$ transfer from the atmosphere is approximately 3,500,000,000 lbs/day*. This source from the atmosphere alone makes the possibility of effective carbon control doubtful at the present time since only about 100,000 lbs/day of carbon is discharged in wastewater with over 330,000 lbs/day from the upper basin.

* The $CO_2$ obtainable from the atmosphere was determined by using a transfer rate of 0.6 $mg/cm^2/min$ [32] for an upper estuary surface area equal to $2.0 \times 10^9$ $ft^2$.

Another aspect of nutrient management is the transport and/or deposit of the various nutrients along the longitudinal profile of the estuary. Because of the great solubility in water, inorganic nitrogen and carbon are easily transported through the estuary especially during high-flow periods in the winter and spring months.

The large quantities of phosphorus and organic carbon which originate in wastewater discharges do not move as easily through the estuary. Large quantities of phosphorus and organic carbon are lost to sediments. Analysis of the sediment confirms the deposit of both carbon and phosphorus (Figure VII-4).

A review of the management requirements for the estuarine reaches was made to determine if management of any single nutrient by wastewater treatment processes can achieve the water quality standards. For the lower and middle reaches, because of the large carbon supply intrusion from the Chesapeake Bay, the management of nitrogen and phosphorus appears to be a feasible approach. Management of the upper estuary is limited primarily to nitrogen and phosphorus control except during periods of extremely low flow when it is anticipated that the estuary will be used for a supplementary water supply. When the estuary is being so used, there will be little or no freshwater inflow thus the amount of inflow from the upper basin, especially carbon, is insignificant. Under these conditions, control of all three nutrients in the wastewater treatment process is feasible.



CARBON, TKN & PHOSPHORUS IN SEDIMENTS
POTOMAC ESTUARY
AUGUST 19-20, 1970
TOTAL CARBON
mg C/mg SEDIMENT
80
60
40
20
0
TKN
mg N/mg SEDIMENT
5.0
4.0
3.0
2.0
1.0
0
TOTAL PO4
mg PO4/mg SEDIMENT
3.0
2.0
1.0
0
0
10
20
30
40
50
60
70
80
90
100
MILES BELOW CHAIN BRIDGE


FIGURE VII-4

D. NUTRIENT CRITERIA

There are no existing nutrient criteria specified by either the State of Maryland or the District of Columbia. To control algal growth, the State of Virginia has set nutrient objectives for nitrogen and phosphorus of 1.0 and 0.2 mg/l respectively in wastewater effluent. Based upon the methodology reported in the previous section, the following nutrient criteria were developed in Section VII-B with the objective of reversal of eutrophication in the freshwater portions of the Potomac Estuary:

| Parameter | Concentration Range |
|---|---|
| Inorganic Nitrogen | 0.30 - 0.5 mg/l |
| Total Phosphorus | 0.03 - 0.1 mg/l |

Since there was over 5.0 mg/l of inorganic carbon in the estuary, even under maximum bloom conditions, no criteria for carbon could be established at the present time.

The lower values in these ranges are to be applied to the freshwater portion of Zone III and to the embayment portions of the estuary in which the environmental conditions are more favorable toward algal growth. The upper ranges of the criteria are more applicable to Zone I of the Potomac Estuary which has a light-limited euphotic zone of usually less than 2 feet.

Studies of the Potomac Estuary showed a relatively sharp transition from freshwater to a typical mesohaline environment as indicated by the rapid increase in salinity. At the upper end of the 22-mile reach at Maryland Point, there are primarily freshwater phytoplankton and zooplankton populations. Above Maryland Point, the salinities are less than two parts per thousand. At low flows, marine forms dominate the lower end of the transition zone at the Route 301 Bridge with salinities in summer approximating 12 parts per thousand.

Based on the past 5 years of field studies, it appears that the growth of massive blue-green algal mats are apparently restricted to the freshwater portions. In the mesohaline environment, dinoflagellates were often encountered in "red tide" proportions.

These observations lead to two points of emphasis in estuarine water quality management:

(1) Fairly discrete biotic provinces may be identified within a given reach of the estuary, responding differently to a given stress.

(2) There is insufficient evidence to date to generalize on nutrient parameters and hypertrophic conditions in all portions of a given estuary.

Therefore, at the present time, no specific nutrient criteria have been established for the mesohaline portion of the Potomac Estuary.

These criteria, along with a high degree of carbon removal for enhancement of dissolved oxygen would not only lead to a reversal of nutrient buildup in the estuary but also creation of an environment conducive to reversal of the aquatic plant succession that has occurred in the Potomac. This reversal has occurred in the lakes surrounding Madison, Wisconsin [17] and Lake Washington [16] when wastewater discharges were diverted from the lakes.

The criteria shown above give maximum concentrations for both nitrogen and phosphorus. Limits for both were incorporated for the following reasons:

(1) Since the flow of the Potomac River is very flashy, neither phosphorus nor nitrogen can be controlled throughout the estuary at all times. To reduce eutrophication in the entire estuary for years having average or above average flow conditions, phosphorus control appears to be more feasible. However, in the middle and upper estuary during low-flow years, nitrogen control appears to be more effective. This is because the nitrogen criterion for restricting algal growth is 10 times that for phosphorus (0.30 versus 0.03 mg/l) while the nitrogen loading from the wastewater treatment facilities is 2.4 times that of phosphorus (60,000 versus 24,000 lbs/day). Considering only the magnitude of the limiting nutrient concentrations and the magnitude of the percentage of the wastewater contribution, this results in more than a fourfold advantage in removing nitrogen over that of phosphorus.

(2) Various investigators report that increases in nitrogen and/or phosphorus can increase heterotrophic activity which in turn stimulates algal growth, and

(3) There is compatibility between wastewater treatment requirements for dissolved oxygen enhancement and eutrophication control.

Compatibility of treatment requirements is probably one of the most important considerations of the four factors influencing the selection of wastewater treatment unit processes. For example, to maintain the dissolved oxygen standard in the upper estuary under summer conditions, a high degree of carbonaceous and nitrogenous oxygen demand removal is required, whereas the control of algal standing crops is predicated on phosphorus and nitrogen removal. To obtain a high degree of carbonaceous oxygen demand removal, a chemical coagulation unit process is usually required beyond secondary treatment. This unit process will also remove a high percentage of phosphorus. The removal of the nitrogenous demand can be satisfied by one of two methods: (1) by converting the unoxidized nitrogen to nitrates (commonly called nitrification), or (2) by removal of nitrogen completely. If a unit process such as biological nitrification-denitrification is employed, both the DO and algal requirements for nitrogen can be met.

Thus with proper selection of wastewater treatment unit processes, it is feasible not only to enhance the DO by removing the carbonaceous and nitrogenous UOD but also to reduce nuisance algal growth by removing nutrients.

# CHAPTER VIII

## CONTROL CONSIDERATIONS FOR BACTERIAL DENSITIES, VIRUSES, HEAVY METALS, AND OTHER WATER QUALITY PARAMETERS

### A. BACTERIAL DENSITIES

#### 1. Indicator Organisms

Four bacterial organisms have been used as indicators of the sanitary water quality of the Potomac. These four are:

(1) Total coliform,

(2) Fecal coliform,

(3) Fecal streptococci, and

(4) Salmonella.

In a 1969 report entitled "Sanitary Bacteriology of the Upper Potomac Estuary" by Lear and Jaworski [33], the following conclusions were reached:

(1) High total coliform, fecal coliform, and fecal streptococci densities were found in the Washington metropolitan area,

(2) Fecal coliform/fecal streptococci ratios indicated that most of the bacterial pollution in the upper estuary was probably of human origin,

(3) A potential health hazard existed in the Washington area in that salmonella organisms were readily and regularly isolated in waters of the estuary, and

(4) In general, greater incidence of salmonella recovery occurred in waters having high total and/or fecal coliform densities.

Data collected during 1969 [34] also reflected the earlier findings including the salmonella isolations.

As reported earlier, all discharges from wastewater facilities in the upper estuary were being chlorinated as of September 1969. This has dramatically reduced fecal coliform densities near the wastewater outfalls. However, overflows from overloaded sanitary and combined sewers still cause high fecal coliform densities as was shown in Figure V-2. These high densities are a result of overflows of untreated wastewater entering the estuary near the confluence with Rock Creek.

The complete control of bacterial densities in the upper estuary cannot be realized until both continuous chlorination of wastewater effluent is maintained and sanitary, combined and storm sewer overflows are reduced or eliminated. While the storm sewers increase bacterial indicator densities in the estuary significantly, the increased flows tend to reduce their populations by dilution and to disperse them downstream. Apparently, the more persistent bacterial problems result from overflows of the combined sewer system, especially during the summer recreation period. This becomes increasingly serious when the estuary is considered as a public water supply source.

2. Bacterial Standards

The bacterial water quality standards for the upper estuary are as given below:

| Jurisdiction | Total Coliform | Fecal Coliform |
| --- | --- | --- |
| Virginia | 2400 MPN/100 ml (monthly avg.) | 200 MPN/100 ml (30-day log mean) |
| Maryland | | 240 MPN/100 ml (by survey) |
| District of Columbia | | 1000 MPN/100 ml (geometric mean) |

For the shellfish producing area of the Potomac, a total coliform density of 70 MPN/100 ml is used by both the States of Maryland and Virginia.

B. VIRUSES

The role of water as a vector in the dissemination of viruses is not well understood. However, enteric viruses are present in sewage effluents and can find their ways into public water supplies [35].

In the Potomac Estuary, the problem of viruses and associated health hazards has three aspects that must be considered: (1) the lower portion of the estuary is a prime shellfish area, (2) the entire estuary is an ideal recreational use area, and (3) the upper estuary has been proposed as a public water supply source. While no epidemiological evidence exists relating waste discharges to the first two aspects presented, a potential hazard does exist at present and will probably become greater as the population increases.

The viral problem will be of major concern if the estuary is to be used as a water supply source. Since both wastewater effluents and overflows from storm, sanitary, and combined sewers contain viruses and do enter the estuary, the need to determine the threat to public health remains.

To evaluate this health hazard, a three-phase investigation is required to determine:

(1) The existing virus population along the longitudinal dimension of the estuary,

(2) The role of wastewater treatment facilities in removing viral particles, and

(3) The effectiveness of water treatment processes in removing viruses.

Studies regarding the viral removal effectiveness of wastewater and water supply treatment processes have been undertaken by FWQA's Advanced Waste Treatment Research Laboratory in Cincinnati, Ohio and by the U. S. Army Corps of Engineers, respectively. The FWQA studies include an investigation of the effect of advanced waste treatment processes on viruses. While a complete review is beyond the scope of this report, virus data on wastewater as reported by Berg [35] indicates that AWT units are approximately 90 percent effective in removing viruses. An evaluation of virus hazards by the American Society of Civil Engineers indicated that chlorination without reaching free chlorine residual will not insure virus free effluents [36].

As one aspect of the cooperative study with FWQA on the feasibility of the estuary as a supplemental water supply, the U. S. Army Corps of Engineers investigated the effectiveness of water supply treatment processes on virus removal. The study dealt primarily with the effectiveness of chlorination in deactivating various types of human enteric viruses.

A joint investigation by FWQA's Chesapeake Technical Support Laboratory and the Cincinnati Advanced Waste Treatment Research Laboratory to determine existing viral populations in the estuary was undertaken. Preliminary results from the first set of samples taken during the low-flow period of September 1970 for the stations presented below were negative.

| Number | Station Location |
|---|---|
| I | Great Falls at Current Water Intake |
| II | Below Chain Bridge Near Site of Proposed Intake |
| III | Near Woodrow Wilson Bridge Below Blue Plains |

This study is being continued and will be repeated under various temperature and flow conditions.

There are no water quality standards for viruses at present. Use of various indicator organisms such as coliforms have been suggested with the Bacillus subtilis spore [37] very promising as an indicator of virus disinfection.

A committee report for the American Water Works Association [38] summarized their study findings by stating: "There is no doubt that water can be treated so that it is always free from infectious micro-organisms--it will be biologically safe. Adequate treatment means clarification (coagulation, sedimentation, and filtration), followed by effective disinfection." They further concluded that there is considerable room for research, both laboratory and epidemologic, to determine if there is a problem in virus disease transmission by water.

C. HEAVY METALS

A cooperative program with the laboratory at the U. S. Naval Ordnance Station in Indian Head, Maryland, to determine periodically the heavy metal occurrence in the Potomac Estuary waters and sediments was initiated during the summer of 1970. While only small concentrations of zinc and manganese were detected in the overlying waters of the estuary, considerable amounts of various heavy metals by acid extraction from the sediments were recorded.

From the sediment analysis (Table VIII-1), it can be seen that there are significant increases of lead, cobalt, chromium, cadmium, copper, nickel, zinc, silver, and barium in the upper estuary near the Woodrow Wilson Bridge. Since concentrations of metal are greatest near the sewage outfalls where other components of wastewater such as phosphorus and carbon are also highly concentrated, it can be concluded that the heavy metals originate in the wastewater discharges. Some accumulations such as cadmium could also be from urban and suburban runoff.

The effect of these heavy metal accumulations on the ecology of the estuary is indeterminate. Since the lower estuary is a prime shellfish production area, a study of the possible availability and effects of the apparently small but continuous discharges of heavy metals on the water quality and biota should be undertaken. With wastewater loadings projected to increase over fourfold and with increases in the number of discharge points farther down the estuary, this heavy metal accumulation could develop into a serious water quality management problem.

Heavy metals in the sediments must also be considered in the disposal of dredged spoil. Dredging operations involving deepening and widening of the channels near Washington, construction of piers and marinas, etc. disturb the sediments and require disposal of the dredged spoil. These activities should also be monitored especially where there are known high concentrations of potentially toxic metals in the sediments.

TABLE VIII-1

Heavy Metal Analvses of Sediment Samples August 18-20, 1970

Potomac Estuary

| LOCATION | Pb ppm | Cd ppm | Co ppm | Cr ppm | Cu ppm | Mn ppm | Ni ppm | Zn ppm | Ca ppm | Mg ppm | K ppm | Fe % | Ag ppm | Li ppm | Ba ppm | V ppm | Al % | Sr ppm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Key Bridge | 33.95 | 0.20 | 9.96 | 21.90 | 11.95 | 438.1 | 21.9 | 114.5 | 563 | 4047.2 | 49.8 | 1.792 | 0.6 | 10.0 | 54 | Θ | 0.946 | 6.2 |
| 14th Street Bridge | 49.74 | Θ | 17.91 | 21.88 | 29.84 | 741.1 | 37.8 | 203.9 | 876 | 4829.5 | 129.3 | 2.736 | 1.4 | 15.1 | 96 | 30 | 1.343 | 9.4 |
| Haines Point | 61.88 | 0.60 | 19.96 | 37.93 | 33.93 | 823.4 | 37.9 | 244.5 | 878 | 4940.2 | 159.7 | 2.844 | 1.2 | 15.8 | 102 | 38 | 1.397 | 14.6 |
| Bellevue | 62.76 | 0.59 | 23.53 | 64.72 | 56.87 | 1029.6 | 43.1 | 318.7 | 495 | 4971.4 | 191.2 | 4.216 | 3.7 | 26.1 | 147 | 49 | 2.599 | 15.9 |
| W. Wilson Bridge | 85.83 | 0.40 | 25.95 | 75.85 | 61.88 | 1312.4 | 37.9 | 349.3 | 644 | 4945.0 | 119.8 | 4.241 | 6.4 | 23.0 | 178 | 42 | 2.096 | 14.2 |
| Broad Creek | 49.88 | Θ | 23.93 | 45.87 | 47.86 | 1740.0 | 37.9 | 269.2 | 1720 | 4826.2 | 99.7 | 3.739 | 3.2 | 17.8 | 114 | 36 | 1.645 | 10.0 |
| Piscataway Creek | 51.86 | Θ | 19.95 | 49.86 | 63.82 | 1645.5 | 47.9 | 279.2 | 439 | 4841.7 | 99.7 | 3.989 | 3.2 | 19.8 | 128 | 28 | 1.845 | 8.0 |
| Dogue Creek | 33.62 | Θ | 17.80 | 27.69 | 45.49 | 1473.1 | 19.8 | 222.5 | 406 | 4415.0 | 64.3 | 2.917 | 2.0 | 12.3 | 83 | 2 | 1.335 | 12.9 |
| Hallowing Point | 35.96 | Θ | 15.98 | 25.97 | 41.96 | 1353.6 | 22.0 | 219.8 | 400 | 4280.5 | 40.0 | 2.697 | 3.6 | 9.6 | 86 | 22 | 1.099 | 12.6 |
| Indian Head | 35.89 | Θ | 13.96 | 25.92 | 45.87 | 1580.4 | 18.0 | 239.3 | 489 | 4088.0 | 24.9 | 2.543 | 3.2 | 7.2 | 88 | 16 | 0.947 | 12.8 |
| Possum Point | 35.78 | Θ | 17.89 | 25.84 | 47.71 | 1709.7 | 23.9 | 258.4 | 393 | 4696.7 | 69.6 | 3.678 | 2.8 | 15.3 | 88 | 30 | 1.441 | 15.9 |
| Sandy Point | 35.71 | Θ | 17.85 | 31.74 | 47.61 | 2539.0 | 27.8 | 277.7 | 1949 | 4691.2 | 74.4 | 3.868 | 2.4 | 16.5 | 107 | 14 | 1.587 | 28.8 |
| Smith Point | 35.95 | Θ | 19.97 | 29.96 | 37.95 | 3225.6 | 36.0 | 244.7 | 170 | 4968.2 | 109.9 | 4.045 | 1.8 | 21.8 | 86 | 18 | 1.648 | 27.6 |
| Maryland Point | 42.66 | Θ | 19.39 | 29.08 | 50.41 | 2060.1 | 29.1 | 290.8 | 92 | 4798.9 | 116.3 | 4.217 | 2.1 | 21.5 | 66 | 19 | 1.697 | 19.0 |
| Kettle Bottom Shoals | 31.85 | Θ | 13.93 | 21.90 | 35.83 | 766.4 | 21.9 | 184.1 | 130 | 4811.5 | 189.1 | 3.185 | 1.0 | 18.7 | 26 | 18 | 1.543 | 18.5 |
| Mouth of Wicomoco River | 7.99 | Θ | 3.99 | 5.99 | 7.99 | 104.8 | 4.0 | 64.9 | 929 | 2026.6 | 15.0 | 0.899 | 1.4 | 5.0 | 10 | Θ | 0.749 | 10.4 |
| Kingopisco River | 19.88 | Θ | 7.95 | 15.91 | 25.85 | 457.3 | 19.9 | 208.8 | 948 | 4817.1 | 169.0 | 2.734 | 0.4 | 17.3 | 16 | 14 | 1.342 | 38.2 |
| Ragged Point | 19.80 | Θ | 9.90 | 15.84 | 39.59 | 623.6 | 25.7 | 183.1 | 248 | 4850.2 | 217.8 | 3.019 | Θ | 16.2 | 18 | 24 | 1.386 | 18.6 |
| Piney Point | Θ | Θ | 5.93 | 5.93 | 7.90 | 74.1 | 4.0 | 54.3 | 40 | 2404.8 | 19.8 | 0.741 | Θ | 3.4 | 4 | 10 | 0.790 | 1.6 |

Θ = Concentration below detection limit.

Mo ppm, Se ppm, As ppm undetectable.

## D. OTHER WATER QUALITY INDICATORS

Other water quality parameters are temperature, color, odor, taste, total dissolved solids, carbon chloroform extractions, pesticides, and herbicides.

### 1. Thermal

The most pronounced effect of thermal discharges on elevation of ambient water temperature can be found in the reach of the Potomac between Hains Point and Woodrow Wilson Bridge and in the Anacostia River near the Benning and East Capitol Street Bridges. Of these two areas, the rise in the Anacostia is the greatest with a 5-degree rise occurring above the ambient water temperature, reaching a high of 33°C.

Since the two areas periodically contain low dissolved oxygen concentrations, the effect of the elevated temperature is difficult to assess. Future thermal control may be required to provide a more favorable environment for aquatic life and to enhance dissolved oxygen when the wastewater plants are upgraded and the overflows from combined sewers are eliminated.

### 2. Carbon Chloroform Extraction

Using carbon chloroform extraction (CCE) as an indicator of potentially toxic organic materials, it can be seen in Figure VIII-1 that there is a significant increase in the waters between Great Falls and Memorial Bridge upstream from the combined sewer overflow discharges. At times, the relative increase is high, approximately 400 ug/l or 0.4 mg/l, twice the recommended standard for CCE.

## CARBON CHLOROFORM EXTRACT
### POTOMAC ESTUARY
### 1963 – 1968

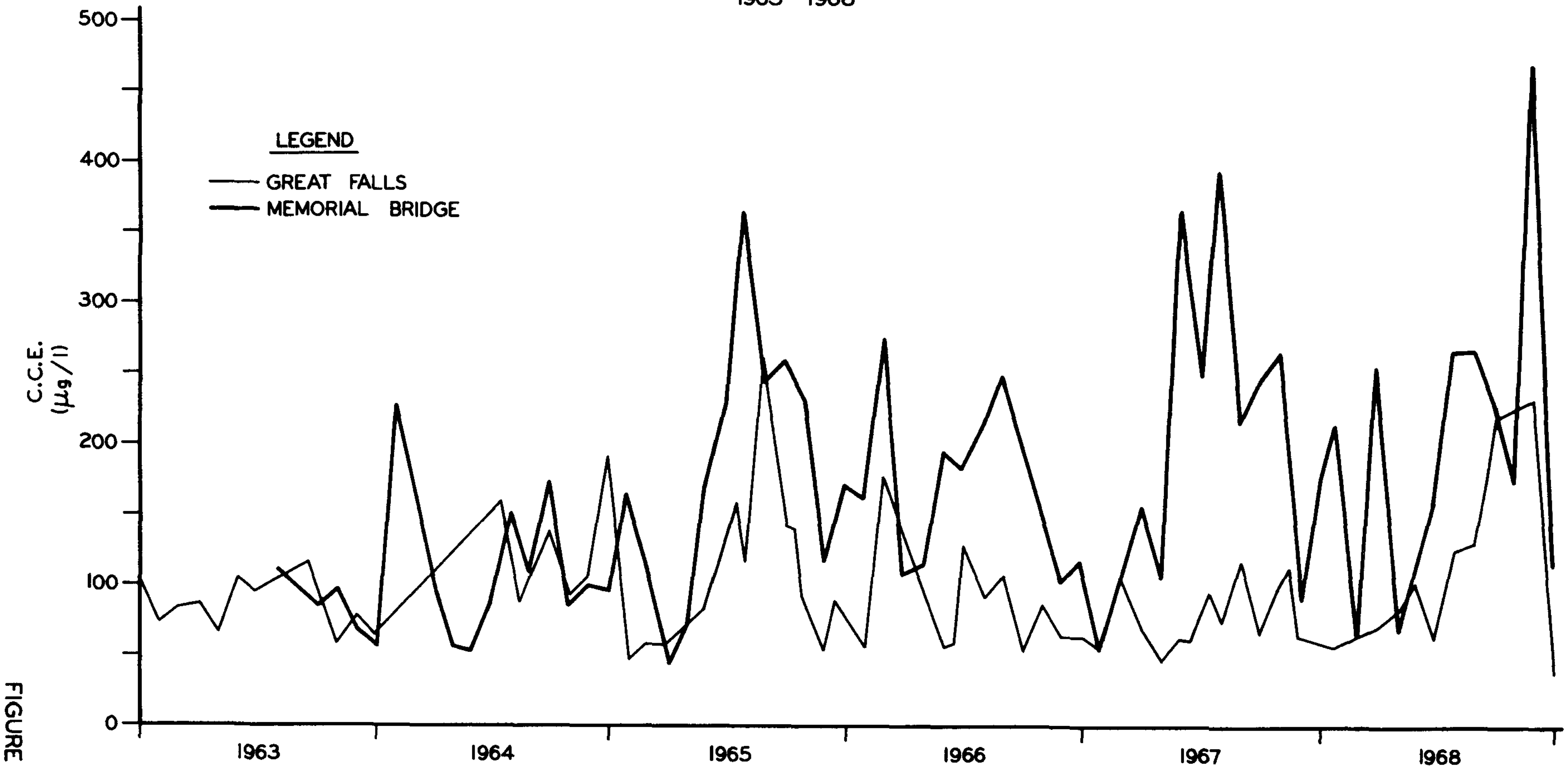



FIGURE VIII - I

If the estuary is to be used for a water supply, a more detailed analysis of CCE should be undertaken. A study of the effects of water supply withdrawals on CCE should also be initiated.

3. Chlorides and Total Dissolved Solids

Of the remaining parameters, increases in total dissolved solids and chlorides are major considerations in the use of the estuary as a water supply. The concentrations of total dissolved solids and chlorides at the proposed intake are functions of concentrations in the freshwater flow, location of the salt wedge, and total increase of each parameter resulting from water treatment, domestic use, and waste treatment. Water quality simulations for both parameters were made using the FWQA Dynamic Estuary Mathematical Model.

To demonstrate the model's capability to simulate changing salinity conditions in the estuary, a test condition was selected for which sufficient data were available to establish the salinity gradient through the system at two different points in time. An historic period (July through December 1965) was selected for which flow conditions in the prototype were relatively uniform throughout the period. The mean Potomac River flow over Great Falls remained near 1300 cfs with the mean monthly flows varying between 1018 and 1586 cfs during this period.

Chloride and salinity data were available to establish the salt wedge position in the main stem of the Potomac near the start of this period (July 7-8, 1965) and near the end (December 1-2, 1965). These data were utilized to establish visually the "best fit" profiles for these two points in time as illustrated in Figure VIII-2.

The profile for July 7-8, 1965, was specified as the initial profile in the model. For the simulation, the network extended to Piney Point near River Mile 96. The specified chloride concentration at the seaward boundary was changed during the simulation in correspondence to the change noted in the prototype during the same period, i.e., the concentration was increased from 8400 mg/l to 10930 mg/l in small steps (increased 55 mg/l every 3 days). A uniform flow of 1300 cfs in the Potomac River was maintained throughout the simulation.

The chloride profile predicted by the mathematical model after the 147 day simulation period is also illustrated in Figure VIII-2 along with that measured in the estuary. The predicted and observed profiles, which overlap, indicate that the model can accurately simulate the intrusion of chloride from the Chesapeake Bay.

The simulation was completed utilizing a dispersion coefficient ranging from approximately 0.5 square miles per day (175 square feet per second) in the upper 55 miles of the estuary, 5.0 square miles per day (1600 $ft^2$/sec) in the next 15 miles, and 12.5 $mi^2$/day (4000 $ft^2$/sec) in the lower 26 miles of the estuary. These coefficients are of the order of magnitude suggested by Harleman [49] for the freshwater and salinity incursion zones, respectively, of estuary. These coefficients were utilized for the chloride and TDS simulations presented later in this report.

# CHLORIDE CONCENTRATION

## POTOMAC ESTUARY

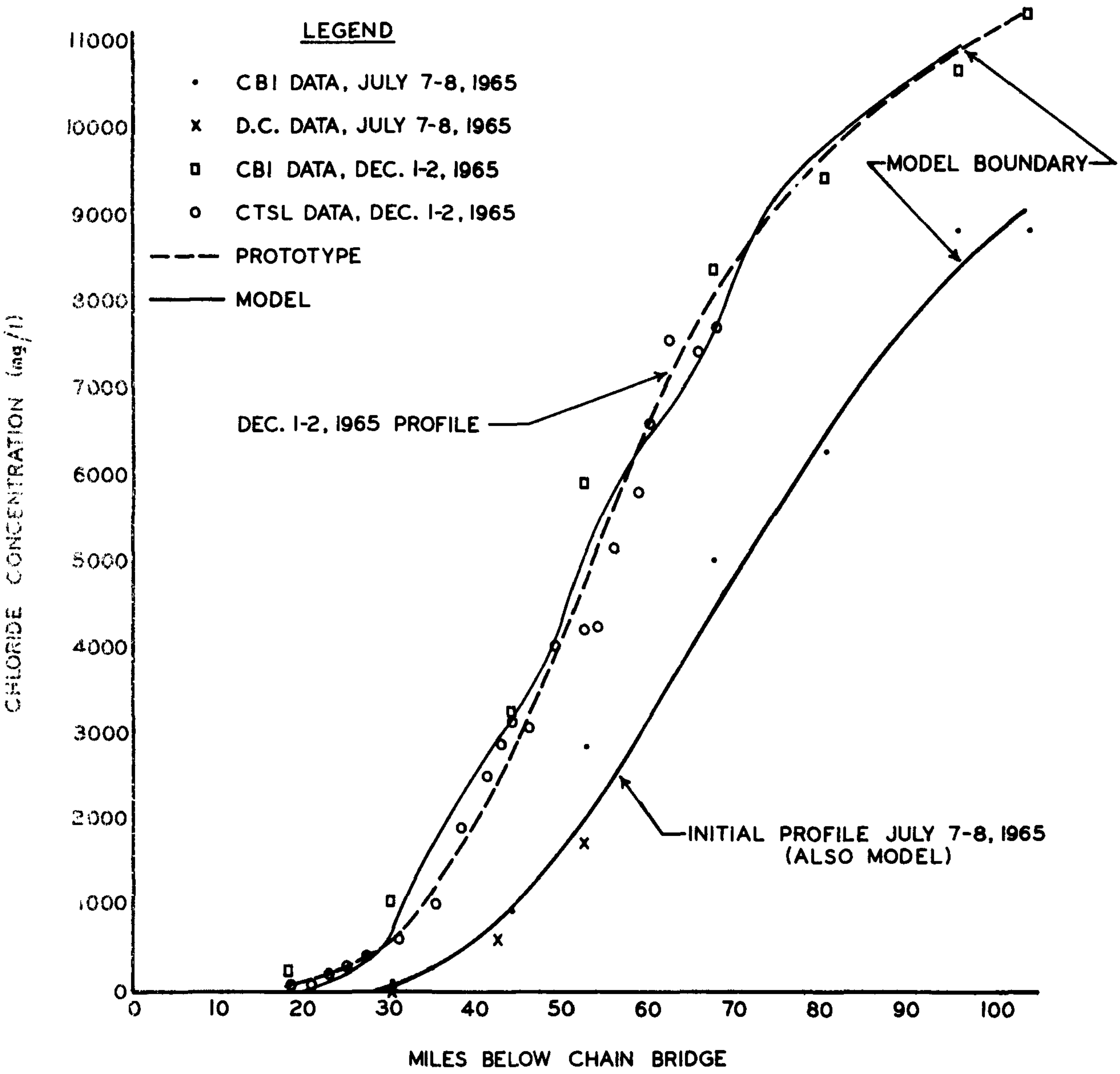



FIGURE VIII-2

4. Pesticides and Herbicides

Samples taken from six points in the Potomac Estuary were analyzed for 12 hydrocarbon pesticides in August 1969. None of these compounds were found at detectable concentrations in the samples nor in a 24-hour composite sample taken from the Blue Plains Sewage Treatment Plant effluent [34]. Since there is considerable agricultural use of pesticides and herbicides within the Potomac River Basin at certain times of the year, further EPA surveys to include those seasons of use are indicated as well as a data search of investigations by other agencies.

# CHAPTER IX

# POPULATION AND WASTEWATER PROJECTIONS

## A. POPULATION PROJECTIONS

To facilitate the determination of wastewater loading rates and water supply requirements for the entire Washington metropolitan area, population projections were developed for 13 service areas. Delineation of watersheds within each service area is presented in Table IX-1.

Population data for the Virginia and Maryland portions of the Washington metropolitan area along with the District of Columbia are shown in Figure IX-2 for the three benchmarks investigated. Summarized below are the total population projections for the Washington metropolitan area:

| Year | Population |
|---|---|
| 1969 | 2,800,000 |
| 1980 | 4,000,000 |
| 2000 | 6,700,000 |
| 2020 | 9,300,000 |

Population projections for the benchmark years of 1980 and 2000 were furnished by the Metropolitan Washington Council of Governments (COG). Control populations for these benchmarks were based on the "low-estimate" figures prepared for COG by Hammer, Green, Siler Associates [39]. Distribution by individual service areas was essentially determined from 1960-1968 population trends with consideration

Table IX-1
DATA SUMMARY
FACILITY SERVICE AREAS

| Number | Service Area | State | Watersheds |
|---|---|---|---|
| I | Upper Potomac | Virginia | Goose Creek, Broad Run, Sugarland Run, Nichols Run, Ponds Branch, Mine Run, Mine Run, Difficult Run |
| II | Upper Potomac | Maryland | Upper County, Seneca Creek, Muddy Branch, Cabin John, Rock Run |
| III | Rock Creek | Maryland | Rock Creek |
| IV | Pentagon | Virginia | Pentagon |
| V | Anacostia Valley | Maryland | Anacostia River |
| VI | Arlington | Virginia | Arlington (Pimmit and Four Mile Runs) |
| VII | District of Columbia | - | District of Columbia, Oxon Run |
| VIII | Alexandria | Virginia | Alexandria |
| VIII-A | Cameron Run and Belle Haven | Virginia | Cameron Run and Belle Haven |
| IX | Piscataway | Maryland | Piscataway Creek, Swan Creek, Henson Creek, Andrews Air Force Base |
| X | Lower Potomac | Virginia | Accotink Creek, Pohick Creek, Dogue Creek, Little Hunting Creek, Fort Belvoir |
| XI | Mattawoman | Maryland | Mattawoman Creek (Prince George's County), Mattawoman Creek (Charles County), Indian Head Naval Station |
| XII | Occoquan | Virginia | Lorton, Occoquan Tributaries (Fairfax County), Occoquan Tributaries (Prince William County), Marumsco Creek, Neabsco Creek, Powell Creek, Quantico Creek, Quantico Marine Base |

given to land use potential and other attenuating factors. A similar methodology was employed by FWQA's Middle Atlantic Region economists to develop population estimates for the year 2020 benchmark except that the control figure was derived from a long-term relationship of national, regional, and metropolitan area population trends.

# WASTEWATER SERVICE AREAS
## WASHINGTON METROPOLITAN AREA

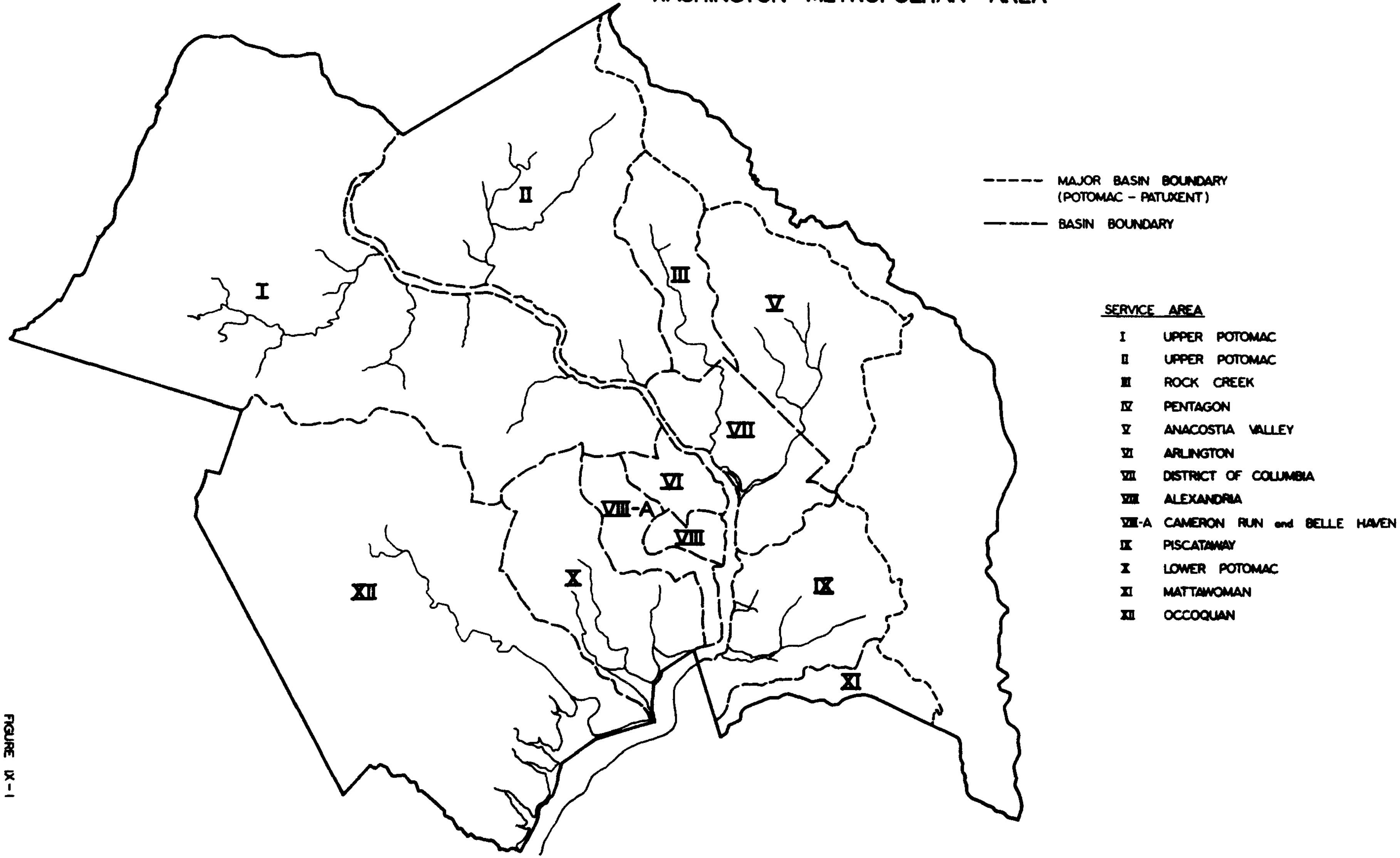
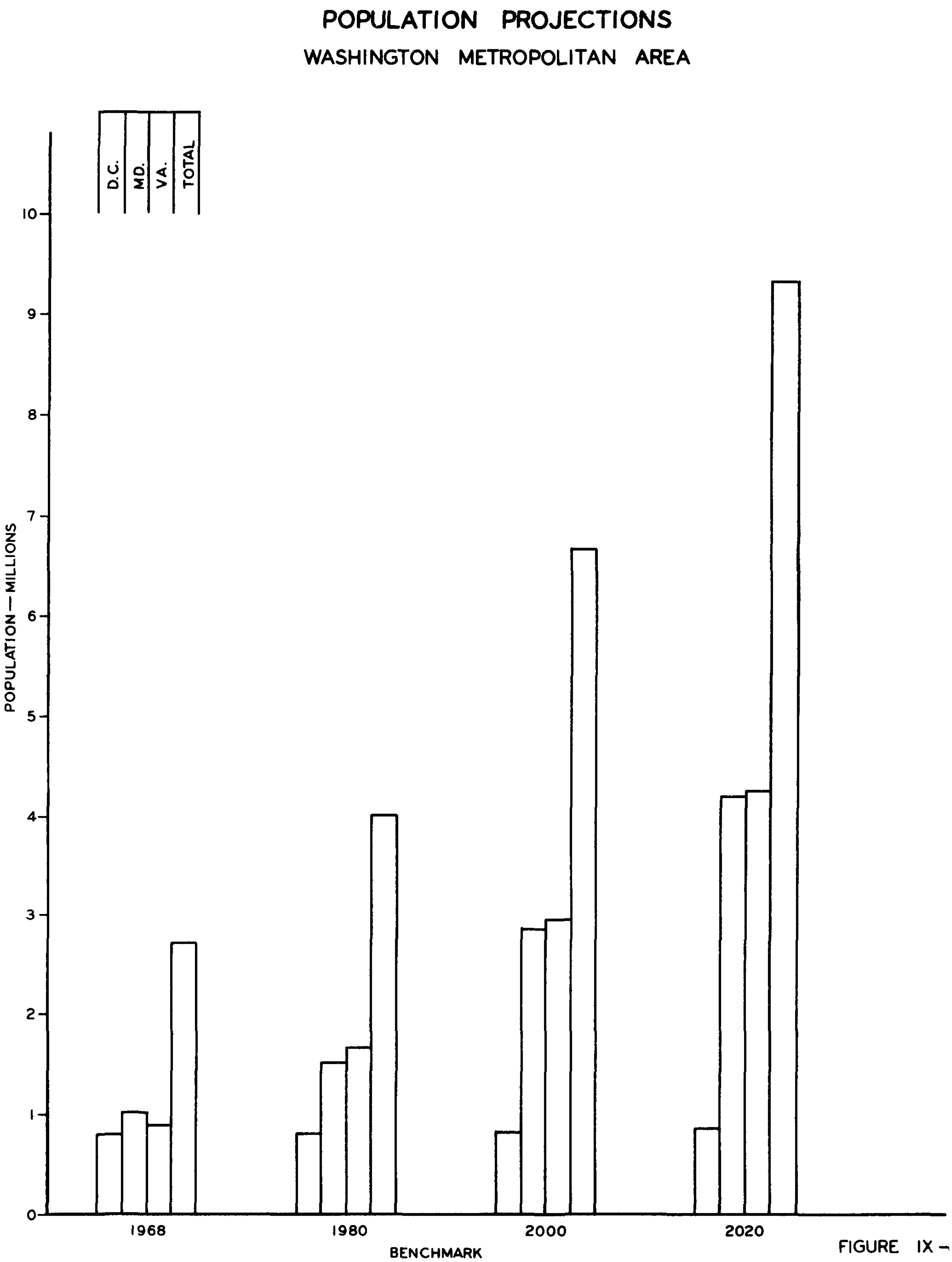



FIGURE IX-1


POPULATION PROJECTIONS
WASHINGTON METROPOLITAN AREA
D.C.
MD.
VA.
TOTAL
POPULATION — MILLIONS
0
1
2
3
4
5
6
7
8
9
10
1968
1980
2000
2020
BENCHMARK
FIGURE IX-2

B. WATER SUPPLY REQUIREMENTS

Data pertaining to current water supply demands and per capita usage were obtained from the major water suppliers in the metropolitan area and served as a baseline for the water supply projections shown in Table IX-2. The total projected average yearly water requirements for the three benchmarks are presented as follows:

| Year | Projected Usage |
|---|---|
| 1969 | 370 mgd |
| 1980 | 556 mgd |
| 2000 | 1009 mgd |
| 2020 | 1568 mgd |

Water supply requirements for shorter demand periods are delineated in Table IX-3.

The per capita water use was assumed to increase through the year 2020 at a rate of one gpcd/year. Allowing for the maximum dependable yield of other existing sources of water such as Occoquan and Goose Creeks, it appears that all of the District of Columbia's water supply and a major portion of the water supply for the metropolitan area within Virginia and Maryland must be provided by a combination of the Potomac River and the upper Potomac Estuary. Of the total projected 2020 demand, these latter sources are expected to supply approximately 1400 mgd or 90 percent. The Patuxent River currently supplies 42 mgd to the Washington metropolitan area but will be unable to serve this area in the future due to projected needs within the Patuxent Basin [40].

Table IX-2

WATER SUPPLY REQUIREMENTS
WASHINGTON METROPOLITAN AREA

| | Present (1969) | | | 1980 | | | 2000 | | | 2020 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Population Served | Total Water Usage (mgd) | Per Capita Water Usage (gpd) | Population Served | Per Capita Water Usage (gpd) | Total Water Usage (mgd) | Population Served | Per Capita Water Usage (gpd) | Total Water Usage (mgd) | Population Served | Per Capita Water Usage (gpd) | Total Water Usage (mgd) |
| **District of Columbia** | 800,000 | 161.00 | 200 | 823,800 | 210 | 173.00 | 843,700 | 230 | 194.00 | 855,000 | 250 | 214.00 |
| **Maryland** | 1,100,000 | 131.00 | 120 | 1,534,000 | 130 | 199.00 | 2,863,300 | 150 | 430.00 | 4,201,700 | 170 | 714.00 |
| **Virginia** | 800,000 | 78.00 | 100 | 1,674,600 | 110 | 184.00 | 2,963,000 | 130 | 385.00 | 4,268,900 | 150 | 640.00 |
| **Totals** | 2,700,000 | 370.00 | | 4,032,400 | | 556.00 | 6,670,000 | | 1009.00 | 9,325,600 | | 1568.00 |

Table IX-3

VARIOUS WATER SUPPLY DEMANDS
Washington Metropolitan Area

| Duration | 1980 (mgd) | 2000 (mgd) | 2020 (mgd) |
|---|---|---|---|
| Maximum Day | 1,001 | 1,816 | 2,822 |
| Maximum Five Day | 950 | 1,730 | 2,680 |
| Maximum Month | 723 | 1,312 | 2,038 |
| Maximum Two Months | 712 | 1,292 | 2,007 |
| Maximum Three Months | 695 | 1,261 | 1,960 |
| Maximum Six Months | 634 | 1,150 | 1,788 |
| Yearly Average | 556 | 1,009 | 1,568 |

## C. WASTEWATER LOADINGS

Utilizing the population projections discussed previously and the current waste flows and loading rates for each existing treatment facility as shown in Table IX-4, future wastewater trends were developed for the 13 service areas comprising the Washington metropolitan area. These data are presented in Tables IX-5, IX-6, and IX-7 for 1980, 2000, and 2020 respectively. It can be seen from these tables that the BOD, nitrogen and phosphorus loadings before treatment are projected to increase drastically. The table below summarizes these loading conditions:

| | | Before Treatment | | |
|---|---|---|---|---|
| Year | Flow | $BOD_5$ (lbs/day) | TKN as N (lbs/day) | T. P as P (lbs/day) |
| 1969 | 325 | 483,500 | 63,500 | 27,300 |
| 1980 | 473 | 823,500 | 95,600 | 43,100 |
| 2000 | 861 | 1,463,500 | 155,700 | 70,300 |
| 2020 | 1342 | 2,195,000 | 215,600 | 97,400 |

Wastewater flows were adjusted upward to reflect the additional per capita water usage. Consumptive losses were maintained at approximately 14 percent. In the case of Federal installations, waste flow was computed by assuming a per capita contribution of 100 gpd. The per capita BOD load was also increased slightly in accordance with historical loading trends while current per capita nitrogen and phosphorus loadings were held constant for each of the benchmark years.

Table IX-4

PRESENT WASTEWATER LOADINGS
WASHINGTON METROPOLITAN AREA

| Facility | Average Waste Flow (mgd) | Population Served | Per Capita Waste Flow (gpd) | Untreated $BOD_5$ (lbs/day) | Per Capita $BOD_5$ Load (lbs/day) | Untreated TKN as N (lbs/day) | Per Capita TKN Load (lbs/day) | Untreated $TPO_4$ as $PO_4$ (lbs/day) | Per Capita $TPO_4$ Load (lbs/day) |
|---|---|---|---|---|---|---|---|---|---|
| Pentagon | 1.060 | 10,600* | 100 | 2,100 | 0.20 | 440 | 0.042 | 182 | 0.017 |
| Arlington | 19.390 | 247,000 | 79 | 33,500 | 0.14 | 4,800 | 0.019 | 4,575 | 0.018 |
| Sewer Overflows-D. C. | 2.516 | 18,300** | 138 | 3,740 | 0.20 | 460 | 0.025 | 645 | 0.035 |
| U. S. Naval Laboratory | 0.095 | 950* | 100 | 25 | 0.03 | 30 | 0.030 | 30 | 0.030 |
| District of Columbia | 251.660 | 1,830,000 | 138 | 373,700 | 0.20 | 46,000 | 0.025 | 64,539 | 0.035 |
| Alexandria | 23.300 | 190,000 | 123 | 38,000 | 0.20 | 4,580 | 0.024 | 6,060 | 0.031 |
| Fairfax-Westgate | 11.570 | 124,400 | 93 | 11,500 | 0.09 | 3,140 | 0.025 | 3,394 | 0.027 |
| Piscataway | 5.810 | 55,000 | 106 | 6,300 | 0.11 | 1,650 | 0.030 | 1,106 | 0.020 |
| Andrews AFB No. 1 | 0.820 | 8,200* | 100 | 1,200 | 0.15 | 70 | 0.008 | 152 | 0.018 |
| Andrews AFB No. 4 | 0.086 | 860* | 100 | 104 | 0.12 | 12 | 0.014 | 18 | 0.021 |
| Naval Comm. Station | 0.067 | 670* | 100 | 110 | 0.16 | 15 | 0.020 | 15 | 0.020 |
| Fairfax-Hunting Creek | 3.260 | 25,000 | 130 | 4,060 | 0.16 | 720 | 0.029 | 833 | 0.033 |
| Fairfax-Dogue Creek | 2.441 | 20,000 | 122 | 4,048 | 0.20 | 465 | 0.023 | 606 | 0.030 |
| Fort Belvoir No. 1 | 0.600 | 3,600 | 167 | 1,100 | 0.30 | 145 | 0.040 | 76 | 0.021 |
| Fort Belvoir No. 2 | 2.340 | 18,400 | 127 | 3,500 | 0.19 | 960 | 0.052 | 394 | 0.021 |
| Fairfax-Lower Potomac*** | - | - | - | - | - | - | - | - | - |
| Naval Ordnance Station Indian Head | | | | | | | | | |
| Site I | 0.250 | 2,500* | 100 | 155 | 0.06 | 30 | 0.012 | 50 | 0.020 |
| Site II | 0.360 | 3,600* | 100 | 355 | 0.10 | 10 | 0.003 | 30 | 0.008 |
| Site III | 0.006 | 60* | 100 | 2 | 0.03 | 2 | 0.033 | 5 | 0.083 |
| Site IV | 0.001 | 10* | 100 | 2 | 0.20 | 2 | 0.200 | 5 | 0.500 |
| TOTALS | 325.630 | 2,559,150 | | 483,501 | | 63,531 | | 82,715 | |

* Based on 100 gpcpd
** Based on dry weather flow to wastewater facility
*** Under construction

Table IX-5

1980 WASTEWATER LOADINGS
WASHINGTON METROPOLITAN AREA

| Facility | Population Served | Per Capita Waste Flow (gpd) | Average Waste Flow (mgd) | Per Capita $BOD_5$ Load (lbs/day) | Untreated $BOD_5$ (lbs/day) | Per Capita TKN Load (lbs/day) | Untreated TKN (lbs/day) | Per Capita $TPO_4$ Load (lbs/day) | Untreated $TPO_4$ (lbs/day) |
|---|---|---|---|---|---|---|---|---|---|
| Upper Potomac, Va. | 231,340 | 110 | 25.45 | 0.22 | 50,895 | 0.025 | 5,784 | 0.035 | 8,097 |
| Upper Potomac, Md. | 241,818 | 110 | 26.60 | 0.22 | 53,200 | 0.025 | 6,045 | 0.035 | 8,464 |
| Rock Creek, Md. | 232,548 | 110 | 25.58 | 0.22 | 51,161 | 0.025 | 5,814 | 0.035 | 8,139 |
| Pentagon, Va. | 10,600 | 100 | 1.06 | 0.22 | 2,332 | 0.042 | 445 | 0.017 | 180 |
| Anacostia Valley, Md. | 614,295 | 110 | 67.57 | 0.22 | 135,145 | 0.025 | 15,357 | 0.035 | 21,500 |
| Arlington, Va. | 228,000 | 100 | 22.80 | 0.20 | 45,600 | 0.020 | 4,560 | 0.030 | 6,840 |
| District of Columbia | 823,818 | 170 | 140.05 | 0.22 | 181,240 | 0.025 | 20,595 | 0.035 | 28,834 |
| Alexandria, Va. | 155,300 | 130 | 20.19 | 0.22 | 34,166 | 0.025 | 3,883 | 0.035 | 5,436 |
| Cameron Run & Bell Haven, Va. | 163,100 | 110 | 17.94 | 0.22 | 35,882 | 0.025 | 4,078 | 0.035 | 5,709 |
| Piscataway, Md. | 191,000 | 120 | 22.92 | 0.17 | 32,470 | 0.030 | 5,730 | 0.030 | 5,730 |
| Lower Potomac, Va. | 423,933 | 110 | 46.63 | 0.22 | 93,265 | 0.025 | 10,598 | 0.035 | 14,838 |
| Mattawoman, Md. | 35,032 | 110 | 3.85 | 0.22 | 7,707 | 0.025 | 876 | 0.035 | 1,226 |
| Occoquan, Va. | 411,966 | 110 | 45.32 | 0.22 | 90,633 | 0.025 | 10,299 | 0.035 | 14,419 |
| Sewer Overflows, D. C. | 10,588 | 170 | 1.80 | 0.22 | 2,329 | 0.025 | 265 | 0.035 | 371 |
| U. S. Naval Laboratory | 1,000 | 100 | 0.10 | 0.05 | 50 | 0.030 | 30 | 0.030 | 30 |
| Andrews AFB No. 1 | 9,000 | 100 | 0.90 | 0.17 | 1,530 | 0.010 | 90 | 0.020 | 180 |
| Andrews AFB No. 4 | 1,000 | 100 | 0.10 | 0.14 | 140 | 0.016 | 16 | 0.023 | 23 |
| Naval Communications Station | 700 | 100 | 0.07 | 0.18 | 126 | 0.020 | 14 | 0.020 | 14 |
| Fort Belvoir No. 1 | 4,200 | 167 | 0.70 | 0.30 | 1,260 | 0.040 | 168 | 0.020 | 84 |
| Fort Belvoir No. 2 | 18,900 | 127 | 2.40 | 0.20 | 3,780 | 0.050 | 945 | 0.020 | 378 |
| Naval Ordnance Station Indian Head | | | | | | | | | |
| Site I | 3,000 | 100 | 0.30 | 0.06 | 180 | 0.012 | 36 | 0.020 | 60 |
| Site II | 4,000 | 100 | 0.40 | 0.10 | 400 | 0.003 | 12 | 0.008 | 32 |
| Site III | 100 | 100 | 0.01 | 0.03 | 3 | 0.033 | 3 | 0.083 | 8 |
| Site IV | 10 | 100 | - | 0.20 | 2 | 0.200 | 2 | 0.500 | 5 |
| TOTALS | 3,815,248 | | 472.74 | | 823,496 | | 95,645 | | 130,597 |

Table IX-6

2000 WASTEWATER LOADINGS
WASHINGTON METROPOLITAN AREA

| Facility | Population Served | Per Capita Waste Flow (gpd) | Average Waste Flow (mgd) | Per Capita $BOD_5$ Load (lbs/day) | Untreated $BOD_5$ (lbs/day) | Per Capita TKN Load (lbs/day) | Untreated TKN (lbs/day) | Per Capita $TPO_4$ Load (lbs/day) | Untreated $TPO_4$ (lbs/day) |
|---|---|---|---|---|---|---|---|---|---|
| Upper Potomac, Va. | 412,596 | 130 | 53.64 | 0.24 | 99,023 | 0.025 | 10,315 | 0.035 | 14,441 |
| Upper Potomac, Md. | 700,000 | 130 | 91.00 | 0.24 | 168,000 | 0.025 | 17,500 | 0.035 | 24,500 |
| Rock Creek, Md. | 319,959 | 130 | 41.59 | 0.24 | 76,790 | 0.025 | 7,999 | 0.035 | 11,199 |
| Pentagon, Va. | 10,600 | 100 | 1.06 | 0.24 | 2,544 | 0.042 | 445 | 0.017 | 180 |
| Anacostia Valley, Md. | 971,175 | 130 | 126.25 | 0.24 | 233,082 | 0.025 | 24,279 | 0.035 | 33,991 |
| Arlington, Va. | 309,000 | 120 | 37.08 | 0.22 | 67,980 | 0.020 | 6,180 | 0.030 | 9,270 |
| District of Columbia | 843,724 | 190 | 160.31 | 0.24 | 202,494 | 0.025 | 21,093 | 0.035 | 29,530 |
| Alexandria, Va. | 199,900 | 150 | 29.99 | 0.24 | 47,976 | 0.025 | 4,998 | 0.035 | 6,997 |
| Cameron Run& Belle Haven, Va. | 241,800 | 130 | 31.43 | 0.24 | 58,032 | 0.025 | 6,045 | 0.035 | 8,463 |
| Piscataway, Md. | 340,000 | 140 | 47.60 | 0.19 | 64,600 | 0.030 | 10,200 | 0.030 | 10,200 |
| Lower Potomac, Va. | 769,347 | 130 | 100.02 | 0.24 | 184,643 | 0.025 | 19,234 | 0.035 | 26,927 |
| Mattawoman, Md. | 66,140 | 130 | 8.60 | 0.24 | 15,874 | 0.025 | 1,654 | 0.035 | 2,315 |
| Port Tobacco, Md. | 47,000 | 130 | 6.11 | 0.24 | 11,280 | 0.025 | 1,175 | 0.035 | 1,645 |
| Occoquan, Va. | 930,355 | 130 | 120.95 | 0.24 | 223,285 | 0.025 | 23,259 | 0.035 | 32,562 |
| Sewer Overflows, D. C. | 1,842 | 190 | 0.35 | 0.24 | 442 | 0.025 | 46 | 0.035 | 64 |
| U. S. Naval Laboratory | 1,000 | 100 | 0.10 | 0.05 | 50 | 0.030 | 30 | 0.030 | 30 |
| Andrews AFB No. 1 | 9,000 | 100 | 0.90 | 0.17 | 1,530 | 0.010 | 90 | 0.020 | 180 |
| Andrews AFB No. 4 | 1,000 | 100 | 0.10 | 0.14 | 140 | 0.016 | 16 | 0.023 | 23 |
| Naval Communications Station | 700 | 100 | 0.07 | 0.18 | 126 | 0.020 | 14 | 0.020 | 14 |
| Fort Belvoir No. 1 | 4,200 | 167 | 0.70 | 0.30 | 1,260 | 0.040 | 168 | 0.020 | 84 |
| Fort Belvoir No. 2 | 18,900 | 127 | 2.40 | 0.20 | 3,780 | 0.050 | 945 | 0.020 | 378 |
| Naval Ordnance Station Indian Head | | | | | | | | | |
| Site I | 3,000 | 100 | 0.30 | 0.06 | 180 | 0.012 | 36 | 0.020 | 60 |
| Site II | 4,000 | 100 | 0.40 | 0.10 | 400 | 0.003 | 12 | 0.008 | 32 |
| Site III | 100 | 100 | 0.01 | 0.03 | 3 | 0.033 | 3 | 0.083 | 8 |
| Site IV | 10 | 100 | - | 0.20 | 2 | 0.200 | 2 | 0.500 | 5 |
| TOTALS | 6,205,348 | | 860.96 | | 1,463,516 | | 155,738 | | 213,098 |

Table IX-7

2020 WASTEWATER LOADINGS
WASHINGTON METROPOLITAN AREA

| Facility | Population Served | Per Capita Waste Flow (gpd) | Average Waste Flow (mgd) | Per Capita $BOD_5$ Load (lbs/day) | Untreated $BOD_5$ (lbs/day) | Per Capita TKN Load (lbs/day) | Untreated TKN (lbs/day) | Per Capita $TPO_4$ Load (lbs/day) | Untreated $TPO_4$ (lbs/day) |
|---|---|---|---|---|---|---|---|---|---|
| Upper Potomac, Va. | 588,600 | 150 | 88.29 | 0.26 | 153,036 | 0.025 | 14,715 | 0.035 | 20,601 |
| Upper Potomac, Md. | 1,328,600 | 150 | 199.29 | 0.26 | 345,436 | 0.025 | 33,215 | 0.035 | 46,501 |
| Rock Creek, Md. | 341,100 | 150 | 51.17 | 0.26 | 88,686 | 0.025 | 8,528 | 0.035 | 11,939 |
| Pentagon, Va. | 10,600 | 100 | 1.06 | 0.26 | 2,756 | 0.042 | 445 | 0.017 | 180 |
| Anacostia Valley, Md. | 1,233,400 | 150 | 185.00 | 0.26 | 320,684 | 0.025 | 30,835 | 0.035 | 43,169 |
| Arlington, Va. | 320,400 | 140 | 44.86 | 0.24 | 76,896 | 0.020 | 6,408 | 0.030 | 9,612 |
| District of Columbia | 855,000 | 210 | 179.55 | 0.26 | 222,300 | 0.025 | 21,375 | 0.035 | 29,925 |
| Alexandria, Va. | 236,200 | 170 | 40.15 | 0.26 | 61,412 | 0.025 | 5,905 | 0.035 | 8,267 |
| Cameron Run & Belle Haven, Va. | 284,800 | 150 | 42.72 | 0.26 | 74,048 | 0.025 | 7,120 | 0.035 | 9,968 |
| Piscataway, Md. | 485,100 | 160 | 77.62 | 0.21 | 101,871 | 0.030 | 14,553 | 0.030 | 14,553 |
| Lower Potomac, Va. | 1,115,000 | 150 | 167.25 | 0.26 | 289,900 | 0.025 | 27,875 | 0.035 | 39,025 |
| Mattawoman, Md. | 89,100 | 150 | 13.37 | 0.26 | 23,166 | 0.025 | 2,228 | 0.035 | 3,119 |
| Port Tobacco, Md. | 75,000 | 150 | 11.25 | 0.26 | 19,500 | 0.025 | 1,875 | 0.035 | 2,625 |
| Occoquan, Va. | 1,567,900 | 150 | 235.19 | 0.26 | 407,654 | 0.025 | 39,198 | 0.035 | 54,877 |
| Sewer Overflows, D. C. | 714 | 210 | 0.15 | 0.26 | 186 | 0.025 | 18 | 0.035 | 25 |
| U. S. Naval Laboratory | 1,000 | 100 | 0.10 | 0.05 | 50 | 0.030 | 30 | 0.030 | 30 |
| Andrews AFB No. 1 | 9,000 | 100 | 0.90 | 0.17 | 1,530 | 0.010 | 90 | 0.020 | 180 |
| Andrews AFB No. 4 | 1,000 | 100 | 0.10 | 0.14 | 140 | 0.016 | 16 | 0.023 | 23 |
| Naval Communications Station | 700 | 100 | 0.07 | 0.18 | 126 | 0.020 | 14 | 0.020 | 14 |
| Fort Belvoir No. 1 | 4,200 | 167 | 0.70 | 0.30 | 1,260 | 0.040 | 168 | 0.020 | 84 |
| Fort Belvoir No. 2 | 18,900 | 127 | 2.40 | 0.20 | 3,780 | 0.050 | 945 | 0.020 | 378 |
| Naval Ordnance Station Indian Head | | | | | | | | | |
| Site I | 3,000 | 100 | 0.30 | 0.06 | 180 | 0.012 | 36 | 0.020 | 60 |
| Site II | 4,000 | 100 | 0.40 | 0.10 | 400 | 0.003 | 12 | 0.008 | 32 |
| Site III | 100 | 100 | 0.01 | 0.03 | 3 | 0.033 | 3 | 0.083 | 8 |
| Site IV | 10 | 100 | - | 0.20 | 2 | 0.200 | 2 | 0.500 | 5 |
| TOTALS | 8,573,424 | | 1341.90 | | 2,195,002 | | 215,609 | | 295,200 |

# CHAPTER X

# WATER QUALITY SIMULATIONS

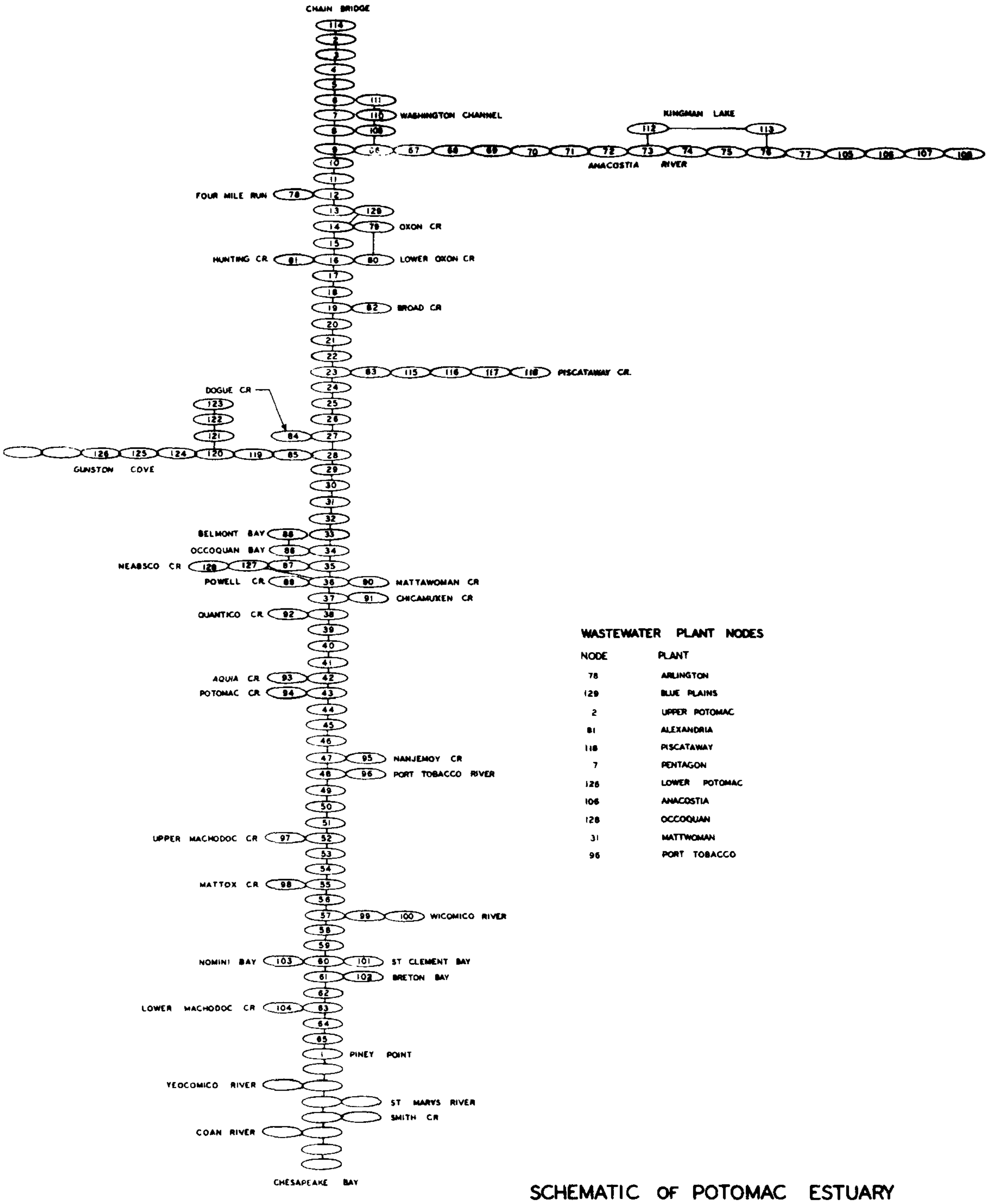
## A. WATER QUALITY SIMULATION MODELS

Water quality simulations for this report were made using the FWQA Dynamic Estuary Model (DEM) and DECS III. The DEM, which was used to evaluate allowable wastewater loadings and chloride intrusion as discussed subsequently in this chapter, is a real-time system incorporating a hydraulic component that describes tidal movement and a quality component that considers the basic transport mechanisms of advection and dispersion as well as the pertinent sources and sinks of each constituent. The ability to utilize a two-dimensional network of interconnecting junctions and channels makes it possible to include the embayments directly in the flow network. A detailed description of the model is available from FWQA [41]. DECS III is based on a time-dependent tidal average solution of the basic mass balance equations as originally developed by Thomann [54]. This model was used to investigate seasonal variations in the nitrogen and phosphorus distributions of the upper Potomac Estuary.

A study investigating the relative merits of the FWQA Dynamic Estuary Model versus the tidal average approach has been made by CTSL and a report of this investigation is currently in preparation.

A schematic diagram of the Potomac Estuary used in the Dynamic Estuary Model is given in Figure X-1. The location nodes for the existing discharges and proposed locations for future discharges are also shown in this figure. A similar segmentation of the main Potomac was also used for DECS III.

In simulating the various water quality constitutents, a water flow system as shown in Figure X-2 was incorporated into the Dynamic Estuary Model. This feature was necessary to simulate conservative constituents such as chlorides and total dissolved solids.




**WASTEWATER PLANT NODES**

| NODE | PLANT |
|---|---|
| 78 | ARLINGTON |
| 129 | BLUE PLAINS |
| 2 | UPPER POTOMAC |
| 81 | ALEXANDRIA |
| 118 | PISCATAWAY |
| 7 | PENTAGON |
| 126 | LOWER POTOMAC |
| 106 | ANACOSTIA |
| 128 | OCCOQUAN |
| 31 | MATTWOMAN |
| 96 | PORT TOBACCO |

SCHEMATIC OF POTOMAC ESTUARY
FOR FWQA DYNAMIC MODEL

FIGURE X-1

## SCHEMATIC OF WATER FLOW

### WATER QUALITY SIMULATION

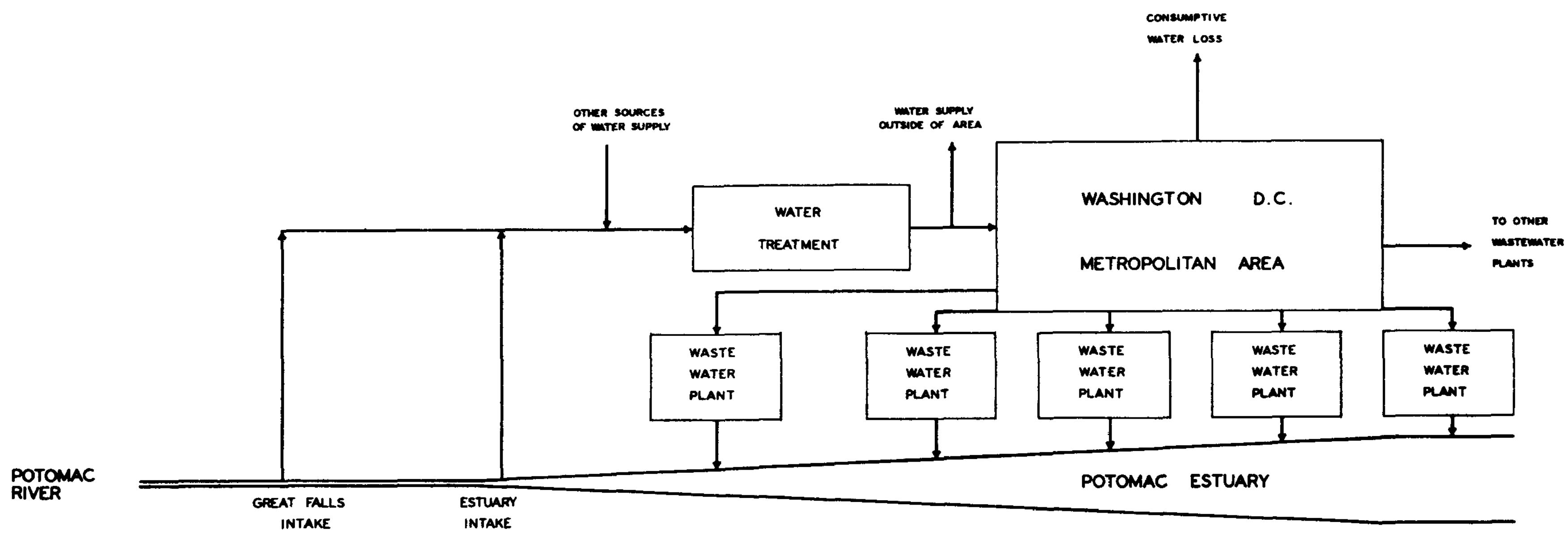



FIGURE X-2

## B. ALTERNATIVE WASTEWATER TREATMENT SYSTEMS

As shown in Figures X-3, X-4, and X-5, three basic alternative wastewater treatment systems were investigated. A fourth system, similar to Alternative III except for a facility on Rock Creek, was also investigated; however, the population projections indicated that the expanded Blue Plains, Upper Potomac, and Anacostia plants could readily serve the Rock Creek area and this alternative was subsequently omitted. Alternative discharge locations for two of the above schemes were considered in the mathematical model simulation and are presented in Figures X-6 and X-7.

Alternative I consisted of nine wastewater treatment plants in the upper Potomac Estuary. The projected waste flows for each of these facilities are shown in the following table:

Table X-1

WASTEWATER FACILITIES AND PROJECTED FLOWS
Alternative I

| Facility | 1980 (mgd) | 2000 (mgd) | 2020 (mgd) |
|---|---|---|---|
| Pentagon | 1 | 1 | 1 |
| Arlington | 23 | 37 | 45 |
| Blue Plains | 285* | 473 | 702 |
| Alexandria | 38 | 61 | 83 |
| Piscataway | 24 | 49 | 79 |
| Lower Potomac | 50 | 103 | 170 |
| Occoquan | 45 | 121 | 235 |
| Mattawoman | 5 | 9 | 13 |
| Port Tobacco | 0 | 6 | 11 |

* Proposed capacity = 309 mgd

# WASTEWATER TREATMENT SYSTEMS

## UPPER POTOMAC ESTUARY

### ALTERNATIVE I

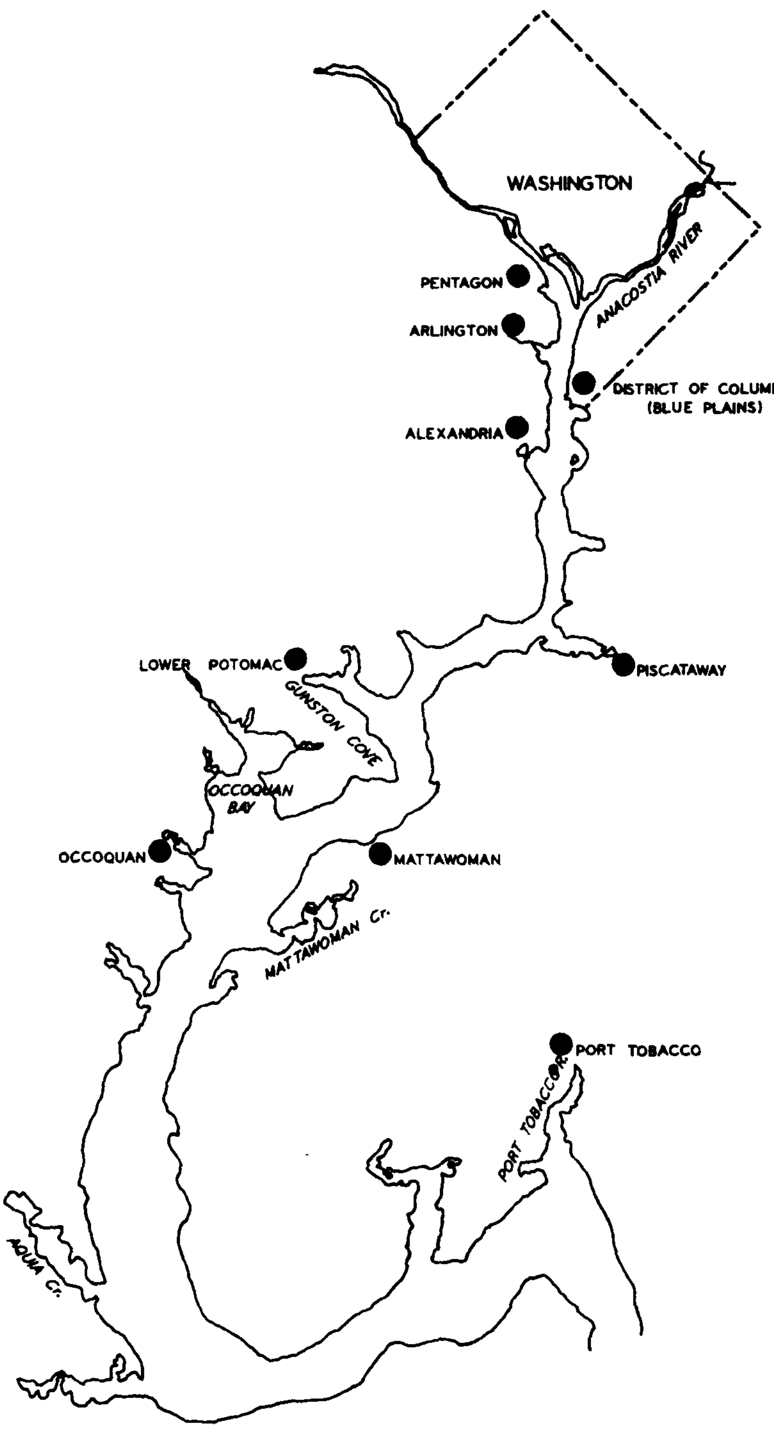



FIGURE X-3

# WASTEWATER TREATMENT SYSTEMS

## UPPER POTOMAC ESTUARY

### ALTERNATIVE II

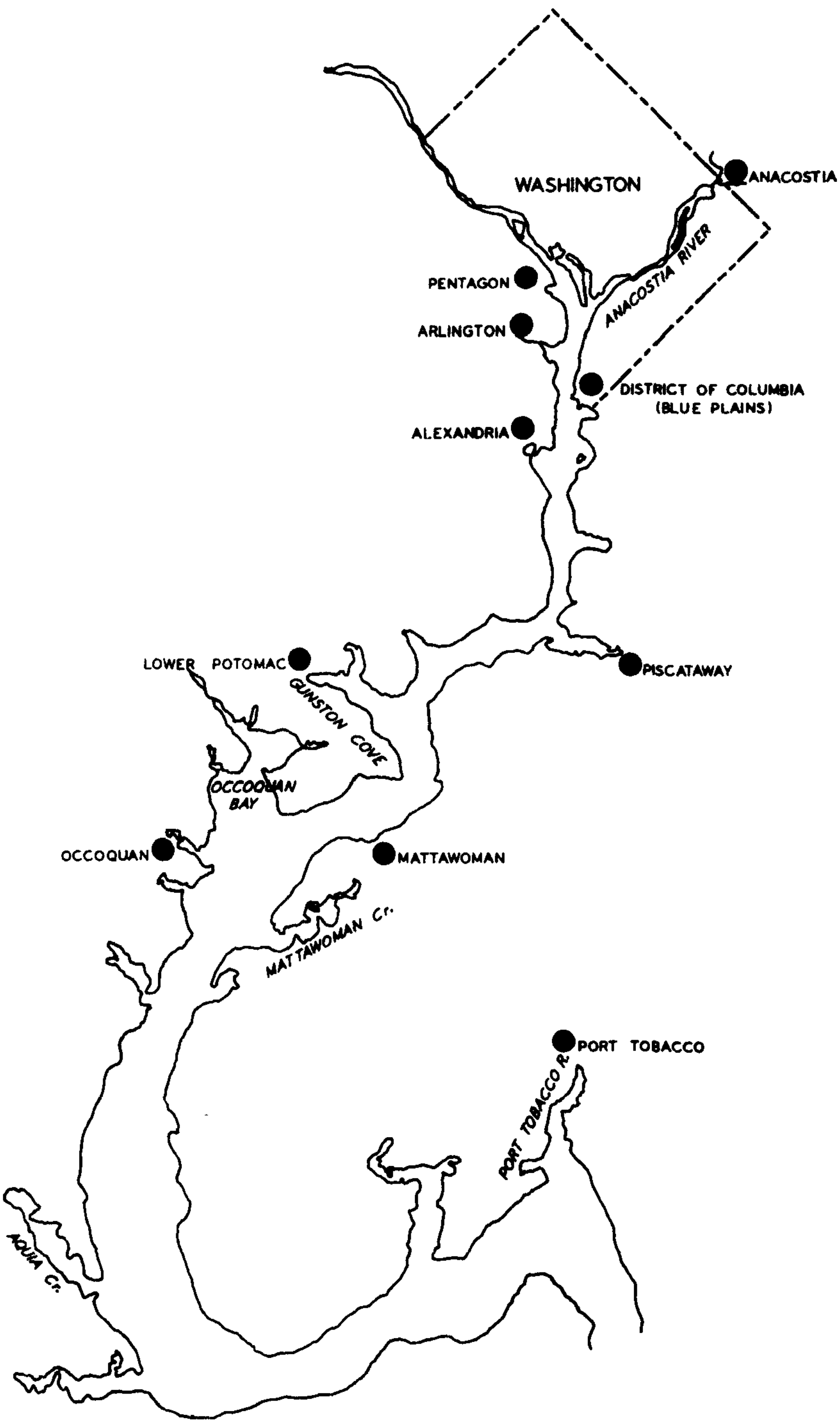



FIGURE X-4

# WASTEWATER TREATMENT SYSTEMS

## UPPER POTOMAC ESTUARY

### ALTERNATIVE III

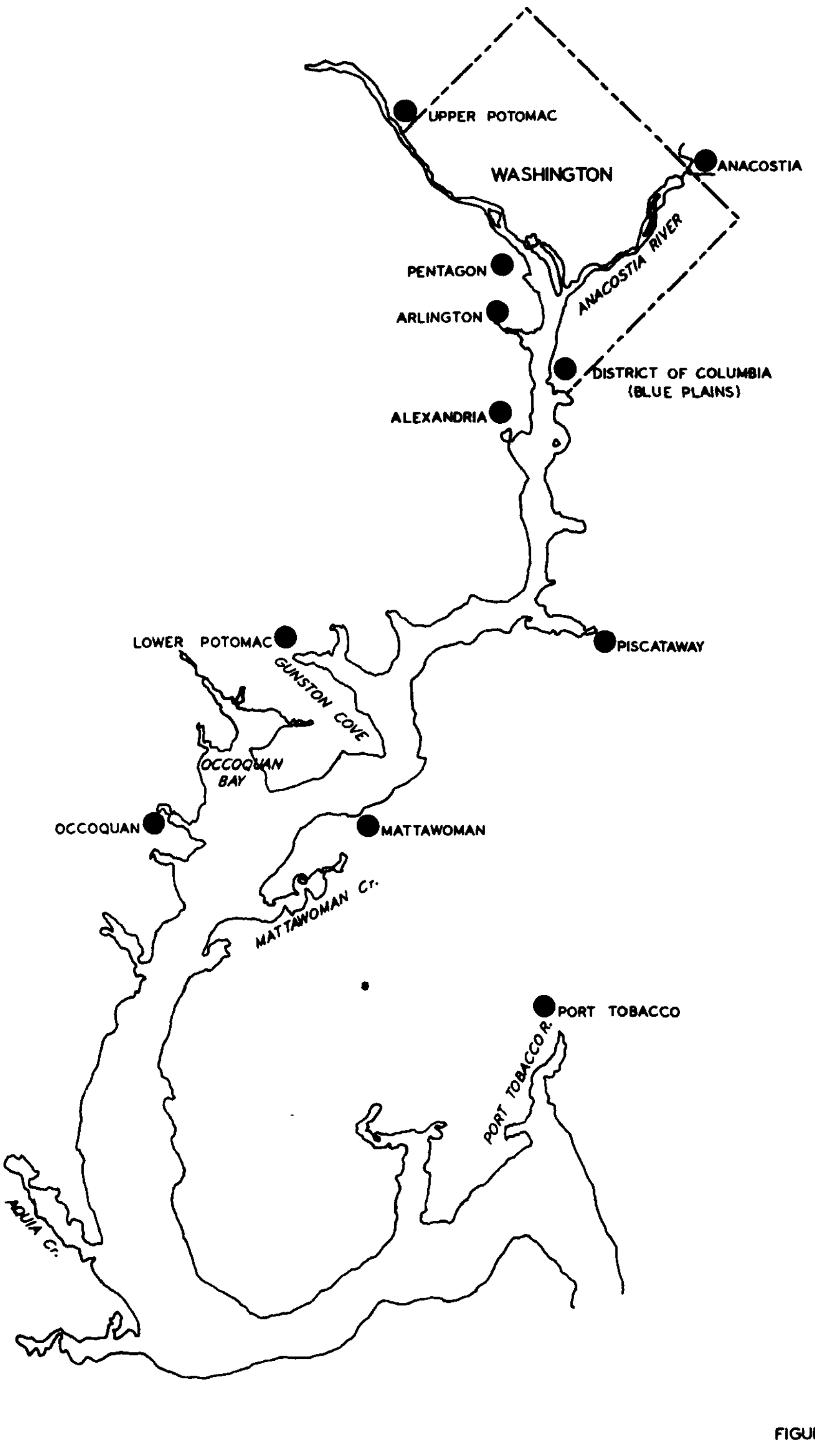



FIGURE X-5

# WASTEWATER TREATMENT SYSTEMS

## UPPER POTOMAC ESTUARY

### ALTERNATIVE IV

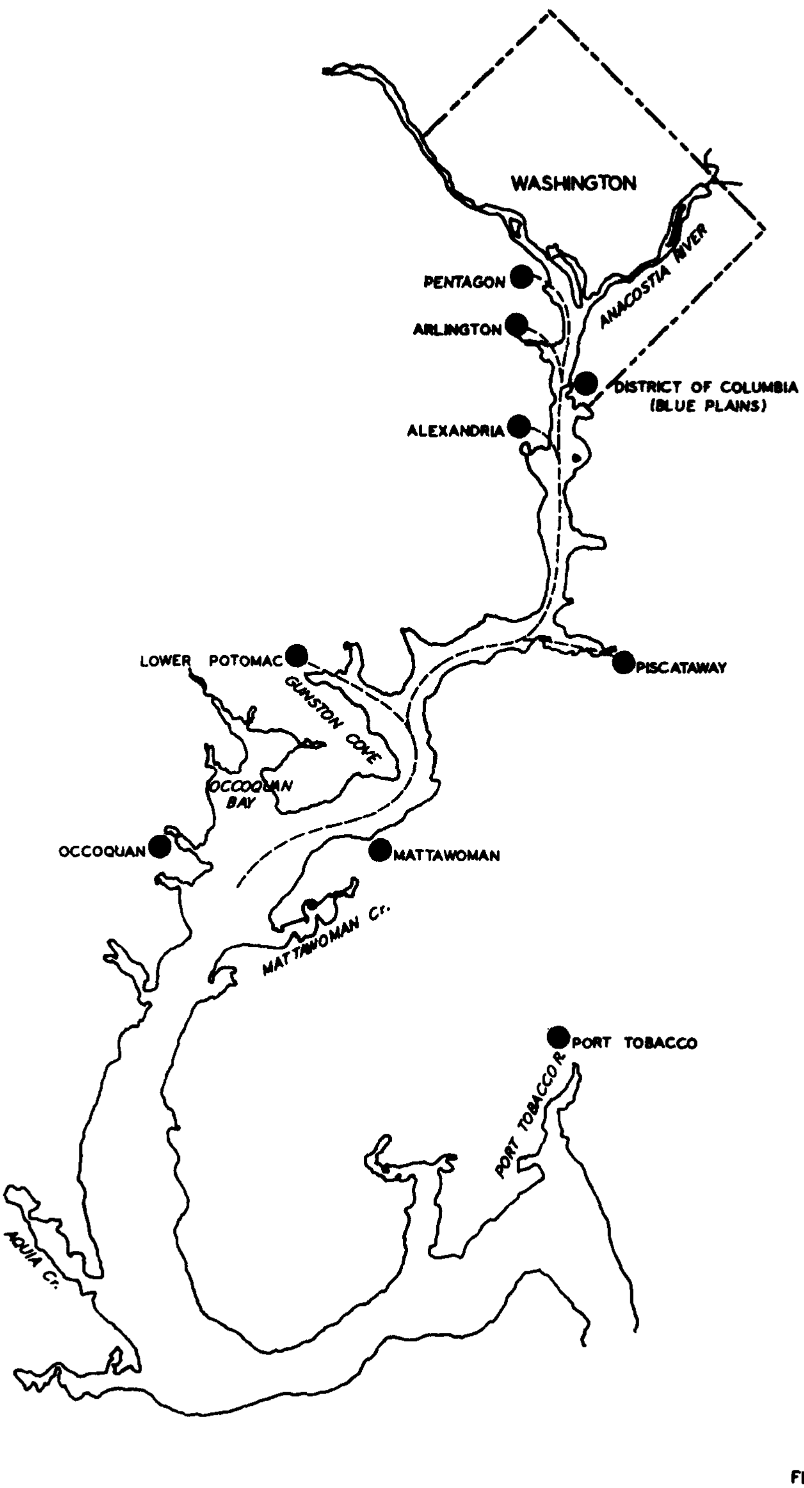



FIGURE X-6

# WASTEWATER TREATMENT SYSTEMS

## UPPER POTOMAC ESTUARY

### ALTERNATIVE V

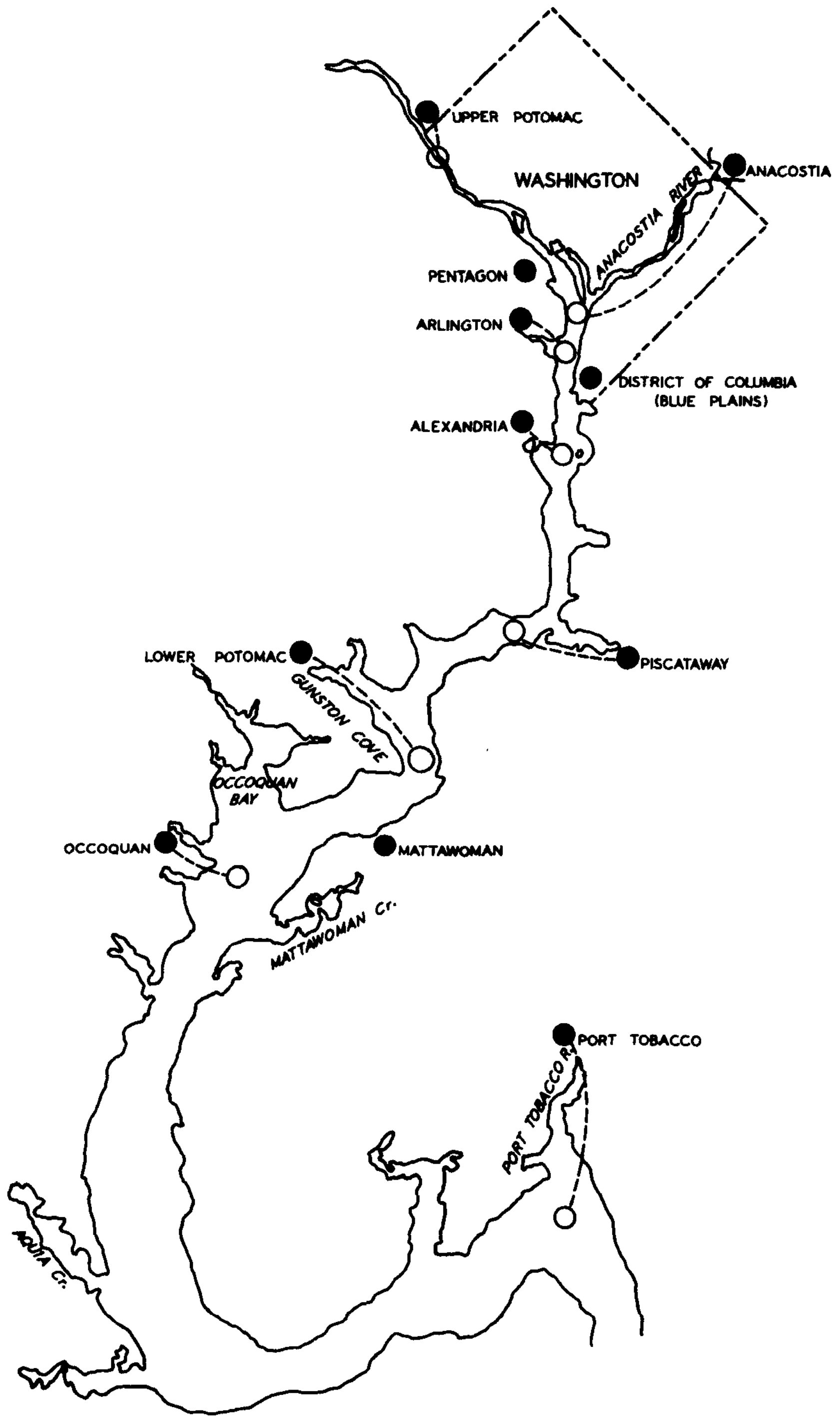



FIGURE X-7

Under Alternative I, the District of Columbia's Blue Plains facility will also serve the upper Potomac area within Virginia and Maryland, the Anacostia Valley, and the Rock Creek Basin. In this alternative, it is assumed that the expansion at Blue Plains is not restricted. In all three alternatives, Alexandria's facility will also serve the Cameron Run and Belle Haven areas, Piscataway will serve Andrews Air Force Base, and the Lower Potomac plant will serve Fort Belvoir. The existing Fairfax Dogue and Little Hunting Creek plants are to be abandoned and the waste transported to the Lower Potomac facility.

Alternative II was identical to Alternative I except that a wastewater plant was assumed on the Anacostia River. This facility will only serve the Anacostia Valley. It was also assumed that the Blue Plains treatment plant would be expanded to accomodate the remainder of the flow. The facilities and wastewater flows associated with Alternative II are shown in Table X-2.

Table X-3 shows wastewater facility data corresponding to Alternative III which assumes another plant built in 1980 to serve the upper Potomac area. In Alternative III, the maximum size of Blue Plains is limited to 309 mgd. The Anacostia facility would serve the Anacostia Valley and the remainder of the flow shown as transported to Blue Plains in the first two alternatives would be conveyed to the upper Potomac plant.

Table X-2

WASTEWATER FACILITIES AND PROJECTED FLOWS
Alternative II

| Facility | 1980 (mgd) | 2000 (mgd) | 2020 (mgd) |
|---|---|---|---|
| Pentagon | 1 | 1 | 1 |
| Arlington | 23 | 37 | 45 |
| Anacostia | 0 | 126 | 185 |
| Blue Plains | 285* | 347 | 518 |
| Alexandria | 38 | 61 | 83 |
| Piscataway | 24 | 49 | 79 |
| Lower Potomac | 50 | 103 | 170 |
| Occoquan | 45 | 121 | 235 |
| Mattawoman | 5 | 10 | 13 |
| Port Tobacco | 0 | 6 | 11 |

* Proposed capacity = 309 mgd

Table X-3

WASTEWATER FACILITIES AND PROJECTED FLOWS
Alternative III

| Facility | 1980 (mgd) | 2000 (mgd) | 2020 (mgd) |
|---|---|---|---|
| Pentagon | 1 | 1 | 1 |
| Upper Potomac | 0 | 38 | 209 |
| Anacostia | 0 | 126 | 185 |
| Arlington | 23 | 37 | 45 |
| Blue Plains | 285* | 309 | 309 |
| Alexandria | 38 | 61 | 83 |
| Piscataway | 24 | 49 | 79 |
| Lower Potomac | 50 | 103 | 170 |
| Occoquan | 45 | 121 | 235 |
| Mattawoman | 5 | 10 | 13 |
| Port Tobacco | 0 | 6 | 11 |

* Proposed capacity = 309 mgd

Alternative III is similar to the proposals in the "Memorandum of Understanding" with reference to the Washington metropolitan regional water pollution control plan as presented at a special session of the Potomac River Washington Metropolitan Area Enforcement Conference on October 13, 1970. In this memorandum, a maximum capacity of 309 mgd for the Blue Plains facility was proposed. It also required the appropriate parties to provide another regional plant or plants to accomodate the projected increases in wastewater volumes.

While there can be numerous variations of Alternative III in respect to flow distribution, the basic layout concept is fundamental. Alternative V, presented later in this report, is one variation with discharge points to the main Potomac.

Alternative IV, which is identical with Alternative I for wastewater treatment plant location, differs in that the effluents from the upper six plants are conveyed downstream as far as Occoquan Bay. This plan was investigated to determine the effects of discharges lower in the estuary on its use as a water supply source (Figure X-6).

Alternative V was developed to investigate the effects of discharging the effluents directly into the main Potomac instead of the embayments. This alternative, which is identical to Alternative III in facility locations has the Anacostia, Arlington, Alexandria, Piscataway, Lower Potomac, Occoquan, and Port Tobacco facilities discharging into the Potomac main channel. The Blue Plains, Upper Potomac, and Mattawoman facilities either do or were assumed to discharge into the main channel.

The estuary water supply intake was assumed to be one-half mile below Chain Bridge. In Figure X-1, the schematic diagram for the model, the water supply intake is at Node 114.

When the current wastewater collection and treatment facilities, projected populations, "Memorandum of Understanding," and water supply needs are reviewed, it can readily be observed that:

(1) Shortly after 1980, the Dulles Interceptor with its current capacity of 64 mgd will be overloaded.

(2) To provide for future wastewater collection and treatment services in the upper Potomac, either the Dulles Interceptor should be significantly enlarged or wastewater treatment facilities constructed in this region.

(3) If the Dulles Interceptor is enlarged, wastewater treatment capacity must be increased at either Blue Plains, Anacostia Valley, and Piscataway or a combination of all three.

(4) With the current capacity limitation of 309 mgd at Blue Plains, it appears that treatment facilities will be needed not only in the upper Potomac but also in the Anacostia Valley.

(5) Large wastewater volumes will be generated in the lower counties of Virginia, mainly in the Occoquan and Pohick watersheds.

The above five observations indicate that consideration in selection of wastewater management programs should not only include treatment facilities but also collection systems. This is discussed in greater detail later in this report when the water supply aspects are presented.

## C. WASTEWATER MANAGEMENT ZONES AND STREAMFLOW CRITERIA

To facilitate determination of wastewater management requirements, the upper and middle estuary were initially divided into three 15-mile zones with similar physical characteristics beginning at Chain Bridge. This allowed greater flexibility in developing control needs.

River mile distances for the three upper zones, from both the Chesapeake Bay and Chain Bridge, are given in Table X-4. The zonal concept was adopted by the Conferees at the Potomac Enforcement Conference Progress Meeting on May 8, 1969.

More recent studies have suggested that Zone I be divided into three subzones as shown in Figure X-8. The three subzones are described as follows:

| Subzone | Description |
|---|---|
| I-a | Potomac Estuary from Chain Bridge to Hains Point, a distance of 7.6 miles |
| I-b | Anacostia tidal river from Bladensburg, Maryland to the confluence with the Potomac, a distance of 9.0 miles |
| I-c | Potomac Estuary from Hains Point to Broad Creek, a distance of 7.4 miles |

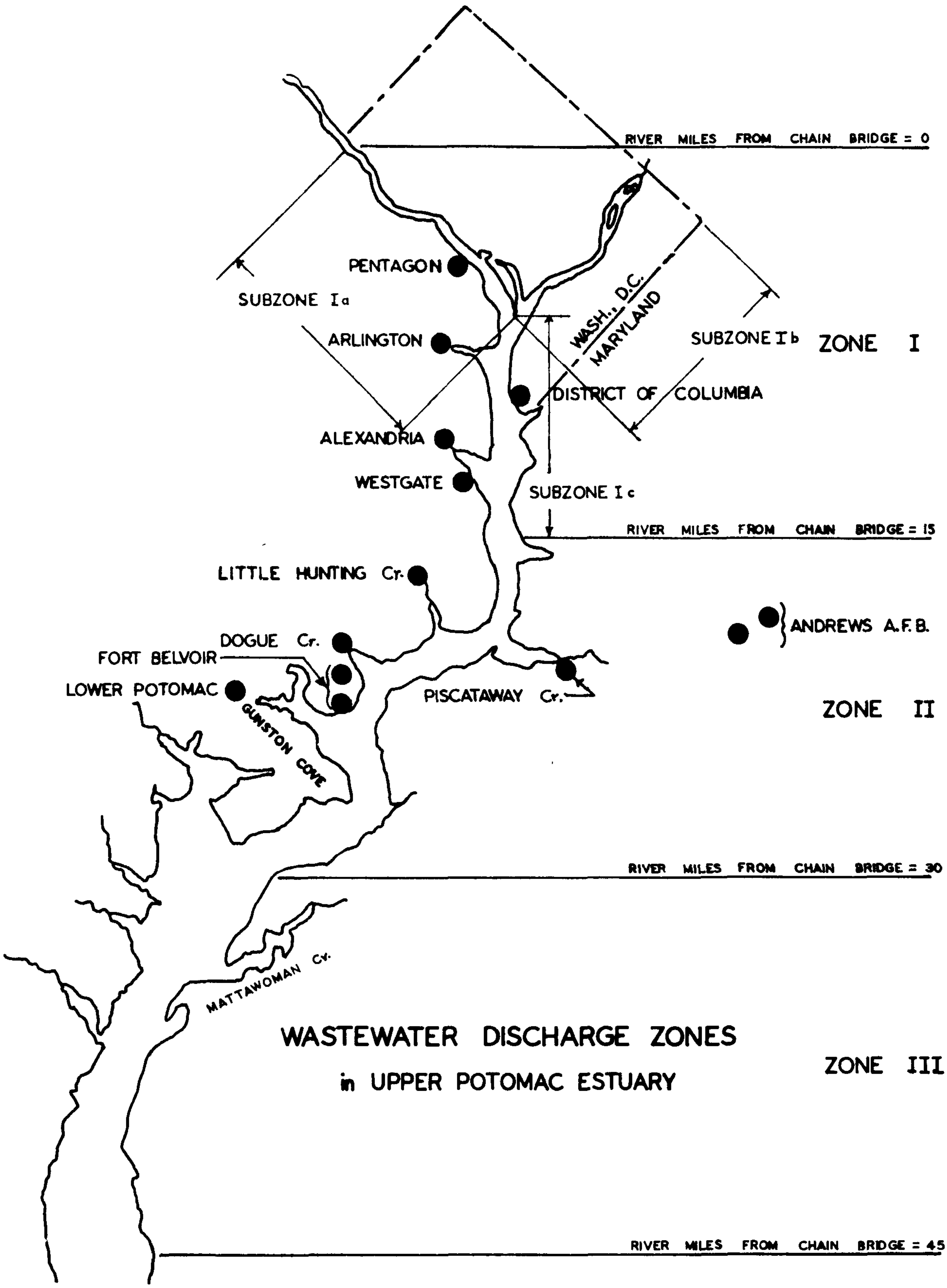
Discharges to embayments are also considered in this report.

Using the zonal concept, a total maximum loading for a specific pollutant is given for each zone. Allocation of pound loading for each discharge can be obtained by prorating the total zonal poundage using various bases such as population, drainage areas, and geographical subdivisions.

Table X-4

ZONES OF THE UPPER AND MIDDLE REACHES OF THE POTOMAC ESTUARY

| Zone and Description | River Mile Upper End of Zone | | River Mile Lower End of Zone | |
|---|---|---|---|---|
| | from Chain Bridge | from Chesapeake Bay | from Chain Bridge | from Chesapeake Bay |
| I | | | | |
| Chain Bridge to Broad Creek | 0.0 | 114.4 | 15.0 | 99.4 |
| II | | | | |
| Broad Creek to Indian Head | 15.0 | 99.4 | 30.0 | 84.4 |
| III | | | | |
| Indian Head to Maryland Point | 30.0 | 84.4 | 45.0 | 69.4 |




WASTEWATER DISCHARGE ZONES
in UPPER POTOMAC ESTUARY

FIGURE X-8

The 7-day-low-flow into the Potomac Estuary, with a recurrence interval of once-in-10-years, is 954 cfs before water supply diversion. Since the need for water supply is projected to utilize all of the river flow during critical flow conditions by 1980, a design flow of 300 cfs was used in determining wastewater loadings. This minimum flow serves to maintain an ecological balance in critical stream segments during low-flow periods as well as preserve the aesthetic appearance of this historic area. Where applicable, effects of flow changes including withdrawal from the estuary for water supply are also presented.

D. ULTIMATE OXYGEN DEMAND

The interrelationship between ultimate oxygen demand* (UOD) and dissolved oxygen (DO) in the Potomac Estuary was determined using a verified mathematical model. Studies included investigations of alternative wastewater treatment schemes, UOD loading rates, and net flows into the estuary for the three benchmark years. Maximum allowable UOD loadings in pounds per day, based upon compliance with existing DO stream standards were established for each of the zones including the embayments.

In developing the allowable UOD loadings, the reaction kinetics, as given in Chapter VI, were used, including the following DO criteria:

| Parameter | Value |
|---|---|
| Water temperature | 29.0°C |
| DO standard (average) | 5.0 mg/l |
| DO saturation at 29°C | 7.7 mg/l |
| Background DO deficit | 0.7 mg/l |
| Allowable deficit | 2.0 mg/l |

Included in the 0.7 mg/l DO deficit for background are the effects of algal growth and benthic demand. In using this deficit, it was assumed that the algal populations were under control and that the benthic demand resulting from wastewater sludge deposits had been substantially reduced from existing conditions. The UOD loadings were based upon maintaining 5.0 mg/l of DO averaged over the tidal cycle.

* The ultimate oxygen demand represents the sum of unoxidized carbon and nitrogen

Table X-5

UOD LOADINGS FOR POTOMAC ESTUARY
Based Upon Maintaining 5.0 mg/1 DO
Freshwater Inflow = 300 cfs (after water supply diversion)
Water temperature = 29°C

| Zone | Allowable UOD (lbs/day) |
|---|---|
| I-a | 4,000 |
| I-b | 3,000* |
| I-c | 75,000 |
| II | 190,000 |
| III | 380,000 |

* The loading increases with increase in waste flow (See text for more details).

Subzone I-c currently receives wastewater effluents from the Blue Plains Sewage Treatment Plant which serves the District of Columbia and surrounding portions of Maryland and Virginia, and from sewage treatment plants in Arlington, Alexandria, and Fairfax County, Virginia. As shown in Table X-5, a maximum UOD loading of approximately 75,000 lbs/day may be discharged into Subzone I-c regardless of the alternative investigated.

The effect of eliminating effluent aeration as a treatment process was determined for Subzone I-c. If a dissolved oxygen concentration of 2.0 mg/l instead of 6.0 mg/l in the wastewater is assumed, the allowable UOD loading in Subzone I-c would be about 60,000 lbs/day, or a reduction of 20 percent.

Two other subzones within Zone I, Subzone I-a of the Potomac Estuary in the vicinity of Chain Bridge and Subzone I-b of the Anacostia tidal river, were evaluated separately for Alternatives II and III because their waste assimilative capacities are quite limited. The allowable UOD loading for Subzone I-a based upon a freshwater flow of 200 to 300 cfs is 4000 lbs/day. The lack of adequate transport under low-flow conditions, and more important, the limited reaeration capability due to the considerable depth of water in this area greatly reduce the maximum allowable UOD loadings in the Potomac near Chain Bridge. CTSL mathematical modeling studies have shown that the allowable UOD load to this portion of the estuary increases substantially with increasing water supply flow withdrawals. This relationship, which is due to the direct removal of UOD before it is exerted in the receiving water, is shown below:

| Net Flow into the Estuary* (cfs) | Allowable UOD (lbs/day) |
|---|---|
| + 250 | 4000 |
| - 500 | 6000 |
| -1250 | 12000 |
| -2000 | 18000 |

The allowable UOD loadings in Subzone I-b, which is the upper Anacostia tidal river (Alternative II), are given for the three waste flow conditions as follows:

| Wastewater Flow (mgd) | Allowable UOD (lbs/day) |
|---|---|
| 68 | 3000 |
| 126 | 6000 |
| 185 | 9000 |

Again the absence of adequate transport and dilution restricts the waste assimilative capacity of the Anacostia tidal river. The increase in the allowable UOD shown above can be attributed to the progressive increase in wastewater discharges which greatly exceeds the natural inflow to the Anacostia tidal system in importance. In effect, the proposed wastewater discharge would substantially

* Negative net flows represent water supply withdrawal from the estuary assuming that all freshwater inflow from the upper basin, except for a base flow of 200 mgd, has already been diverted.

increase the downstream advective movement and the assimilative capacity of the Anacostia River.

Zone II of the Potomac Estuary currently receives effluents from the Piscataway and Lower Potomac wastewater treatment facilities via the Piscataway Creek and Gunston Cove embayments. By 1980, a third facility serving Mattawoman Creek basin in Charles County will also discharge into Zone II near Indian Head. Two basic schemes were investigated to determine UOD loadings in this zone. One scheme (Alternative V) assumes that all effluents discharge directly into the Potomac main channel whereas the other (Alternative I) assumes that the Piscataway Creek and Gunston Cove embayments continue to receive treated effluents from their respective wastewater plants.

According to Table X-5, the maximum UOD which can be discharged into Zone II and still permit the DO standard of 5.0 mg/l to be realized is 190,000 lbs/day. It should be noted that prior to determination of this allowable load, the residual or carryover effects of Zone I and Zone III loadings upon Zone II were determined and included.

If Piscataway Creek and Gunston Cove receive the wastewater effluents projected in Alternative I, the maximum allowable UOD loadings will be reduced considerably when compared to Zone II loadings. The relative inability of these embayments to assimilate organic wastewater is reflected in the data shown below:

UOD LOADINGS FOR PISCATAWAY CREEK AND GUNSTON COVE

| Piscataway Creek | | Gunston Cove | |
|---|---|---|---|
| Flow (mgd) | Maximum UOD Load (lbs/day) | Flow (mgd) | Maximum UOD Load (lbs/day) |
| 24 | 10,000 | 50 | 7,000 |
| 49 | 10,000 | 103 | 11,000 |
| 79 | 12,000 | 170 | 16,000 |

Since the physical characteristics for each embayment vary widely, it must be emphasized that separate determinations of loadings will be required for embayments other than those given above.

Because of the stringent loading requirements associated with discharges to embayments, it would appear advisable to discharge wastewater effluents directly to the Potomac (as in Alternative V) and utilize the additional dilution and transport capability it affords.

There are at present no significant wastewater discharges within Zone III of the Potomac Estuary; however, a treatment facility to serve the Occoquan watershed in Virginia has been proposed for construction by 1980. Moreover, it was assumed that a facility at Port Tobacco, Maryland, would also be in existence prior to the year 2000. With Zone II receiving its allowable UOD load (190,000 lbs/day) and deducting the necessary carryover effects, the allowable UOD loading for Zone III was estimated at 380,000 lbs/day (Table X-5).

E. PHOSPHORUS

Simulation of phosphorus discharges in the Potomac Estuary was made using the mathematical model with second-order reaction kinetics previously described. Included in the model was a phosphorus deposition rate of 0.05 mg/day at a temperature of 29°C. The allowable phosphorus loadings in pounds per day were determined based on maintaining an average of 0.067 mg/l of phosphorus (P) within Zones I and II and 0.03 mg/l (P) within Zone III and all embayments. All effluents were assumed to be of the same concentration. While various freshwater inflow rates (before water supply diversions) between 300 cfs and 1800 cfs were investigated, their effect on the allowable phosphorus loadings appeared to be quite small.

The allowable phosphorus loading for Subzone I-c of the Potomac Estuary is 900 lbs/day as shown in Table X-6. It should be noted that this loading remains about the same for each alternative investigated.

When Alternative III was considered, the limited waste assimilative capacity of the Potomac Estuary in Subzone I-a near Chain Bridge became evident. For a freshwater flow of 300 cfs, the allowable phosphorus loading to this area was determined to be 200 lbs/day. If water supply withdrawals are assumed, a certain portion of the phosphorus will be removed directly, thereby increasing the allowable load from wastewater

Table X-6

PHOSPHORUS LOADINGS FOR POTOMAC ESTUARY
Freshwater Inflow = 300 cfs (after water supply diversion)

| Zone | Allowable Phosphorus (lbs/day |
|---|---|
| I-a | 200 |
| I-b | 85* |
| I-c | 900 |
| II | 1500 |
| III | 2000 |

* The loading in this zone is sensitive to wastewater flow as described in the text of this report.

effluents. The relationship of allowable phosphorus load to rate of withdrawal is presented in the following table:

| Net Flow Into Estuary (cfs) | Allowable Phosphorus Loadings (lbs/day) |
|---|---|
| + 300 | 200 |
| - 500 | 300 |
| -1250 | 400 |
| -2000 | 500 |

For Alternative II, which includes a discharge into the Anacostia River, simulation runs indicate that the minimum transport and dilution greatly restricts the allowable phosphorus load that may be discharged into the Anacostia tidal system. As in the case of UOD, the phosphorus loadings into Subzone I-b are also a function of wastewater as follows:

| Wastewater Flow (mgd) | Allowable Phosphorus Loadings (lbs/day) |
|---|---|
| 68 | 85 |
| 126 | 135 |
| 185 | 180 |

As shown in Table X-6, the allowable phosphorus loading into Zone II of the Potomac is 1500 lbs/day. The appropriate carryover effects from both Zones I and III were incorporated into the phosphorus analysis for Zone II.

When wastewater effluents are discharged into the embayments of Zone II, there is a much larger increase in phosphorus concentration for a given phosphorus loading. As an example, assuming 1980 wastewater flow data and a 1000 cfs inflow, if the effluent contains 10 mg/l of phosphorus, the result in the Piscataway embayment would be as follows:

| Discharge Location | Increase in Phosphorus Upper End of Embayment (mg/l) | Increase in Phosphorus Lower End of Embayment (mg/l) |
|---|---|---|
| Into Embayment | 3.93 | 1.22 |
| Into Main Potomac | 0.78 | 0.92 |

A similar tabulation for Gunston Cove, again assuming 1980 conditions, follows:

| Discharge Location | Increase in Phosphorus Upper End of Embayment (mg/l) | Increase in Phosphorus Lower End of Embayment (mg/l) |
|---|---|---|
| Into Embayment | 8.62 | 0.61 |
| Into Main Potomac | 0.49 | 0.62 |

The above tabulations clearly show that concentrations in the upper end of the embayments can be drastically reduced by diverting discharges to the main Potomac. However, they also show that the phosphorus concentrations in the lower end of the embayments are considerably less affected. This can be attributed to the tidal exchange between the main Potomac and the embayments.

If discharges projected in Alternative I are made to the upper end of the Piscataway Creek and Gunston Cove embayments, the maximum allowable phosphorus loadings are as follows:

PHOSPHORUS LOADINGS TO EMBAYMENTS

| Piscataway Creek | | Gunston Cove | |
|---|---|---|---|
| Flow (mgd) | Maximum Phosphorus Load (lbs/day) | Flow (mgd) | Maximum Phosphorus Load (lbs/day) |
| 24 | 35 | 50 | 35 |
| 49 | 50 | 103 | 60 |
| 79 | 65 | 170 | 140 |

The loadings given apply to these embayments only. A separate determination will be required for other embayments because of different physical configuration. The effect of the main Potomac on the embayments was previously demonstrated by Jaworski and Johnson in a preliminary study of the Piscataway embayment [42].

It can be concluded that there is a significant advantage in discharging wastewater effluents into the main channel (Zone II) from the standpoint of phosphorus buildup. Moreover, it appears that with the lack of transport in the embayments, the allowable phosphorus concentration in discharges to the embayments begins to approach the developed criteria.

In order to realize the phosphorus criterion for Zone III of the Potomac Estuary (0.03 mg/l), the maximum phosphorus loading from wastewater effluents within this zone was determined to be 2,000 lbs/day as shown in Table X-6.

Using phosphorus as a tracer, simulation runs were made to determine how quickly any component in the wastewater discharge could reach the proposed estuary water intake. Table X-7 shows that in the extreme case investigated, about 4 days would elapse before detection there. For the projected year 2020, wastewater discharges and a river flow of 1800 cfs, the time would be increased to 8 days.

Table X-7

INTRUSION TIMES FOR PHOSPHORUS INTO ESTUARY WATER INTAKE
Wastewater Alternative I

| Year | Net Inflow | Days Required to Detect an Increase in Phosphorus at Water Intake |
|---|---|---|
| 1980 | +1250 | --* |
| 1980 | + 250 | --* |
| 1980 | - 500 | 10 |
| 2000 | + 500 | --* |
| 2000 | - 500 | 9 |
| 2000 | -1000 | 5 |
| 2020 | - 500 | 8 |
| 2020 | -1500 | 5 |
| 2020 | -2000 | 4 |

* With a positive net inflow, there was no measurable intrusion into the intake.

F. NITROGEN

Inorganic nitrogen was simulated using a mathematical model which had already been verified based upon observed data. For purposes of developing zonal loadings, the total inorganic nitrogen was assumed to behave conservatively. Since nitrogen appears to be limiting the rate of algal growth in Zones II and III, more stringent criteria were adopted for those areas. The upper nitrogen concentration limits used for Zones I, II, and III were 0.5, 0.4, and 0.3 mg/l respectively at a temperature of 29°C. With these levels of inorganic nitrogen, some algal growth will occur but nuisance conditions should be prevented. The net estuary inflow, water supply withdrawal rates, population benchmarks, and alternative wastewater treatment schemes incorporated in the analysis of nitrogen were identical to those used for determining phosphorus loadings.

The allowable nitrogen loading for Subzone I-c of the Potomac Estuary is 3,400 lbs/day (Table X-8). For Alternative III and a freshwater inflow of 300 cfs, Subzone I-a can receive and adequately assimilate 1,000 lbs/day of nitrogen from wastewater effluents. If nitrogen is removed from this portion of the estuary via water supply withdrawals, the allowable nitrogen loadings will, of course, increase in a manner similar to that shown previously for UOD and phosphorus.

Table X-8

NITROGEN LOADINGS FOR POTOMAC ESTUARY
Freshwater Inflow = 300 cfs (after water supply diversion)

| Zone | Allowable Nitrogen (lbs/day) |
|---|---|
| I-a | 1000 |
| I-b | 300* |
| I-c | 3400 |
| II | 5800 |
| III | 9000 |

* The loading in this zone is sensitive to waste flow as described in the text of this report.

Allowable nitrogen loadings for Subzone I-b, which is the upper Anacostia tidal river, are also a function of wastewater flow and are as follows:

| Flow (mgd) | Allowable Nitrogen (lbs/day) |
|---|---|
| 68 | 300 |
| 126 | 550 |
| 185 | 800 |

With all major wastewater effluents discharging to the main channel, Zone II of the Potomac Estuary can receive 5800 lbs/day of inorganic nitrogen (Table X-8) and still maintain the criterion of 0.4 mg/l. As shown in Table X-8, the allowable nitrogen loading for Zone III of the Potomac is 9000 lbs/day.

The importance of nitrogen as a potential rate-limiting nutrient within Zone II must be considered when evaluating the loading requirements for embayments such as Piscataway Creek and Gunston Cove. As in the case of phosphorus, the lack of movement from the head end of the embayments necessitates reducing the nitrogen concentration in wastewater effluents to a level approaching the established criteria.

For discharges made to the upper end of the embayments for Alternative I, the maximum allowable nitrogen loadings are:

NITROGEN LOADINGS TO EMBAYMENTS

| Piscataway | | Gunston Cove | |
|---|---|---|---|
| Flow (mgd) | Maximum Nitrogen Load (lbs/day) | Flow (mgd) | Maximum Nitrogen Load (lbs/day) |
| 24 | 120 | 50 | 130 |
| 49 | 170 | 103 | 270 |
| 79 | 270 | 170 | 460 |

Independent determinations of nitrogen loadings must be made for other embayments because of varying hydrography and tidal characteristics. In view of this stringent allowable loading, a definite advantage is evident in discharging into the main channel.

## G. CHLORIDE AND TOTAL DISSOLVED SOLIDS SIMULATIONS

### 1. Estuary Water Supply Withdrawal

In March 1969, Hetling [43] investigated the possible use of the upper Potomac Estuary as a water supply source, primarily from the chloride intrusion aspect. From this study, it was concluded that (1) under most critical summer-flow conditions on record (1930-1931) and the year 2010 demand, the estuary could be used for potable water supply purposes, and (2) if the wastewater is discharged out of the basin, such as to the Chesapeake Bay, the water supply potential of the estuary is reduced considerably. In light of the large projected wastewater volumes in the lower counties of Virginia along the upper Potomac, a review of the possible intrusion of chlorides and total dissolved solids into the estuary water intake was undertaken.

Data in Figure X-9 indicate that the chloride intrusion from Chesapeake Bay varies appreciably. This variation is mainly a function of freshwater inflow rate and duration. The November 1930 profile shows the farthest upstream intrusion as a result of prolonged low flows of less than 700 cfs from July through November. Although the drought conditions in September 1966 were more severe with flows of approximately 220 cfs, the duration was shorter and hence the intrusion was not as great.

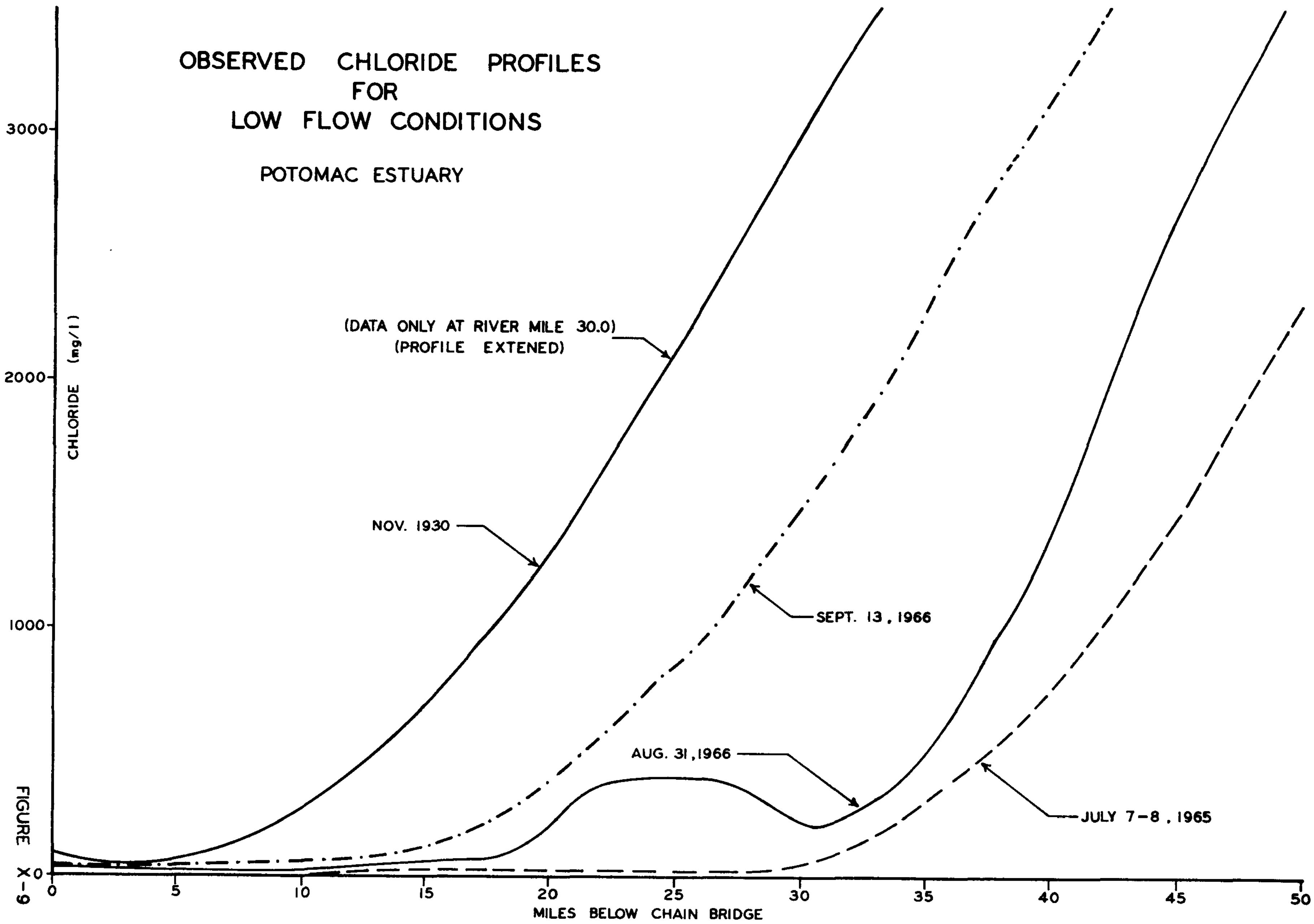

OBSERVED CHLORIDE PROFILES
FOR
LOW FLOW CONDITIONS
POTOMAC ESTUARY
(DATA ONLY AT RIVER MILE 30.0)
(PROFILE EXTENED)
NOV. 1930
SEPT. 13, 1966
AUG. 31, 1966
JULY 7-8, 1965
CHLORIDE (mg/l)
3000
2000
1000
0
0
5
10
15
20
25
30
35
40
45
50
MILES BELOW CHAIN BRIDGE

FIGURE X-9

Using four historic low-flow conditions, the rate of intrusion was calculated as follows:

| Flows (cfs) | Upstream Movement (miles/day) |
|---|---|
| 5000 | 0.00 |
| 1100 | 0.07 |
| 580 | 0.21 |
| 214 | 0.71 |

The above tabulation clearly shows the effect of freshwater inflow on the rate of the chloride intrusion from the Chesapeake Bay.

The intrusion of chlorides and total dissolved solids was simulated using the FWQA Dynamic Estuary Quality Model. For Alternatives I and IV, the simulations were made assuming the following freshwater inflows and water supply withdrawals:

| | Freshwater Inflow at Great Falls (cfs) | Water Supply Withdrawal (cfs) | Net Flow Into the Estuary* (cfs) |
|---|---|---|---|
| Year 1980 | 1870 | 870 | +1000 |
| | 1120 | 870 | + 250 |
| | 370 | 870 | - 500 |
| Year 2000 | 1750 | 1500 | + 250 |
| | 1000 | 1500 | - 500 |
| | 250 | 1500 | -1250 |
| Year 2020 | 1900 | 2400 | - 500 |
| | 1150 | 2400 | -1250 |
| | 400 | 2400 | -2000 |

* Negative net flow represents withdrawal from estuary for water supply

Two sets of initial conditions were used for each simulation: (1) an initial chloride wedge position as observed on September 13, 1966, and (2) a less severe condition using July 7-8, 1965, observations. The upper end of the chloride wedges under these two conditions is shown in Figure X-9.

To obtain the initial conditions for total dissolved solids (TDS), a relationship between TDS and chlorides was established from existing data as follows:

TDS (mg/l) = 1.69 Chlorides (mg/l) + 300

Boundary and loading conditions used in the simulations are itemized below:

| | 1966 Wedge | 1965 Wedge |
|---|---|---|
| Chesapeake Bay chloride concentration | 11000 mg/l | 9000 mg/l |
| Chesapeake Bay TDS concentration | 18000 mg/l | 14000 mg/l |
| Freshwater inflow chloride concentration | 30 mg/l | 15 mg/l |
| Freshwater inflow TDS concentration | 160 mg/l | 160 mg/l |
| Wastewater TDS concentration* | 300 mg/l | 300 mg/l |
| Water use chloride increment | 25 mg/l | 25 mg/l |
| Water use TDS increment (Run 1) | 40 mg/l | 40 mg/l |
| Water use TDS increment (Run 2) | 240 mg/l | 240 mg/l |

Currently the average concentration of chlorides and TDS in the wastewater effluents are about 40 and 300 mg/l, respectively. The above 40 and 240 increments for TDS are well within the range of accepted concentrations in the effluent of 200 to 400 mg/l. In this study,

* The total TDS increase from water intake to wastewater discharge is currently about 140 mg/l

maximum upper limits for municipal water supply of 250 and 500 mg/l of chlorides and TDS respectively in the blended mix of estuary water and freshwater inflow were used as recommended by the U. S. Public Health Service [44].

With the concentration of TDS in both the estuary and the wastewater effluent higher than for chlorides, the restricting limitation on the use of the estuary is TDS. This finding is also supported by Hydroscience [45] in their preliminary report on the feasibility of the Potomac Estuary as a supplemental water supply source.

Summaries of the results of the TDS simulations for the initial conditions of July 7-8, 1965, and September 13, 1966, are given in Tables X-9 and X-10. Based on data summarized in these two tables as well as from other simulations runs, it can be concluded that:

1. Even with no water supply withdrawals from the estuary, chloride and TDS intrusion will occur farther upstream in the Potomac Estuary as a result of the larger percentages of total wastewater volumes discharged farther downstream and projected increases in consumptive loss. Currently, less than 20 mgd is discharged into saline waters. By 2020, approximately 31 percent of the wastewater or over 400 mgd will be discharged into the saltwater wedge. The consumptive loss, which is water supply withdrawal minus wastewater discharge, is projected to increase as shown below:

| Year | Consumptive Loss (mgd) |
|---|---|
| 1966* | 44 |
| 1980 | 83 |
| 2000 | 148 |
| 2020 | 226 |

* During the month of August in which the flow into the estuary was 538 cfs, the consumptive loss was about 13.5 percent

This increased downstream discharge, coupled with the above increased consumptive loss will reduce the net seaward flow in the upper estuary even without any water supply withdrawal.

2. The number of days that the estuary can be used for water supply depends mainly on (a) duration and magnitude of drought conditions, (b) location of wastewater treatment facility discharges, and (c) position of the salt wedge before low-flow conditions begin.

3. The effect of the incremental increase in TDS in the wastewater on the concentration at Chain Bridge is not significant for the upper or lower wedge positions for Alternative IV. The number of days that the estuary could be used for a water supply did not vary if 40 or 240 mg/l was used. The major effect on the concentration was the intrusion from the Chesapeake Bay which is controlled by freshwater inflow and wastewater discharge locations (Table X-9).

For the upper wedge position, as given in Table X-10, the effect of the concentration of TDS in the effluent is more significant especially for Alternative I and the year 2020. The time was reduced by 24 days when the TDS increment was increased from 40 to 240 mg/l.

4. With the salt wedge in the upper position as of September 13, 1966, using the TDS criterion of 500 mg/l in the blended water, Alternative I, and with less than 400 cfs coming over Great Falls before

water supply withdrawal, the estuary could be used for water supply for the following periods:

| Year | 40 mg/l Increment (days of use) | 240 mg/l Increment (days of use) |
|---|---|---|
| 1980 | > 166 | > 166 |
| 2000 | 90 | 35 |
| 2020 | 45 | 15 |

This reduction in usage between 1980 and 2020 is primarily the result of increased incursion due to reduced net seaward flow and increased consumptive losses. For the lower position or the July 7-8, 1965, location of the wedge and the other conditions given above, the estuary could be used for water supply for the following periods:

| Year | 40 mg/l Increment (days of use) | 240 mg/l Increment (days of use) |
|---|---|---|
| 1980 | > 166 | > 166 |
| 2000 | 140 | 45 |
| 2020 | 95 | 20 |

The above reduction with time again reflects the increasing downstream discharges and the increasing consumptive losses.

5. Assuming about 1800 cfs freshwater inflow and the September 13, 1966, initial wedge location, the estuary can be used as a water supply source for over 166 days (the upper limit of the simulation period) for both chlorides and TDS for all three population benchmark years 1980, 2000, and 2020.

6. The number of days that the estuary can be used as a water supply for the year 2020 beginning with the September 13, 1966, wedge location as a function of freshwater flow is given below:

MAXIMUM DAYS OF USE OF ESTUARY

| Freshwater Inflow Before Water Supply Withdrawal | Alternative I Water Use Increment of TDS | | Alternative IV Water Use Increment of TDS | |
|---|---|---|---|---|
| (cfs) | 40 mg/l (days) | 240 mg/l (days) | 40 mg/l (days) | 240 mg/l (days) |
| 400 | 45 | 15 | 18 | 18 |
| 1100 | >166 | 42 | >166 | 41 |
| 1800 | >166 | >166 | >166 | >166 |

7. Since the projected water supply needs for the year 2020 cannot be met by either the upper basin with seven reservoirs or the estuary alone, both sources will be needed to supply the water needs for the Washington metropolitan area.

8. It is necessary to coordinate both the water supply and wastewater treatment requirements for planning in the Washington area since use of the estuary for water supply purposes is dependent on the location and distribution of wastewater discharges.

Table X-9

TIME, IN DAYS, TO REACH INDICATED
CONCENTRATION OF TOTAL DISSOLVED SOLIDS
IN ESTUARY
AT PROPOSED WATER INTAKE NEAR CHAIN BRIDGE
(Initial Conditions as of July 7-8, 1965)

| | 1980 | | 2000 | | 2020 | |
|---|---|---|---|---|---|---|
| | Alt. I | Alt. IV | Alt. I | Alt. IV | Alt. I | Alt. IV |
| Freshwater Flow* | 1000 cfs | | 250 cfs | | -500 cfs | |
| Water Use Increment 40 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | >166 | >166 | 132 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| Water Use Increment 240 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | >166 | >166 | 162 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| Freshwater Flow | 250 cfs | | -500 cfs | | -1250 cfs | |
| Water Use Increment 40 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | 124 | >166 | 63 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | 100 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | 126 |
| Water Use Increment 240 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | 123 | 32 | 60 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | 97 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | 122 |
| Freshwater Flow | -500 cfs | | -1250 cfs | | -2000 cfs | |
| Water Use Increment 40 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | 118 | 130 | 58 | [illegible] | [illegible] |
| TDS (1000) mg/1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

Table X-10

TIME, IN DAYS, TO REACH INDICATED
CONCENTRATION OF TOTAL DISSOLVED SOLIDS
IN ESTUARY
AT PROPOSED WATER INTAKE NEAR CHAIN BRIDGE
(Initial Conditions as of September 13, 1966)

| | 1980 | | 2000 | | 2020 | |
|---|---|---|---|---|---|---|
| | Alt. I | Alt. IV | Alt. I | Alt. IV | Alt. I | Alt. IV |
| Freshwater Flow* | 1000 cfs | | 250 cfs | | -500 cfs | |
| Water Use Increment 40 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | >166 | >166 | 132 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| Water Use Increment 240 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | >166 | >166 | 162 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| Freshwater Flow | 250 cfs | | -500 cfs | | -1250 cfs | |
| Water Use Increment 40 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | 124 | >166 | 63 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | 100 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | 126 |
| Water Use Increment 240 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | 123 | 32 | 60 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | 97 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | 122 |

Table X-10

TIME, IN DAYS, TO REACH INDICATED
CONCENTRATION OF TOTAL DISSOLVED SOLIDS
IN ESTUARY
AT PROPOSED WATER INTAKE NEAR CHAIN BRIDGE
(Initial Conditions as of September 13, 1966)

| | 1980 | | 2000 | | 2020 | |
|---|---|---|---|---|---|---|
| | Alt. I | Alt. IV | Alt. I | Alt. IV | Alt. I | Alt. IV |
| Freshwater Flow | 1000 cfs | | 250 cfs | | -500 cfs | |
| Wastewater Increment 40 mg/l | | | | | | |
| TDS ( 500) | >166 | >166 | >166 | >166 | >166 | 71 |
| TDS (1000) | >166 | >166 | >166 | >166 | >166 | 115 |
| TDS (1500) | >166 | >166 | >166 | >166 | >166 | 150 |
| TDS (2000) | >166 | >166 | >166 | >166 | >166 | >166 |
| Wastewater Increment 240 mg/l | | | | | | |
| TDS ( 500) | >166 | >166 | >166 | >166 | >166 | 71 |
| TDS (1000) | >166 | >166 | >166 | >166 | >166 | 115 |
| TDS (1500) | >166 | >166 | >166 | >166 | >166 | 148 |
| TDS (2000) | >166 | >166 | >166 | >166 | >166 | >166 |
| Freshwater Flow | 250 cfs | | -500 cfs | | -1250 cfs | |
| Increment 40 mg/l | | | | | | |
| TDS ( 500) | >166 | >166 | >166 | 70 | >166 | 28 |
| TDS (1000) | >166 | >166 | >166 | 110 | >166 | 47 |
| TDS (1500) | >166 | >166 | >166 | 135 | >166 | 61 |
| TDS (2000) | >166 | >166 | >166 | 157 | >166 | 78 |
| Increment 240 mg/l | | | | | | |
| TDS ( 500) | >166 | >166 | 57 | 70 | 28 | 28 |
| TDS (1000) | >166 | >166 | >166 | 110 | >166 | 46 |
| TDS (1500) | >166 | >166 | >166 | 135 | >166 | 60 |
| TDS (2000) | >166 | >166 | >166 | 156 | >166 | 76 |
| Freshwater Flow | -500 cfs | | -1250 cfs | | -2500 cfs | |
| Increment 40 mg/l | | | | | | |
| TDS ( 500) | >166 | 74 | 78 | 28 | 39 | 24 |
| TDS (1000) | >166 | 106 | 132 | 45 | 78 | 32 |
| TDS (1500) | >166 | 129 | 165 | 58 | 100 | 39 |
| TDS (2000) | >166 | 145 | >166 | 70 | 122 | 49 |
| Increment 240 mg/l | | | | | | |
| TDS ( 500) | 83 | 74 | 26 | 28 | 15 | 17 |
| TDS (1000) | >166 | 106 | 103 | 45 | 60 | 29 |
| TDS (1500) | >166 | 129 | 140 | 58 | 88 | 38 |
| TDS (2000) | >166 | 145 | >166 | 70 | 103 | 49 |

Table X-10

TIME, IN DAYS, TO REACH INDICATED
CONCENTRATION OF TOTAL DISSOLVED SOLIDS
IN ESTUARY
AT PROPOSED WATER INTAKE NEAR CHAIN BRIDGE
(Initial Conditions as of September 13, 1966)

| | 1980 | | 2000 | | 2020 | |
|---|---|---|---|---|---|---|
| | Alt. I | Alt. IV | Alt. I | Alt. IV | Alt. I | Alt. IV |
| Freshwater Flow* | 1000 cfs | | 250 cfs | | -500 cfs | |
| Water Use Increment 40 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | >166 | >166 | 132 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| Water Use Increment 240 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | >166 | >166 | 162 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | >166 |
| Freshwater Flow | 250 cfs | | -500 cfs | | -1250 cfs | |
| Water Use Increment 40 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | 124 | >166 | 63 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | 100 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | 126 |
| Water Use Increment 240 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | >166 | >166 | 123 | 32 | 60 |
| TDS (1000) mg/1 | >166 | >166 | >166 | >166 | >166 | 97 |
| TDS (1500) mg/1 | >166 | >166 | >166 | >166 | >166 | 122 |
| Freshwater Flow | -500 cfs | | -1250 cfs | | -2000 cfs | |
| Water Use Increment 40 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | >166 | 118 | 130 | 58 | 84 | 43 |
| TDS (1000) mg/1 | >166 | >166 | >166 | 88 | 130 | 68 |
| TDS (1500) mg/1 | >166 | >166 | >166 | 107 | 159 | 86 |
| Water Use Increment 240 mg/1 of TDS | | | | | | |
| TDS ( 500) mg/1 | 83 | 117 | 126 | 57 | 15 | 43 |
| TDS (1000) mg/1 | >166 | 160 | 147 | 87 | 130 | 66 |
| TDS (1500) mg/1 | >166 | >166 | >166 | 106 | 159 | 86 |

* Inflow to estuary after water supply withdrawal

Table X-9

TIME, IN DAYS, TO REACH INDICATED CONCENTRATION OF TOTAL DISSOLVED SOLIDS IN ESTUARY AT PROPOSED WATER INTAKE NEAR CHAIN BRIDGE
(Initial Conditions as of July 7-8, 1965)

| | 1980 | | 2000 | | 2020 | |
|---|---|---|---|---|---|---|
| | Alt. I | Alt. IV | Alt. I | Alt. IV | Alt. I | Alt. IV |
| Freshwater Flow* | 1000 cfs | | 250 cfs | | -500 cfs | |
| Water Use Increment 40 mg/l of TDS | | | | | | |
| TDS ( 500) mg/l | >166 | >166 | >166 | >166 | >166 | 132 |
| TDS (1000) mg/l | >166 | >166 | >166 | >166 | >166 | >166 |
| TDS (1500) mg/l | >166 | >166 | >166 | >166 | >166 | >166 |
| Water Use Increment 240 mg/l of TDS | | | | | | |
| TDS ( 500) mg/l | >166 | >166 | >166 | >166 | >166 | 162 |
| TDS (1000) mg/l | >166 | >166 | >166 | >166 | >166 | >166 |
| TDS (1500) mg/l | >166 | >166 | >166 | >166 | >166 | >166 |
| Freshwater Flow | 250 cfs | | -500 cfs | | -1250 cfs | |
| Water Use Increment 40 mg/l of TDS | | | | | | |
| TDS ( 500) mg/l | >166 | >166 | >166 | 124 | >166 | 63 |
| TDS (1000) mg/l | >166 | >166 | >166 | >166 | >166 | 100 |
| TDS (1500) mg/l | >166 | >166 | >166 | >166 | >166 | 126 |
| Water Use Increment 240 mg/l of TDS | | | | | | |
| TDS ( 500) mg/l | >166 | >166 | >166 | 123 | 32 | 60 |
| TDS (1000) mg/l | >166 | >166 | >166 | >166 | >166 | 97 |
| TDS (1500) mg/l | >166 | >166 | >166 | >166 | >166 | 122 |
| Freshwater Flow | -500 cfs | | -1250 cfs | | -2000 cfs | |
| Water Use Increment 40 mg/l of TDS | | | | | | |
| TDS ( 500) mg/l | >166 | 118 | 130 | 58 | 84 | 43 |
| TDS (1000) mg/l | >166 | >166 | >166 | 88 | 130 | 68 |
| TDS (1500) mg/l | >166 | >166 | >166 | 107 | 159 | 86 |
| Water Use Increment 240 mg/l of TDS | | | | | | |
| TDS ( 500) mg/l | 83 | 117 | 126 | 57 | 15 | 43 |
| TDS (1000) mg/l | >166 | 160 | 147 | 87 | 130 | 68 |
| TDS (1500) mg/l | >166 | >166 | >166 | 106 | 159 | 86 |

* Inflow to estuary after water supply withdrawal

## 2. Direct Reuse of Treated Wastewater

In the system where treated wastewater is discharged into the fresh-water estuary, intrusion of salt from Chesapeake Bay is one of the major restrictions if the upper estuary is to be used as a potable water supply. The direct reuse system (that is, going directly from the advanced waste-water treatment facility to the water supply facility) removes this restriction.

Using the water requirements for the year 2020 and conditions as defined in the previous section, simulations were made with the direct reuse system to determine the rate of buildup of both chlorides and TDS. The results of these simulations for various flow conditions are presented below:

| | | Equilibrium Concentrations | | |
|---|---|---|---|---|
| Water from Upper Basin (cfs) | Water from Direct Reuse (cfs) | Chlorides max. Concentration (mg/l) | 40 mg/l of TDS Increase (mg/l) | 240 mg/l of TDS Increase (mg/l) |
| 400 | 2000 | 140 | 360 | 1360 |
| 1150 | 1250 | 42 | 203 | 421 |
| 1900 | 500 | 22 | 171 | 233 |

The equilibrium concentrations or maximum concentrations to which the system would build up with partial direct recycling usually were reached in less than 20 days except for the first flow condition (400 cfs from Great Falls) in which 40 days were required.

The above tabulation indicates that direct reuse is a feasible solution to the future water supply needs of the Washington metropolitan area with respect to TDS and chlorides. The only restriction is that with over 80 percent of the water supply from renovated wastewater, the maximum combined buildup in TDS from both the water supply and wastewater treatment facilities has to be less than 65 mg/l. For a flow of 670 cfs (the seven-day-low-flow with a recurrence interval of once-in-50-years) or with approximately 70 percent of the water supply from renovated wastewater, the maximum TDS buildup would have to be restricted to 140 mg/l. As reported earlier, this is the current buildup in the entire water use system.

Based on data obtained from the AWT pilot plant operation at Blue Plains [46], the TDS, excluding the bicarbonate system, is not anticipated to increase and in fact may decrease. Since the bicarbonate concentration can be controlled by proper selection of unit processes of the AWT treatment facilities, the 140 mg/l increment can readily be maintained.

The direct reuse concept has the following advantages:

(1) Effects of intrusion from the Chesapeake Bay are eliminated,

(2) Need for the protection of the upper estuary from accidental spills, urban runoff, storm and combined sewer overflows with respect to water supply is eliminated,

(3) Restriction on the location of wastewater facilities with respect to water supply needs is eliminated,

(4) With proper planning, the need for massive wastewater collection and water distribution systems can be reduced. For example, both facilities can be located in the upper Potomac area with reuse being instituted whenever needed. During high-flow periods, the effluent may be discharged into the Chesapeake and Ohio Canal and conveyed past the downstream water intake.

(5) The need for the proposed upstream impoundments for water supply in the Washington area would be eliminated.

The major disadvantages are:

(1) Ammonia nitrogen conversion or removal will be required at temperatures approaching 5°C. Technology for this requirement is not fully developed at the present time.

(2) With the potential buildup of TDS, unit process will have to be carefully selected.

(3) A high degree of operation efficiency, including "fail safe" concepts, must be maintained at both the wastewater and the water supply facilities.

The direct reuse concept has great potential. However, there are many aspects which need to be investigated. These concepts could also be readily applied to small areas such as the Occoquan watershed, a sub-basin of the Potomac below Washington, and the Patuxent River Basin, a watershed between Baltimore and Washington.

# CHAPTER XI

# WASTEWATER TREATMENT FACILITIES AND COSTS

## A. TREATMENT CONSIDERATIONS

To meet the carbon (UOD), nitrogen, and phosphorus requirements previously specified, a high degree of wastewater treatment will be required for Zone I. Based upon the performance of the FWQA pilot plant at Blue Plains, Bishop [46] indicates that the following removal rates can be anticipated from April to November (winter operation reliability has not been demonstrated):

| Parameter | After Treatment | % Removal |
|---|---|---|
| $BOD_5$ | $< 2.0$ | $> 99$ |
| Nitrogen as N | 1.0 - 2.0 | 90 - 95 |
| Phosphorus as P | $< 0.1$ | $> 99$ |

To achieve the above removals, the following unit process sequence could be selected:

(1) Primary settling and activated sludge,

(2) Biological nitrification,

(3) Biological denitrification,

(4) Lime treatment,

(5) Dual media filtration,

(6) Effluent breakpoint chlorination, and

(7) Effluent aeration.

The above unit processes can produce an effluent which will meet the removal requirements for phosphorus and ultimate oxygen demand. However, with respect to nitrogen removal for algal control, it appears that the requirement cannot be readily met. Since over 99 percent of phosphorus can be removed, it appears that with a combination having a high percentage of carbon removal and 90 percent nitrogen removal, such as the preceeding seven unit processes can provide, both the DO enhancement and algal control will be realized. At present, the need for activated carbon adsorption has not been adequately demonstrated.

An important aspect of wastewater treatment will be the additional effluent aeration required, especially in Zone I, or for large discharges into small embayments. For example, a discharge of 185 mgd into the Anacostia River will be over 35 times greater than the freshwater inflow during low-flow periods. Hence, to maintain a DO level of 5.0 mg/l, the discharge will have to have at least 5.0 mg/l of DO. The unit process for this effluent quality is included in all costs presented in this report.

Additional removal of inorganic nitrogen and carbon could be provided by activated carbon. The activated carbon beds become media for bacterial growths which convert some of the organic nitrogen to ammonia. The ammonia can then be removed by additional chlorination. Since the continued effectiveness of this additional nitrogen removal process is not well established, the effectiveness or the need for carbon adsorption as an additional wastewater unit process has not at present been established. Its utility appears to be more predicated on the use of the estuary as a water supply than for wastewater treatment.

B. WASTEWATER TREATMENT COSTS

Cost estimates for conventional secondary treatment and six advanced waste treatment (AWT) processes were developed for 15 present and planned facilities. The AWT processes considered include lime clarification with dual media filtration (for phosphorus removal and for additional carbon removal), carbon adsorption, biological nitrification and denitrification (for removal of ammonia and nitrate nitrogen respectively), and effluent aeration (to increase the DO from 1.0 to 6.0 mg/l). Capital costs and operation and maintenance (O & M) costs for each process were obtained chiefly from the Bechtel Corporation's report [47] on AWT at Blue Plains and cost data prepared by Smith and McMichael [48]. Where necessary, these costs were adjusted to reflect mid-1970 engineering indexes.

Cost data for specific years were determined by a computer systems program which incorporated equations describing the dollar per unit discharge relationship. One of the cost curves used is shown in Figure XI-1. Basic assumptions and alternative amortization and plant operation schemes included:

(1) Expenditures for new construction required in 1970, 1980, and 2000 are based upon design for conditions 10 or 20 years hence.

(2) In the case of existing treatment plants, construction of AWT units would begin in 1970 with O & M cost accruing from that time. Other plants were assumed to be constructed in 1980.

# ACTIVATED SLUDGE COST

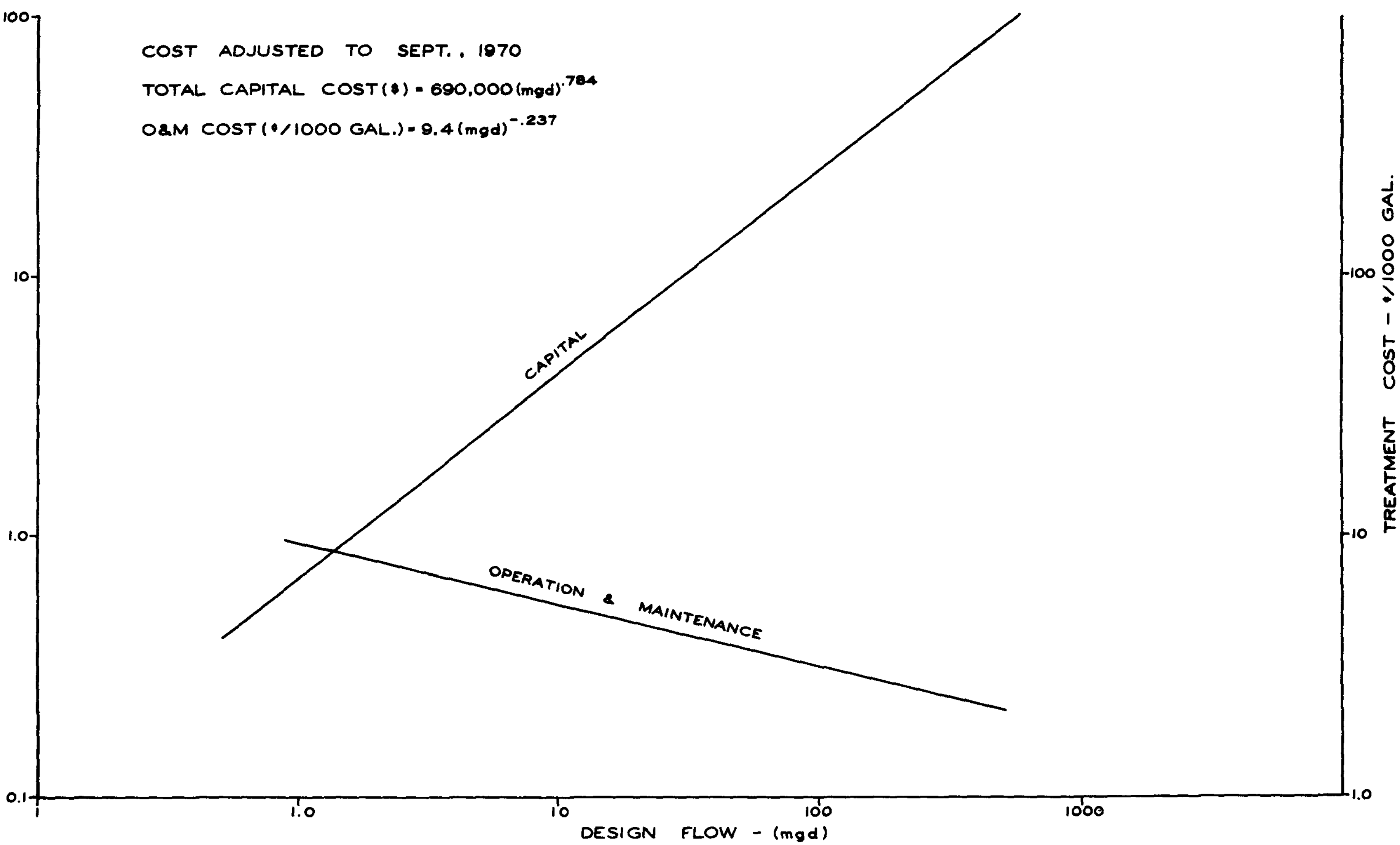



FIGURE XI-1

(3) If a new AWT plant is to be constructed in 1970, a 15-percent replacement of this plant would be necessary by 1980 in addition to required expansion. For the year 2000 construction, it was assumed that the entire original plant built in 1970 and 30 percent of the plant built in 1980 would be replaced.

(4) If a new AWT plant is to be constructed in 1980, 30-percent replacement would be provided for the year 2000 along with expansion to meet 2020 needs.

(5) With the exception of Arlington, conventional treatment units at the existing plants were considered to be new in 1970. The current capacity at Piscataway was assumed to be 30 mgd since construction of additional facilities is well under way.

(6) O & M costs for AWT units were based on 6-month and 12-month operating periods and the average projected waste flows for the specific time frame.

(7) The amortization of capital costs was assumed over a 20-year period with an interest rate of 5-1/8 percent.

Table XI-1 presents a summary of the treatment cost data for the upper Potomac Estuary through the year 2020.

Using Alternative III, the total present worth cost of wastewater treatment expenditures from 1970 to 2020 was determined to be $1,340 million (Table XI-1). If activated carbon is added, the cost will increase to $1,700 million. The annual cost basis for an average population of six million people reduces to approximately $11 per person per year. With the activated carbon units, the cost increases to $14 per person per year.

Capital cost expenditures and O & M costs are presented by unit process for the three periods (1) 1970-1980, (2) 1980-2000, and (3) 2000-2020 in Table XI-2. As can be seen in the table, the largest capital costs of the total initial cost of $2,272 million are $737 million for secondary and $463 million for activated carbon unit process, with the O & M cost being largest for the lime clarification and activated carbon processes.

With nitrification and denitrification required for only 7 months out of 12, an annual O & M savings of $3 million from 1970-1980, $4 million from 1980-2000, and $6 million from 2000-2020 can be realized. Continued studies will be required to further define the temporal removal requirements for nitrogen.

Table XI-1

TOTAL WASTEWATER TREATMENT COST
1970-2020
Alternative III

| Unit Process | TPW* ($ x $10^6$) | TAAC** ($ x $10^6$) |
|---|---|---|
| Primary-secondary | 457 | 13.5 |
| Biological nitrification | 247 | 13.8 |
| Biological denitrification | 133 | 9.4 |
| Lime clarification | 370 | 20.6 |
| Dual media filtration | 101 | 5.7 |
| Effluent Aeration | 10 | 0.6 |
| Chlorination | 22 | 1.2 |
| Subtotal | 1,340 | $64.8 |
| Activated Carbon | 360 | 20.1 |
| Total | 1,700 | $84.9 |

* Total present worth cost includes proposed secondary treatment expansion cost for Blue Plains

** Total average annual cost including operation and maintenance cost based on 12 months of operation

Table XI-2

INITIAL CAPITAL CONSTRUCTION
AND
OPERATION AND MAINTENANCE COSTS
1970-1980, 1980-2000, and 2000-2020 Time Periods

| Unit Process | 1970-1980 Capital ($\$x10^6$) | 1970-1980 Other ($\$x10^3$) | 1980-2000 Capital ($\$x10^6$) | 1980-2000 Other ($\$x10^3$) | 2000-2020 Capital ($\$x10^6$) | 2000-2020 Other ($\$x10^3$) |
|---|---|---|---|---|---|---|
| Primary-secondary | 236.11 | 4141.48 | 129.71 | 7413.07 | 371.11 | 11512.23 |
| Biological nitrification | 70.64 | 3968.66 | 84.53 | 7097.46 | 167.63 | 11044.23 |
| Biological denitrification | 62.11 | 427.29 | 71.84 | 759.32 | 148.24 | 1197.80 |
| Lime clarification | 69.31 | 8661.66 | 81.96 | 15573.46 | 166.12 | 24560.32 |
| Dual media filtration | 27.22 | 889.15 | 35.02 | 3064.69 | 66.09 | 4510.30 |
| Chlorination | 0.37 | 761.59 | 2.00 | 1328.37 | 3.55 | 2165.03 |
| Effluent aeration | 2.91 | 226.61 | 4.35 | 407.73 | 6.90 | 739.27 |
| Subtotal | 468.67 | 19176.44 | 409.49 | 35644.10 | 929.64 | 55729.18 |
| Activated carbon | 101.96 | 5931.92 | 118.38 | 10535.54 | 243.40 | 16643.79 |
| Total | 570.63 | 25108.36 | 527.87 | 46179.64 | 1173.04 | 72372.97 |

The tabulation below is a reduction of the initial capital and operation and maintenance costs to a per capita basis:

| Item | 1970-1980 | 1980-2000 | 2000-2020 |
|---|---|---|---|
| Average Population | 3,350,000 | 5,350,000 | 8,000,000 |
| Total Initial Capital Cost/Time Period | $570,000,000 | $528,000,000 | $1,173,000,000 |
| Capital Cost/Person/Year | $17.0 | $4.9 | $7.3 |
| O & M Cost/Year | $25,100,000 | $46,200,000 | $72,400,000 |
| O & M Cost/Person/Year | $7.5 | $8.6 | $9.1 |
| Total Cost/Person/Year | $24.5 | $13.5 | $16.4 |

The above summary, which does include replacement cost, indicates that the cost of wastewater treatment in the upper Potomac Estuary is about $13 to $24/per person/per year. This expenditure, which includes the cost of the activated carbon process, will renovate the water to the chemical and microbiological qualities meeting drinking water standards.

# CHAPTER XII

# IMPLEMENTATION TO ACHIEVE WATER QUALITY STANDARDS

## A. SEASONAL WASTE TREATMENT REQUIREMENTS

### 1. Ultimate Oxygen Demand

The maximum allowable UOD loadings presented in Chapter X for the three upper zones of the Potomac Estuary apply under warm temperature conditions. The effects of nitrogenous oxygen demanding substances on the dissolved oxygen budget were determined to be quite significant when water temperatures exceed 15°C. At the present time, approximately 250,000 lbs/day of nitrogenous oxygen demand is discharged in wastewater effluents as compared to about 200,000 lbs/day of carbonaceous demand. Therefore, during very warm periods when nitrification rates are high, the nitrogenous component of UOD exerts a greater effect on the dissolved oxygen resources than the carbonaceous material. In order to comply with the allowable UOD loadings shown previously, it is necessary to reduce drastically both the nitrogen and carbon levels at the wastewater treatment plants whenever temperatures exceed 15°C.

During cold weather periods when the ambient water temperature is less than 15°C, the effects of nitrification on the dissolved oxygen budget become negligible as reported in Chapter VI. Therefore, the need for removal or oxidation of ammonia in wastewater discharges is not required during these periods.

To prevent the accumulation of sludge deposits in the vicinity of sewage treatment outfalls during cooler weather and to maintain high DO levels under ice cover, a high degree of removal of suspended solids and carbonaceous oxygen demanding material must be continued. Suspended solids concentrations in the effluent should not exceed 15 mg/l, and a minimum of 90 percent of the carbonaceous oxygen demand should be removed on a year-around basis. Currently, about 72 percent of the UOD load before wastewater treatment is carbonaceous and the remaining 28 percent nitrogenous. Based upon this proportion of carbonaceous and nitrogenous components in raw sewage, the requirement for carbonaceous removal would translate to 70-percent UOD removal.

Since the quantity of dilution flows in the upper end of the tidal embayments is greatly limited, continuous aeration of major wastewater effluents discharged to these areas will be required.

2. Phosphorus

Of the various nutrients that have been associated with the eutrophication problem in the upper and middle reaches of the Potomac Estuary, phosphorus has been found to be most controllable, not only on a seasonal basis but on an annual basis as well. As presented in Chapter VII, approximately 60 to 96 percent of the total phosphorus load to the Potomac Estuary can be controlled depending upon the existing flow conditions. An additional reduction in the uncontrollable phosphorus load from the upper basin occurs in the upper estuary as a result of phosphorus being sorbed upon silt particles accompanying high flows, which is then removed by sedimentation.

The phosphorus criteria required to prevent nuisance algal blooms from occurring, as developed in Chapter VII, varied from 0.03 to 0.1 mg/l. These criteria are approximately an order of magnitude lower than the corresponding criteria for nitrogen. Because of these stringent criteria, particularly in the lower zones of the estuary, and the possibility of recycling previously deposited phosphorus from the bottom muds (this contribution has not been quantitatively defined), year-around phosphorus removal at the wastewater treatment facilities in the upper estuary will be necessary.

The mathematical model used to predict the annual distribution of phosphorus in the critical algal growing areas was verified based upon extensive phosphorus data collected from February 1969 to September 1970. The close agreement between observed and predicted phosphorus profiles during this period for the Potomac Estuary at Indian Head is shown in Figure XII-1. Also shown in Figure XII-1 are the predicted annual phosphorus profiles resulting from year-around removal in the upper estuary, assuming (1) no control and (2) 50-percent control of the phosphorus load originating in the upper Potomac River Basin. It can be concluded after an examination of Figure XII-1 that both phosphorus removal on a year-around basis in the estuary and partial control of the incoming load will be required if the recommended phosphorus criteria are to be achieved.

## ANNUAL PHOSPHORUS PROFILES
### POTOMAC ESTUARY AT INDIAN HEAD

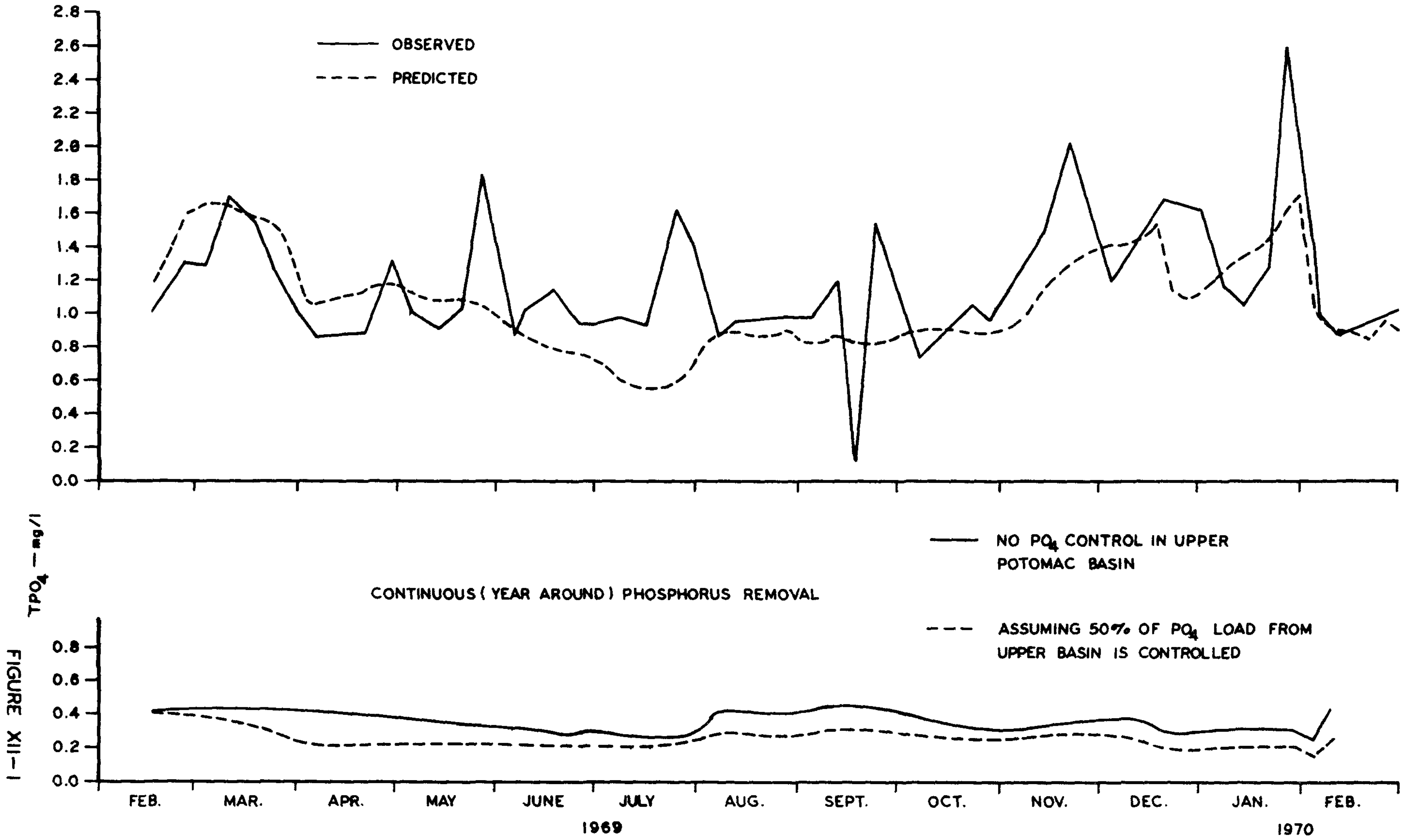



FIGURE XII-1

In order to realize a 50-percent reduction in the current phosphorus load from the upper Potomac River, the wastewater contribution of 6100 lbs/day must be reduced to 700 lbs/day.

3. Nitrogen

As presented earlier in this chapter, the necessity for nitrogen control in wastewater discharges to enhance the dissolved oxygen in the Potomac Estuary is restricted to that time of year when water temperatures exceed 15°C. When evaluating inorganic nitrogen treatment requirements for the prevention of excessive algal blooms, controllability becomes a significant factor.

Mathematical model studies were used to investigate the effects of seasonal and continuous nitrogen removal at the wastewater facilities in the upper Potomac Estuary. Figure XII-2 shows the predicted annual nitrogen profiles for the Potomac Estuary at Indian Head, using the verified mathematical model, assuming (1) no nitrogen removal, (2) nitrogen removal during periods with temperatures above 15°C (April-November), and (3) year-around nitrogen removal. These profiles show that the recommended nitrogen criteria can be obtained during the critical growing periods with either seasonal or continuous nitrogen removal. Though it would be desirable to continuously maintain nitrogen concentrations at or below these criteria, the high flows from the upper basin during the winter and spring months contribute high nitrogen loadings which increase the nitrogen concentrations above acceptable levels regardless of treatment practices (Figure XII-2).

SIMULATED ANNUAL NITROGEN PROFILES

POTOMAC ESTUARY AT INDIAN HEAD

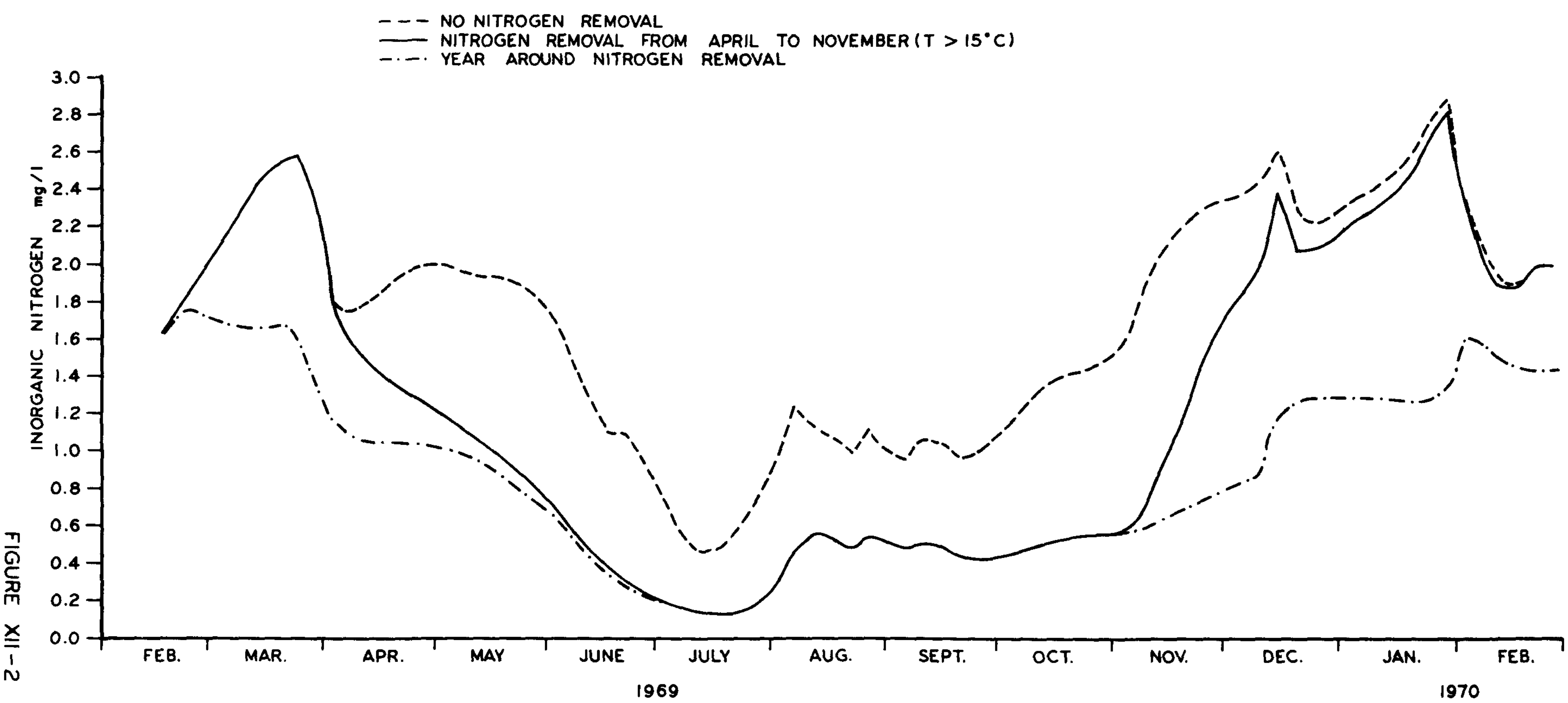



FIGURE XII-2

The controllable nitrogen from the wastewater treatment sources in the Washington metropolitan area is currently limited to about 60 percent of the total contribution from all sources. If nitrogen loadings increase as projected, the controllable amounts will also increase. Thus it appears that while nitrogen removal for algal control could be limited to periods when water temperatures in the estuary exceed 15°C, there may be a need for continuous control by the year 2000.

## B. LOCATION OF WASTEWATER DISCHARGES

### 1. Wastewater Assimilation Versus Salinity Intrusion

Projected wastewater loadings are highest in Zone I, with allowable UOD, nitrogen, and phosphorus loadings the lowest of all three zones. The concentration of wastewater discharges in Zone I will require much higher removal rates there than will be necessary in Zones II and III.

When the high degree of wastewater treatment is considered, it would appear to be advantageous to discharge effluents farther downstream in the estuary. The assimilation and transport capacity in Zone II is about four times that of Zone I. However, when the estuary is considered as a water supply source, no major effluent discharges from the Washington metropolitan area should occur below the middle of Zone II (or below Gunston Cove). This downstream discharge limit is required to keep the salt wedge from moving upstream and causing chloride and TDS intrusion at the water intake.

If direct water reuse is eventually adopted, greater use of the assimilative and transport capacity of the estuary can be realized. Moreover, the farther down the estuary residual nutrient loads are discharged, the less favorable conditions will be for blue-green algae because of higher salinity.

2. Wastewater Discharges to the Embayments

All present treated waste effluents except that from Blue Plains discharge into the tidal portion of various embayments. As presented in the previous chapter, a high degree of UOD, nitrogen, and phosphorus removal will be required if the present embayment discharge practice is continued.

Based upon detailed analyses, including dye studies, of the Anacostia, Piscataway, and Gunston Cove tidal embayments, it appears that major discharges into the upper portion of small tidal embayments should have a maximum concentration of UOD, phosphorus, and nitrogen of 10, 0.2, and 1.0 mg/l, respectively. Effluents from these facilities will require renovation to approach ultimate wastewater renovation* (UWR) levels. Unless UWR is provided, effluents from Alexandria, Arlington, Piscataway, and the Lower Potomac facilities should be discharged into the main channel of the Potomac Estuary.

A detailed investigation is essential for each embayment to determine which option provides the lesser cost, an outfall to the main channel of the river or UWR. Future studies should also include consideration of effluent dispersion devices to minimize local effects.

* Ultimate wastewater renovation can be defined as renovation of the wastewater to such a degree that it can be discharged into the receiving stream in unlimited quantities without restriction of the designated water resource use due to the lack of needed assimilative or transport capability of the stream. This implies that the quality of the effluent from a UWR plant conforms to the stream standards of the receiving waters.

## C. FLOW REGULATION FOR WATER SUPPLY AND WATER QUALITY CONTROL

In the original plan for reservoir development in the upper Potomac River Basin, the U. S. Army Corps of Engineers recommended 16 impoundments including the large Seneca Dam [1]. These 16 reservoirs would regulate the flow of the Potomac at Washington to maintain an approximate 4600 cfs minimum and would provide the maximum daily water supply needs of the basin up to the year 2020. When the Seneca Reservoir is excluded, the remaining 15 impoundments would increase the dependable low flow to approximately 3600 cfs. This would be an adequate flow to meet the maximum monthly water supply demand for the Washington metropolitan area up to the year 2020.

In the original Corps of Engineers' plan, approximately $210 million or 42 percent of the $500 million construction cost was charged to water quality control. Of this $210 million water quality control construction cost, approximately $130 million was required to maintain Potomac Estuary water quality [1].

Davis [50], in his study of the water quality management problems of the Potomac Estuary, suggested that mechanical reoxygenation and low-flow augmentation provided the least costly solution to maintain a specific dissolved oxygen (DO) level. Although the costs for individual wastewater processes as presented by Davis have increased substantually, later investigations have indicated that algal control and nitrification requirements are presently the two most important considerations in water quality management for the upper estuary.

Nevertheless, the Davis studies demonstrate that DO standards could be maintained with a high degree of wastewater treatment at lower cost and with greater dependability than by flow regulation alone.

As summarized by Reinhardt [51], a program of water resource management must be flexible in order to make use of modern technological developments to meet current wastewater treatment requirements. The requirements developed in this study reflect not only a need for high carbonaceous BOD removals but also for nutrient removals to control algal growth. Low-flow augmentation for nutrient control will not be effective since the total nutrient loading in pounds per day entering the estuary *is the primary factor* to be considered in algal control. This insensitivity to flow is especially pronounced in the middle reach where the volume of the estuary is large, advective movement slight, and algal growing conditions ideal.

The maximum waste loadings and treatment costs presented in Chapters X and XI will not be greatly affected by flow regulation considerations, even with construction of either 15 or 16 reservoirs. It appears that the major advantage of flow regulation is for water supply purposes and not for water quality management.

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District of Columbia, Department of Sanitary Engineering

County of Fairfax, Virginia

City of Alexandria, Virginia

County of Arlington, Virginia

Washington Suburban Sanitary Commission

Andrews Air Force Base

Department of the Army, Fort Belvoir

Washington Aqueduct and North Atlantic Division, U. S. Army Corps of Engineers

U. S. Geological Survey, Department of the Interior

Metropolitan Washington Council of Governments

Interstate Commission on the Potomac River Basin

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