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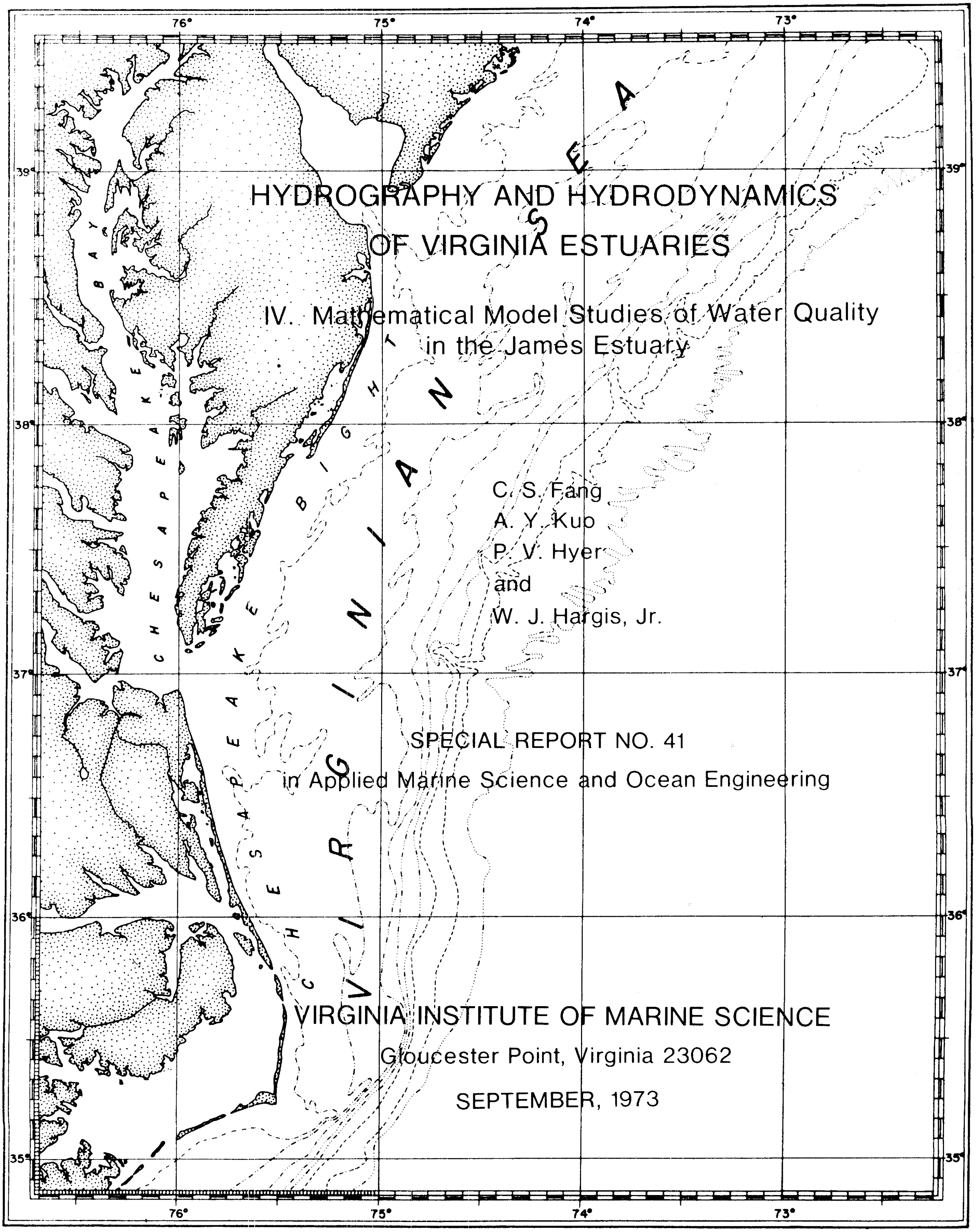
C. S. Fang
Virginia Institute of Marine Science

A. Y. Kuo
Virginia Institute of Marine Science

P. V. Hyer
Virginia Institute of Marine Science

William J. Hargis Jr.
Virginia Institute of Marine Science



HYDROGRAPHY AND HYDRODYNAMICS OF VIRGINIA ESTUARIES

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C. S. Fang
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VIRGINIA INSTITUTE OF MARINE SCIENCE
Gloucester Point, Virginia 23062

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HYDROGRAPHY AND HYDRODYNAMICS OF VIRGINIA ESTUARIES

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by

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Dr. William J. Hargis, Jr.
Director

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SUMMARY

1. The James River Basin is Virginia's largest and most important, containing a quarter of the total land area and over a third of the population. The area is characterized by wet, mild winters and relatively hot and dry summers. Industry in the basin includes petrochemicals, tobacco products, lumber, agriculture, tourism, military bases and space research.

2. A hydrographical survey was conducted in the summer of 1971. Time-series data on temperature, salinity, current, tidal height and dissolved oxygen data were collected from one to three stations on each of fourteen regular transects between Hampton Roads and Richmond. The data were collected between 18 June and 23 August, 1971. Additionally, similar data were collected from several tributaries of the James during the same period (Appomattox and Chickahominy Rivers, and cut-offs at Hatchers Island, Farrar Island, Jones Neck and Turkey Island).

3. Data on long-time variations were collected by means of slack water runs at monthly or semi-monthly intervals. On each slack water run, salinity, temperature, biochemical oxygen demand and dissolved oxygen were sampled at the same fourteen transects. It was found from the slack water runs that salt water intruded to the maximum extent in late fall and intrudes the least in

early spring. At the time of maximum salinity intrusion, the 1 ppt isohaline reaches to about the mouth of the Chickahominy. At the time of minimum intrusion, 1 ppt water may be found opposite Mulberry Island at low water slack.

4. Critical conditions for oxygen depletion, namely, high water temperature and low freshwater discharge were found to occur during the period from the middle of August to the end of September.

   In the Richmond-Hopewell stretch of the James, dissolved oxygen values were often found to be lower than 4 ppm. Occasional values lower than 3 ppm were found in this portion of the James.

   Downstream of the zone influenced by Hopewell wastes, dissolved oxygen values were generally found to be in excess of 5 ppm.

   Warm temperatures in the Richmond-Hopewell stretch of the James often exceeded $25^{o}C$ and in some cases a diurnal fluctuation apparently in direct response to solar heating.

5. The following four models have been completed and verified for the James River estuary.

   i. Explicit scheme salinity model;

   ii. Explicit scheme DO-BOD model;

   iii. Implicit scheme salinity model;

   iv. Implicit scheme DO-BOD model.

6. The accuracy requirements of the input data for the models is determined by the needs of the user. Rough estimates of concentration profiles can be obtained by using a representative range of values for the estuary being studied as input data. If more accurate results are required, data for the model should be obtained from dye releases, velocity measurements, reaeration rate measurements, decay rate studies, benthal deposit studies, photosynthesis studies and other studies.

7. Additional verification of the present models is also needed. The ultimate usefulness of these models can be determined only after extensive computations are made for a wide variety of inter-tidal and intra-tidal conditions.

8. The major advantages of mathematical models are that they can be developed in steps with useful intermediate results, they are relatively inexpensive, actual computer codes can often be applied to many systems with little or no modification, and they have a very low operating cost per "what if". That is to say many alternatives can be considered in a short time and at low cost.

9. For the real-time models, the results appear to be most sensitive to advective transport and least sensitive to the dispersion coefficient. The advective tidal currents were measured with current meters at various transects along the James River estuary.

10. The disadvantage of the steady-state non-tidal model is the greater sensitivity to dispersion coefficients for an estuarine system and the need to relate them to freshwater flows, salinity gradients, and other factors.

11. Because the non-steady state model is a real-time system, it can predict the effect of tidal exchange and excursion on the distribution of a pollutant and, thus, predicts the intratidal variations in water quality.

12. The implicit models are always stable and economically time saving. The input requirements are less stringent and the models are capable of running several alternative data decks back-to-back with a minimum change.

13. A review was made of water quality models used or proposed for use in the James River estuary, enumerating their various features and advantages. The level of sophistication of models in use lags the state-of-the-art of model development, depending on the planner's needs. Advanced dynamics and stochastic models are still at the stage of basic research, and not yet suitable for use in planning.

14. Water quality models based on the non-tidal advective concepts were developed in the pre-computer era as logical extensions of the Streeter-Phelps approach for non-tidal streams and rivers. It is important

to question whether the continued development of the non-tidal advective models is a reasonable exploitation of the capabilities of the computer era.

15. The increasing concern with the total ecological system makes it difficult to ignore the real "time of travel" associated with the tidal motion.

16. The real-time water quality model makes it possible to consider estuarine pollution control by time dependent effluent discharges. For example, a source of pollution located within one tidal excursion of the estuary mouth could make use of a detention basin in order to discharge at a greater rate during the ebb tide portion of the tidal period.

I. INTRODUCTION

One of the prime missions of environmental scientists and engineers is to assess the ultimate effect caused by alterations and human-oriented uses of the environment. Any mathematical expression which describes a physical cause-and-effect relationship can be thought of as a model. Mathematical models are used by scientists to express casual relationships between multiple use pressures and resulting environmental conditions. Water Quality models simulate both quantity and quality of water - both quantity of water and potential pollution of that water.

The objective of this report is to present a technique of mathematical modeling for water quality control and management for the James River estuary and the collection of field data necessary for verification. Recently water quality models have played important roles as predictive tools in helping to make economic and political decisions which will ultimately determine the level of water quality and the type of treatment required for wastes being discharged into natural waters.

All mathematical models are approximations of the complex natural processes which they attempt to represent in a deterministic manner. Theoretically, multi-dimensional models should be better than single dimension models in expressing occurrences in estuaries. It is generally agreed, however, that models involving three spatial dimensions are mathematically and computationally intractable, given the present state of the art. One-dimensional water quality models have the obvious practical advantage of mathematical tractability in comparison with their multi-dimensional counterparts.

The one-dimensional models are best suited for estuaries having vertical and lateral homogeneity. They have also been successfully applied to estuaries with varying degrees of sectional non-homogeneity. In addition, the one-dimensional models utilize and predict information that is related to available or accessible observational data.

Either kind of model requires a given amount of field data for formulation. For an estuarine or tidal river situation, basic information includes: basin geometry, freshwater inflow, water movement (currents), water level fluctuations (tides) and salinity. These parameters must be measured throughout the region to be modeled and, if affected by tidal movement, at frequent intervals for at least one 'typical' tidal cycle. In addition, measurements of diffusion (with dyes), dissolved oxygen, biochemical oxygen demand, suspended sediments and other pertinent parameters should be made spatially and temporally if they have a bearing on the problem under study. Indeed, field data collection can be one of the most expensive stages in development of any model.

The basic formulation for water quality simulation is a mass transfer equation in which the primary dependent variable is concentration of a particular water quality indicator such as BOD, DO and so forth.

The mass transfer equation is a mathematical statement embodying the principle of conservation of mass. It accounts for the various transport processes occurring in an estuarine watercourse, including advective transport of the substance by the flowing water and mixing by longitudinal dispersion. It also accounts for reaction processes which cause the generation or decay of the substance.

Dissolved oxygen, the most common and important biochemical phenomenon in the natural bodies can be viewed as two compensating reactions occurring simultaneously; deoxygenation due to the biochemical oxygen demand or organic wastes, and reaeration due to absorption of atmospheric oxygen at the free surface.

This report has been developed as a part of our ongoing program of development and evaluation of mathematical modeling techniques and of the application of such models and techniques to studies of tidal tributaries and coastal waters. Equal attention is being given to their utility in management, that is to their application in solving practical problems of resource allocation, water quality control and of control of other aspects of tidal and coastal environments and resources.

II. DESCRIPTION OF THE STUDY AREA

The James River in Virginia, the southernmost of the major rivers emptying into the western side of Chesapeake Bay, extends the entire breadth of the state, from its mouth at Hampton Roads to its headwaters in the Appalachian Mountains near the Virginia-West Virginia state line. The James River basin is the largest of Virginia's basins, incorporating just over one-fourth of the states total land area and all or part of 39 counties and 18 cities. Over 2 million people reside in the basin, with the Newport News-Norfolk complex, Hopewell, Richmond and Lynchburg being the major cities along the river path. The basin is approximately 230 miles long and varies from 10 to 90 miles in width.

The tidal portion of the James, herein referred to as the estuarine river, extends 105 miles from the mouth in a general north-west direction to Richmond. Associated with this river section is 3600 square miles of drainage area. Above Richmond the fluvial or riverine portion winds for 230 miles to northern Botetourt county where the Jackson and Cowpasture Rivers meet to form the James. There is 6825 square miles of drainage basin tributary to this part of the river. This study is concentrated on the Tidal James alone considering the fluvial input as the headwaters or principal freshwater source.

Industry in the tidal basin varies. In the Richmond-Hopewell-Petersburg area, heavy chemicals, tobacco products, optics, food products, synthetic fibers and paper, plus much agriculture and lumbering provide the bulk of the industrial basis for the economy of the area. The lower Tidewater area has some agriculture, such as peanuts, but is more dependent on pork and meat processing and chemical processing. However, the mainstay of this area's economy comes from port activities, military complexes, space research facilities, and recreational or historical activities.

Average annual precipitation over the area is 42.5 inches. Snowfall averages from 30 inches per year in the mountain region to 10 inches on the coast. Approximately 34 inches of the average annual precipitation runs off as surface water.

Climatic conditions are such that 80 to 85% of the total average annual evaporation of 40 to 50 inches takes place during the seven-month period from April to October. During this time a relatively small percentage of the rainfall is involved in runoff, the bulk going to plant anabolism or evapotranspiration. During the winter months, this condition reverses.

At the fall line at Richmond, the average flow (based on 37 years of record) is 7,108 cfs., coming from 6,758 square miles of drainage area. Flow has been known to vary from 296,000 cfs to 10 cfs.

Mean tidal range near the mouth of the James at Newport News is 2.6 ft. with a spring range of 3.1 ft. At

Richmond, the mean is 3.2 ft., while the spring range is 3.6 ft.

In the "James River Basin", published by the Division of Water Resources, Volume I through Volume IV have detailed descriptions of the economics and natural resources of the area, a hydrologic analysis, and much other information about the James River and it's basin. Figure 1 is a map of the basin from the mouth of the James to Richmond.

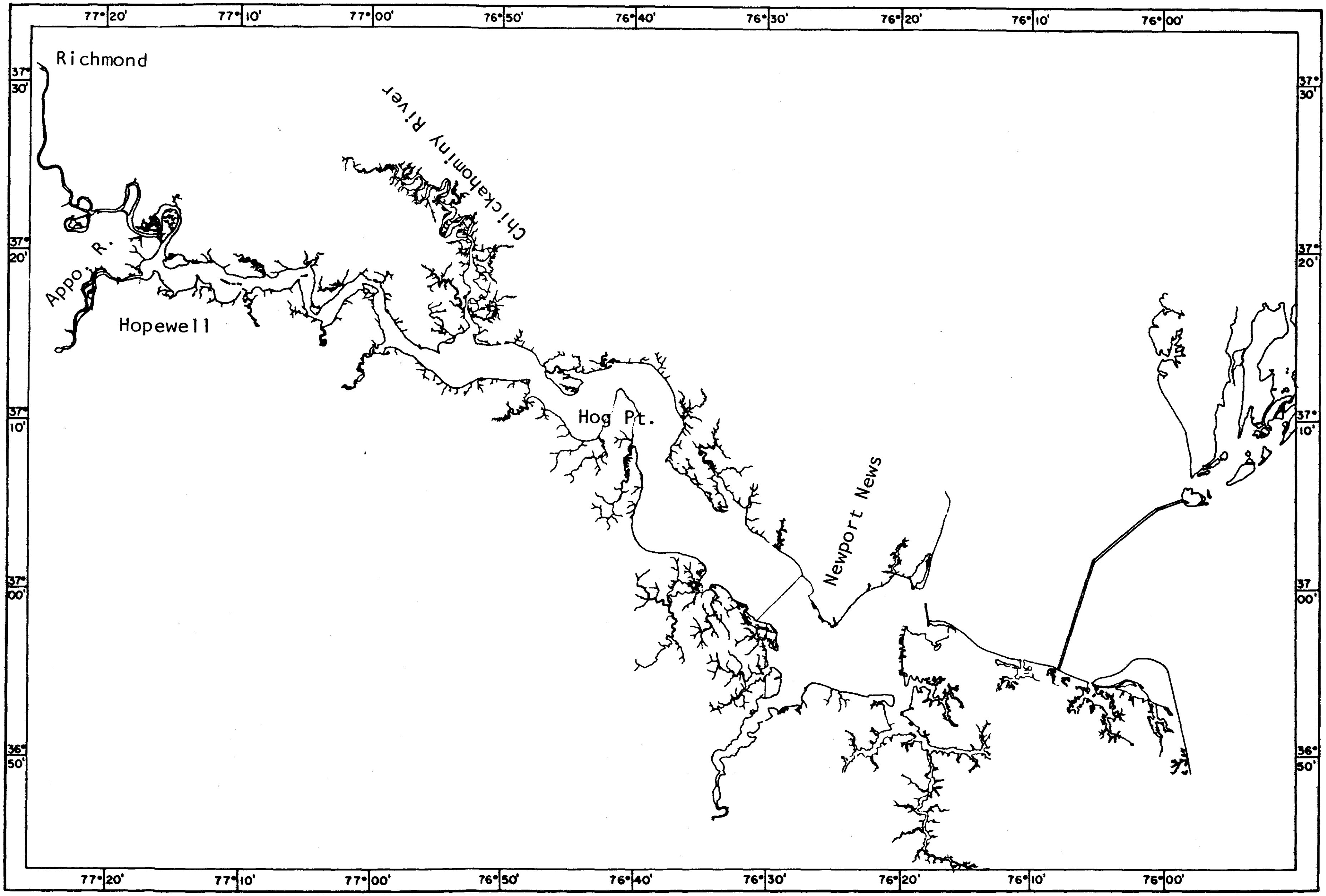


FIGURE 1. JAMES RIVER TIDAL WATER SUB-BASIN.

III. HYDROGRAPHIC SURVEY

The basic requirement in modeling an estuary is the ability to simulate actual estuarine conditions. This can be done physically on a much reduced scale by means of a scale model or by mathematical descriptions. With an accurately developed model, one can predict changes, within known and, usually, reasonable limits, in real conditions due to natural or man-made external phenomena acting on the system. This can be done by a simple turn of a valve or alteration of an equation.

Before accurate models may be developed the conditions to be simulated must, of course, be determined. Mechanisms tending to alter estuarine "states of being" are divided into two major classifications; transport processes (basically hydrodynamic in character) and reaction processes (chemical and biological interactions).

In the first category, all physical phenomena relating to water movement including advection turbulent diffusion and dispersion are grouped. Reaction processes, or those which determine immediate water quality, consist of photosynthesis, respiration, reaeration, deoxygenation and other related activities.

As stated above, the development of correct models depends on the collection of field data to provide basic data for use in design and construction of the model and later calibration and verification. Primary consideration in this study was given to spatial and temporal distributions of salinity and dissolved oxygen in the James River. Therefore, any parameter which could conceivably affect the aforementioned distributions had to be investigated as thoroughly as practicable. Required information included those factors affecting transport processes: basin geometry, freshwater discharge, mean cross-sectional velocities within successive reaches, and mean discharge through cross sections for at least one complete tidal cycle. Those factors which are products of transport and reaction processes; tidal induced fluctuations in water level, mean salinity, and dissolved oxygen for various flow conditions, and longitudinal changes in biochemical oxygen demand for various flow conditions, also had to be thoroughly determined.

The gathering of this basic information was accomplished by two separate, but coordinated, types of field study. The first, a comprehensive study of temperature, salinity, dissolved oxygen, currents and water levels in the tidal portion of the James, was completed during a 42 day period in June and July of 1971. The location of sample stations occupied is depicted in figure 2. In figure 3, these stations are shown schematically with landmarks. Fourteen major transects were sampled during this operation, the distances between them averaging 6 miles. In addition, 2 stations in the Appomattox River and one in the Chickahominy River were sampled. Salinity and DO samples were taken, and temperature measured at hourly intervals on each transect for approximately 96 hours, and

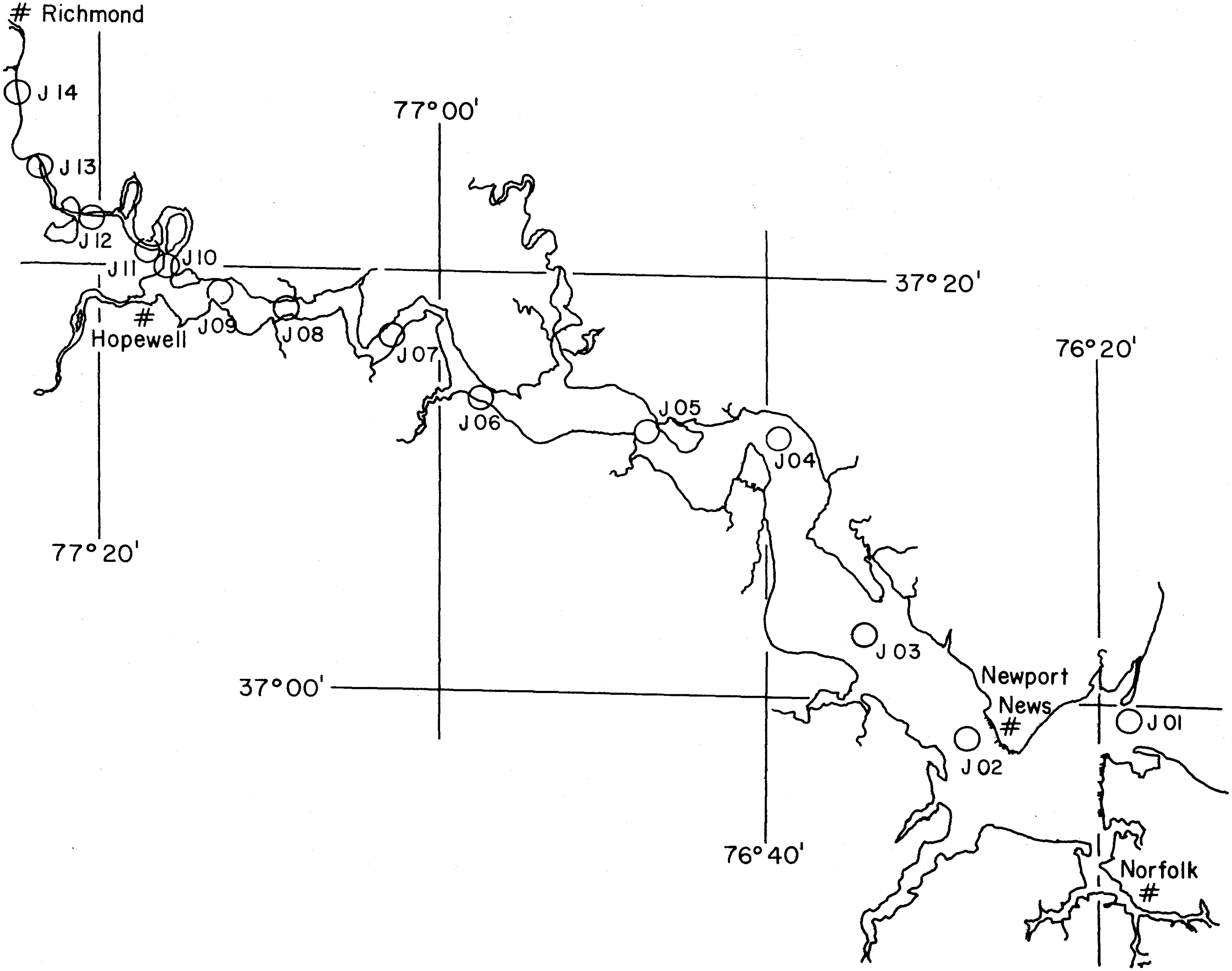


FIGURE 2. OPERATION JAMES RIVER 1971 LOCATION OF SAMPLE STATIONS.

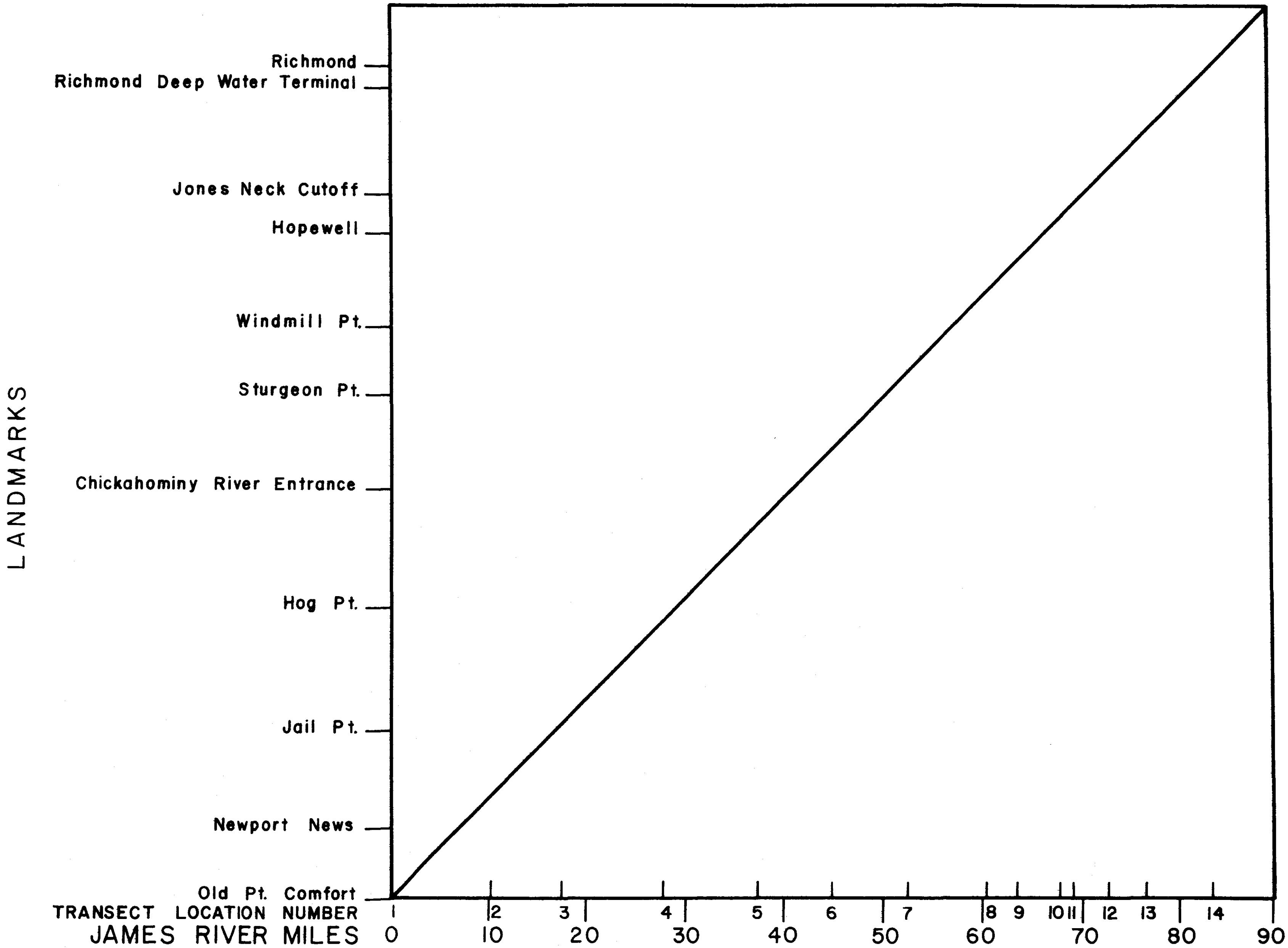


FIGURE 3. HYDROGRAPHICAL SURVEY STATIONS WITH RESPECT TO LANDMARKS.

for key transects, data were gathered for as long as 18 days, continuously.

Current measurements were made automatically by Braincon Model 1381 Histogram current meters placed vertically at 2 meter intervals on steel cable anchored by 600 lb. railroad wheels, and suspended from 14 ft. Braincon "plank-on-edge" buoys. Readings of current velocity and direction were recorded 3 times hourly on film. The films were later analyzed in the physical oceanography laboratory of the Virginia Institute of Marine Science (VIMS).

Salinity and dissolved oxygen samples were taken at surface, mid-depth and bottom levels with Frautschy bottles, then transferred to 130 ml sample bottles to be analyzed later in the laboratory. Salinity levels were obtained using a Beckman Model RS7-A laboratory inductance salinometer. The azide modification of the Winkler method was used to determine dissolved oxygen (DO) in the samples.

Temperature was measured _in situ_ with Applied Research Austin Model ET-100 thermistors and their associated deck-readout meters.

The entire first type of survey was completed by two-man crews in 17 to 22 foot outboard boats, one crew occupying all stations on each transect, and taking samples once each hour.

The second type of study was begun in August of 1970, and is continuing. Once a month, a crew follows slack water before flood or slack water before ebb through the length of the James to Richmond, stopping at the channel station of each of the 14 transects occupied earlier during Operation James River 1971. Weather permitting, both slack water periods are sampled, and in periods of environmental stress, the frequency of these "slack water runs" may be increased to once per day. At each of the stations, temperature is measured, and salinity, dissolved oxygen (DO), and biochemical oxygen demand (BOD) samples are taken at 2-meter intervals from surface to a point just above the bottom.

Table 1 represents the summarized hydrographical survey log.

Analysis of Experimental Data

a.) Data Processing - Data collected in the field and the results of laboratory analyses have been permanently recorded on a magnetic disk.

b.) Data Reduction - From the data stored on the disk, various calculations were made. Section averages of the salinity, dissolved oxygen, and temperature were calculated. These were used to compute tidal exchange fluxes.

Channel widths were determined from U.S. Geological Survey 7.5 minute quadrangles. Cross-sectional areas were determined by planimetry of the bottom profile data in conjunction with the special survey data supplied by the U.S. Army Corps of Engineers, Norfolk District. Section lengths were determined from C&GS navigation charts. The volume

Table 1

Hydrographical Survey
James River, 1971

Station	River Miles	Start Date	Stop Date	Number of Readings	Samples
FO2		20 VI	20 VI	3	T,DO
HO2		20 VI	20 VI	3	T,DO
HOP		23 VI	24 VI	11	T,DO
JN1		22 VI	22 VI	5	T,DO
JN3		19 VI	23 VI	19	T,DO
TO1		19 VI	29 VI	47	T,DO
TO3		20 VI	29 VI	91	T,DO
CO1		8 VII	14 VII	131	T,S,DO
A1A		24 VI	30 VI	129	T,DO
A1B		24 VI	30 VI	127	T,DO
A1C		24 VI	30 VI	119	T,DO
A2A		25 VI	30 VI	65	T,DO
A2B		25 VI	30 VI	64	T,DO
A2C		25 VI	30 VI	63	T,DO
JO2A	J(10.3)	21 VII	26 VII	136	T,S,DO
JO2B	"	21 VII	26 VII	141	T,S,DO
JO2C	"	21 VII	26 VII	139	T,S,DO
JO3A	J(17.9)	22 VII	26 VII	106	T,S,DO
JO3B	"	21 VII	26 VII	98	T,S,DO
JO4A	J(28.2)	15 VII	21 VII	164	T,S,DO
JO4B	"	15 VII	21 VII	186	T,S,DO
JO4C	"	15 VII	21 VII	154	T,S,DO
JO5A	J(37.4)	15 VII	21 VII	132	T,S,DO
JO5B	"	14 VII	21 VII	155	T,S,DO
JO5C	"	14 VII	21 VII	156	T,S,DO
JO6A	J(45.0)	10 VII	14 VII	63	T,S,DO
JO6B	"	8 VII	14 VII	169	T,DO
JO6C	"	10 VII	14 VII	60	T,DO
JO7A	J(52.8)	10 VII	14 VII	64	T,DO
JO7B	"	8 VII	14 VII	165	T,DO
JO7C	"	10 VII	14 VII	60	T,DO
JO8A	J(60.3)	10 VII	26 VII	308	T,DO
JO8B	"	8 VII	26 VII	386	T,DO
JO8C	"	10 VII	26 VII	319	T,DO
JO9A	J(64.0)	24 VI	30 VI	137	T,DO
JO9B	"	24 VI	30 VI	134	T,DO
JO9C	"	24 VI	30 VI	135	T,DO
J10A	J(68.3)	24 VI	30 VI	107	T,DO
J10B	"	23 VI	30 VI	124	T,DO
J10C	"	24 VI	30 VI	117	T,DO
J11A	J(69.9)	22 VI	29 VI	143	T,DO
J11B	"	18 VI	30 VI	266	T,DO
J11C	"	22 VI	29 VI	142	T,DO
J12A	J(73.2)	19 VI	23 VI	53	T,DO
J12B	"	19 VI	23 VI	39	T,DO
J12C	"	19 VI	23 VI	15	T,DO

Table 1 (cont'd)

Station	River Miles	Start	Stop	Number of Readings	Samples
J13A	J(77.3)	19 VI	23 VI	73	T,DO
J13B	"	18 VI	23 VI	111	T,DO
J13C	"	19 VI	23 VI	72	T,DO
J14B	J(83.4)	18 VI	23 VI	113	T,DO
A1A		11 VIII	13 VIII	36	T,DO
A1B		11 VIII	13 VIII	40	T,DO
J01A	J(0.0)	8 VII	26 VII	314	T,S,DO
J01B	"	9 VII	26 VII	198	T,S,DO
J01C	"	8 VII	26 VII	185	T,S,DO
J03A	J(17.9)	7 VIII	22 VIII	162	T,S,DO
J03B	"	7 VIII	22 VIII	211	T,S,DO
J03C	"	7 VIII	22 VIII	179	T,S,DO
J05A	J(37.4)	17 VIII	23 VIII	127	T,S,DO
J05B	"	17 VIII	23 VIII	136	T,S,DO
J06A	J(45.0)	17 VIII	23 VIII	89	T,S,DO
J06B	"	17 VIII	23 VIII	106	T,S,DO
J06C	"	17 VIII	23 VIII	90	T,S,DO
J07A	J(52.8)	17 VIII	23 VIII	125	T,DO
J07B	"	17 VIII	23 VIII	116	T,DO
J07C	"	17 VIII	23 VIII	117	T,DO
J08A	J(60.3)	13 VIII	17 VIII	58	T,DO
J08B	"	14 VIII	16 VIII	35	T,DO
J09A	J(64.0)	11 VIII	18 VIII	96	T,S,DO
J09B	"	11 VIII	18 VIII	101	T,S,DO
J09C	"	11 VIII	17 VIII	82	T,DO
J10A	J(68.3)	11 VIII	17 VIII	84	T,DO
J10B	"	11 VIII	17 VIII	79	T,DO
J10C	"	11 VIII	17 VIII	80	T,DO
J11A	J(69.9)	11 VIII	17 VIII	81	T,DO
J11B	"	11 VIII	17 VIII	83	T,DO
J11C	"	11 VIII	17 VIII	85	T,DO
J12A	J(73.2)	6 VIII	11 VIII	81	T,DO
J12B	"	6 VIII	11 VIII	101	T,DO
J12C	"	6 VIII	11 VIII	82	T,DO
J13A	J(77.3)	6 VIII	11 VIII	103	T,DO
J13B	"	6 VIII	11 VIII	108	T,DO
J13C	"	6 VIII	11 VIII	96	T,DO
J14A	J(83.4)	6 VIII	11 VIII	81	T,DO
J14B	"	6 VIII	11 VIII	103	T,DO
J14C	"	6 VIII	11 VIII	95	T,DO

Station Designations:
- FO2: Farrah Island
- HO2: Hatcher Island
- HOP: James River near Hopewell
- JN1 & JN3: Jones Neck (only 1 station)
- TO1 & TO3: Turkey Island
- CO1: Chickahominy River
- A1A-A2C: Appomattox River
- JO1A-J14C: James River

Table 1 (cont'd)

Station	River Miles	Start	Stop	Currents
F01		18 VI	23 VI	G
H01		18 VI	23 VI	G
JN1		18 VI	23 VI	G
T01		18 VI	30 VI	G
C01		09 VII	14 VII	G
A1A		24 VI	30 VI	G
A1B		24 VI	30 VI	F
A1C		24 VI	30 VI	G
A2A		24 VI	30 VI	G
A2B		24 VI	30 VI	G
A2C		24 VI	30 VI	G
J01A	J(0.0)	07 VII	26 VII	G
J01B	"	07 VII	26 VII	P
J01C	"	07 VII	26 VII	G
J02A	J(10.3)	21 VII	26 VII	G
J02B	"	21 VII	26 VII	G
J02C	"	21 VII	26 VII	G
J03A	J(17.9)	21 VII	26 VII	G
J03B	"	21 VII	26 VII	G
J04A	J(28.2)	15 VII	21 VII	G
J04B	"	15 VII	21 VII	P
J04C	"	15 VII	21 VII	G
J05A	J(37.4)	15 VII	21 VII	G
J05B	"	14 VII	21 VII	G
J05C	"	14 VII	21 VII	G
J06A	J(45.0)	10 VII	14 VII	G
J06B	"	08 VII	14 VII	G
J06C	"	10 VII	14 VII	P
J07A	J(52.8)	10 VII	14 VII	G
J07B	"	08 VII	14 VII	G
J07C	"	10 VII	14 VII	G
J08A	J(60.3)	10 VII	26 VII	G
J08B	"	08 VII	26 VII	G
J08C	"	10 VII	26 VII	G
J09A	J(64.0)	24 VI	30 VI	G
J09B	"	24 VI	30 VI	G
J09C	"	24 VI	30 VI	G
J10B	J(68.3)	23 VI	30 VI	F
J10C	"	24 VI	30 VI	G
J11A	J(69.9)	22 VI	30 VI	G
J11B	"	18 VI	30 VI	G
J11C	"	22 VI	30 VI	G
J12A	J(73.2)	19 VI	23 VI	G
J12B	"	18 VI	30 VI	G
J12C	"	19 VI	23 VI	G

Table 1 (cont'd)

Station	River Miles	Start	Stop	Currents
J13A	J(77.3)	19 VI	23 VI	G
J13B	"	18 VI	23 VI	F
J13C	"	19 VI	23 VI	G
J14B	J(83.4)	18 VI	23 VI	G
A1A		11 VIII	17 VIII	G
A1B		11 VIII	17 VIII	G
J03A	J(17.9)	05 VIII	23 VIII	G
J03B	"	05 VIII	23 VIII	G
J03C	"	05 VIII	23 VIII	F
J05A	J(37.4)	17 VIII	23 VIII	G
J05B	"	17 VIII	23 VIII	G
J06A	J(45.0)	17 VIII	23 VIII	P
J06B	"	17 VIII	23 VIII	G
J06C	"	17 VIII	23 VIII	G
J07A	J(52.8)	17 VIII	23 VIII	P
J07B	"	17 VIII	23 VIII	G
J07C	"	17 VIII	23 VIII	G
J08A	J(60.3)	12 VIII	17 VIII	F
J08B	"	12 VIII	17 VIII	G
J09A	J(64.0)	12 VIII	17 VIII	G
J09B	"	12 VIII	17 VIII	F
J09C	"	12 VIII	17 VIII	G
J10A	J(68.3)	11 VIII	17 VIII	G
J10B	"	11 VIII	17 VIII	G
J10C	"	11 VIII	17 VIII	G
J11A	J(69.9)	11 VIII	17 VIII	G
J11B	"	11 VIII	17 VIII	P
J11C	"	11 VIII	17 VIII	G
J12A	J(73.2)	06 VIII	11 VIII	G
J12B	"	06 VIII	11 VIII	G
J12C	"	06 VIII	11 VIII	G
J13B	J(77.3)	06 VIII	11 VIII	P
J13C	"	06 VIII	11 VIII	G
J14A	J(83.4)	06 VIII	11 VIII	G
J14B	"	06 VIII	11 VIII	G
J14C	"	06 VIII	11 VIII	G

F01: Farrar Island
H01: Hatcher Island
JN1: Jones Neck
T01: Turkey Island
C01: Chickahominy River
A1A-A2C: Appomattox River
J01A-J14C: James River

G - Good 85-100% Good Data
F - Fair 60-85% Good Data
P - Poor Less Than 60% Good Data

of a section was taken to be the mean of the end cross-sectional areas times the section length.

Tidal exchange fluxes were calculated from the vertical integrals of the longitudinal components of velocity. These were averaged over a cross-section and multiplied by the mean areas, as determined from the bottom profile measurements. This approach is a simplification of Harlacher's method (Troskolanski, 1967).

Tide gauge records were corrected for the elevation of the staff with respect to sea level (1929 datum) by surveyors from the Virginia Department of Highways, for variations in the paper feed rate, and then replotted.

IV. HYDROGRAPHICAL SURVEY RESULTS

Figure 4 shows the longitudinal profiles of mean depth for the James River. Figure 5 shows accumulated drainage area of the James estuary.

Table 2 summarizes the geometric data for the system, showing the cross-sectional areas, widths and hydraulic depths at mean tidal height (U.S.C.&G.S. 1971).

Table 3 depicts the local inflow drainage area in the James, from Richmond downstream to Hampton Roads. Figure 5 is a schematic of the information given in Table 3.

Table 4 represents the discharge record of the U.S. Gauging Station near Richmond, Va. during the months of June, July and August of 1971 and Appomattox at Matoaca, for the same months.

Table 5 lists tidal wetland acreage in different counties in estuaries of the James River (supplied by Dr. M. Wass of VIMS).

Table 6 consists of those calculated seven and fourteen consecutive day low flow values near the U.S.G.S. Richmond gauging station, with respect to probability percentage.

Appendix A shows the monthly slack water runs results.

Appendix B includes the profiles of the cross sections, with local mean low water as the datum (U.S.C.&G.S. 1971).

The results of the tidal observations are shown in the figures in Appendix C. The heights shown are referred to mean sea level (1929 datum plain).

Appendix D is the graphical summary of data collected during Operation James, June, July and August 1971.

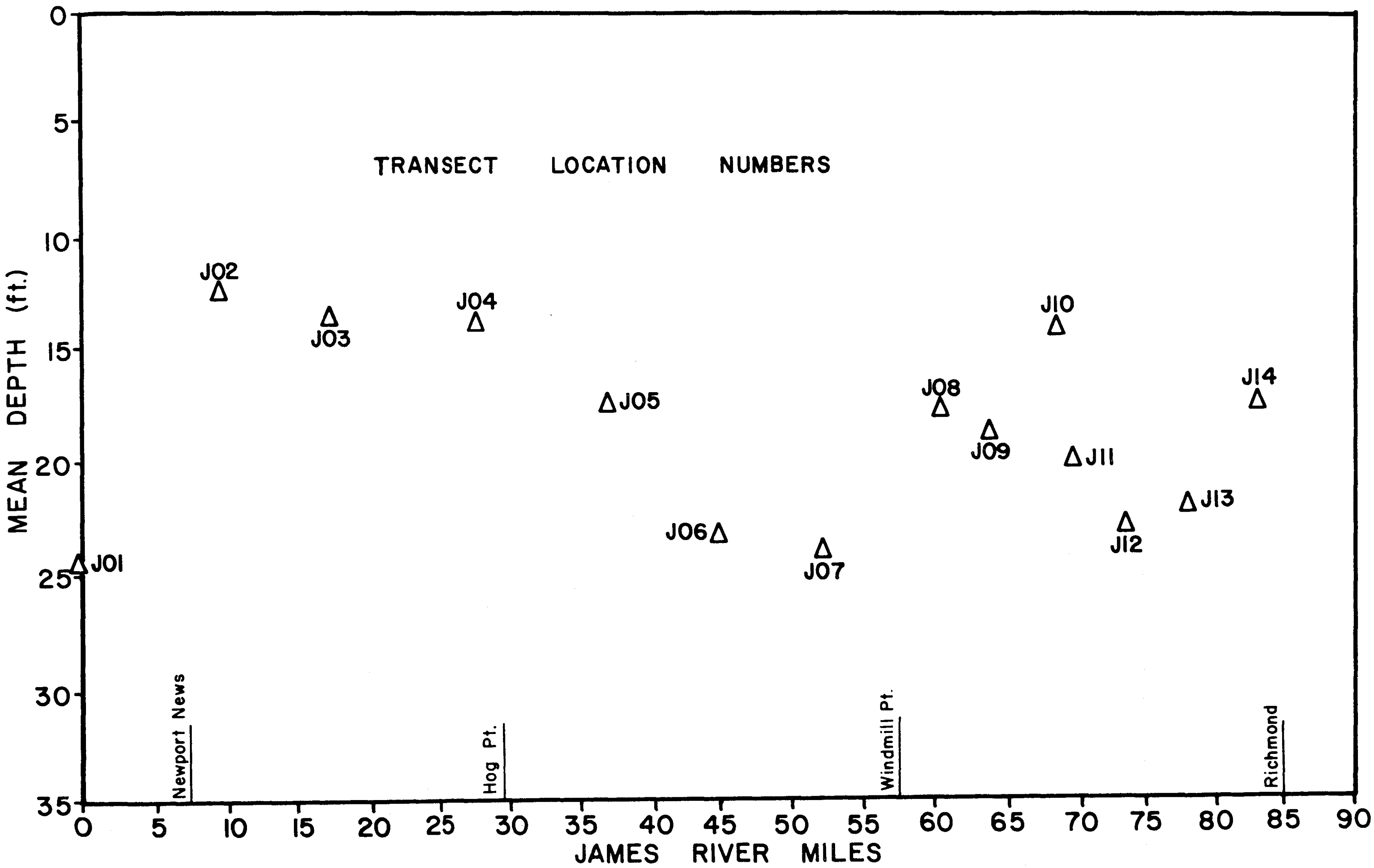


FIGURE 4. LONGITUDINAL PROFILES OF MEAN DEPTH.

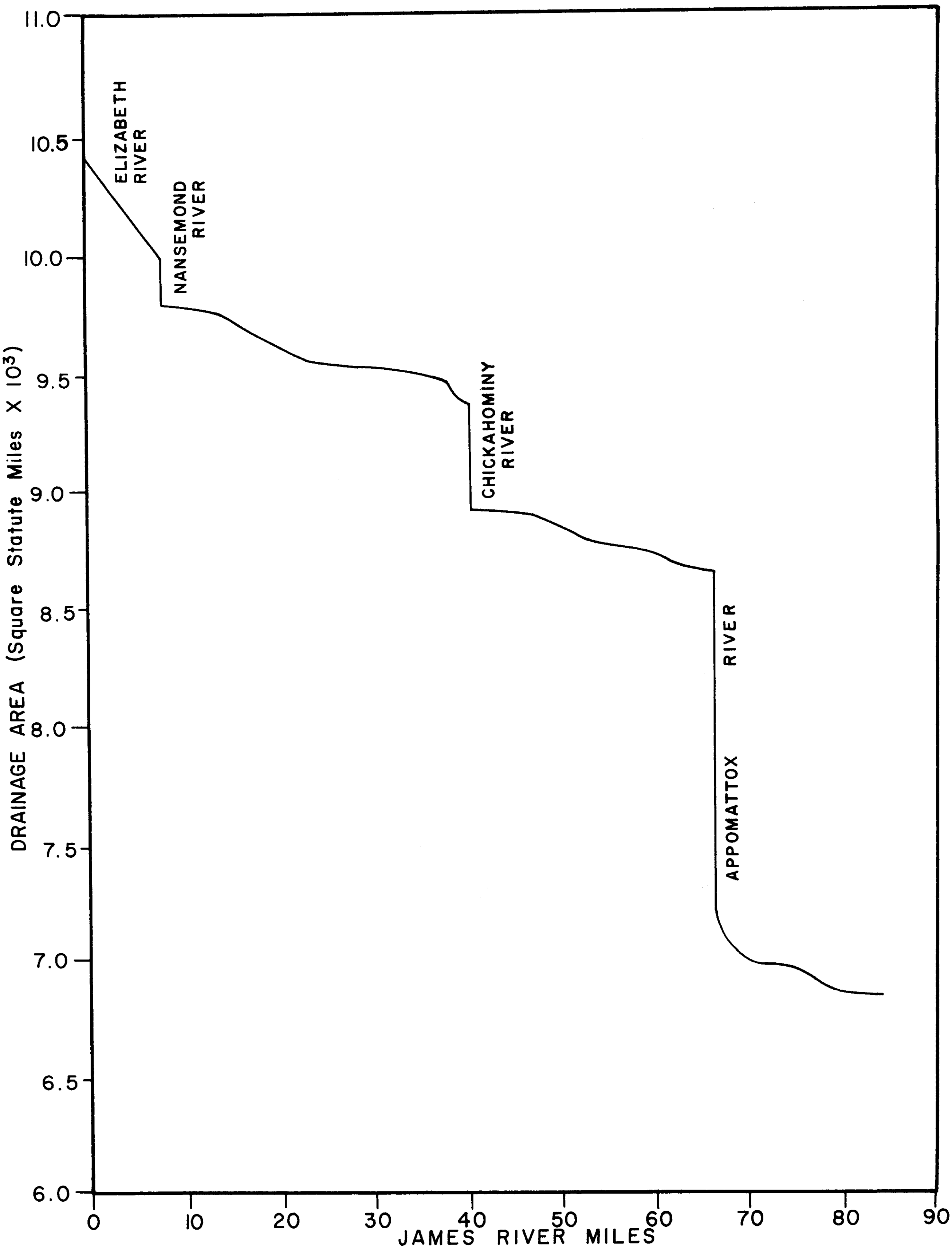


FIGURE 5. CUMULATIVE DRAINAGE AREA.

Table 2

Geometric Data for the System

Cross-Section Number	Cross-Sectional Area (ft^2)	Width (ft)	Mean Depth (ft)
2	8,490	477	17.8
3	12,300	572	21.5
4	11,420	514	22.2
5	17,390	749	23.2
6	20,160	1003	20.1
7	33,460	2323	14.4
8	33,560	3356	10.0
9	89,000	4659	19.1
10	63,000	3480	18.1
11	80,000	6600	12.6
12	56,600	3215	17.6
13	83,170	3436	24.2
14	51,750	1500	34.5
15	100,200	6000	16.7
16	91,650	3900	23.5
17	172,000	12554	13.7
18	91,180	5459	16.7
19	149,700	9018	16.6
20	200,700	14438	13.9
21	229,000	10043	22.8
22	294,300	21962	13.4
23	320,000	22857	14.0
24	328,000	26031	12.6
25	481,200	21675	22.2
26	304,700	12539	24.3

Table 3

Local Inflow Drainage Area

Cross-Section Number	Distance From Mouth (ft.)	Distance (Nautical Miles)	Drainage Area (mi^2)	Cumulative Drainage Area (mi^2)
Upstream of 2			6825	
2	506746	83.4		6825
			15	
3	487902	80.3		6840
			60	
4	469674	77.3		6900
			65	
5	444763	73.2		6965
			35	
6	424712	69.9		7000
			15	
7	414990	68.3		7015
			1610	
8	405269	66.7		8625
			35	
9	388864	64.0		8660
			55	
10	366382	60.3		8715
			33	
11	352408	58.0		8748
			27	
12	339648	55.9		8775
			40	
13	320812	52.8		8815
			22	
14	304407	50.1		8837
			30	
15	289825	47.7		8867
			30	
16	273420	45.0		8897
			469	
17	250331	41.2		9366
			44	
18	227242	37.4		9410
			40	
19	208406	34.3		9450
			70	
20	171343	28.2		9520
			47	
21	143393	23.6		9567
			83	
22	108760	17.7		9650
			95	
23	89317	14.7		9745
			25	
24	62582	10.3		9770
			210	
25	42532	7.0		9980
			438	
26	0	0.0		10418

Table 4

Discharge Record in Cubic Feet Per Second

Day	James R. Near Richmond June	July	August	Appomattox R. Near Matoaca June	July	August
1	86700	3320	2230	9740	486	362
2	74400	3450	2160	9380	540	525
3	31100	3450	2330	8860	545	505
4	18900	3200	2090	8690	428	565
5	17400	3100	3320	8180	377	704
6	13500	3320	5550	4380	330	746
7	10900	3320	3580	1450	316	758
8	9510	3580	3320	1120	284	606
9	9700	3450	2800	800	264	414
10	8380	3150	2140	612	267	309
11	7150	3380	2090	535	270	292
12	6160	5700	1790	500	270	298
13	5400	4450	1690	464	267	236
14	5700	3700	1400	436	251	222
15	6000	2950	1580	960	210	215
16	5850	3320	2090	1320	202	200
17	8760	3050	1830	1780	210	192
18	10900	2070	1790	1450	198	198
19	10500	1880	2090	1160	185	205
20	8020	1760	2310	830	190	200
21	6320	1790	2090	699	185	212
22	5700	1580	1970	1590	185	222
23	5260	1670	1530	2510	185	233
24	5550	1190	1050	1740	185	292
25	5260	1010	1160	1160	185	220
26	4840	1210	890	1240	185	198
27	5260	1030	2880	860	190	436
28	4840	1350	6160	644	188	2410
29	4320	1690	4200	530	188	2450
30	3580	1460	2900	495	185	2510
31	-	2020	1900	-	202	1680
Total	405860	81600	74910	74115	8153	18615
Mean	13530	2632	2416	2471	263	600
Max.	86700	5700	6160	9740	545	2510
Min.	3580	1010	890	436	185	192

(U.S.G.S. Richmond and Matoaca, Virginia)

Table 5-1. Appomattox River Basin Wetlands
(in sequential order from the river mouth)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Acres Swamp
1	Rivermont	Hopewell	220	113
2	Cobbs Island	Hopewell	34	95
3	Sunken Island	Hopewell	24	-
4	Ashton Creek	Hopewell	42	46
5	Gilliams Island	Hopewell	108	123
6	Back Creek Island	Hopewell	35	95
7	Cat Island	Hopewell	11	36
8a	Swift Creek	Hopewell	17	173
8b	Swift Creek	Chester	68	270
9a	Halls Island	Hopewell	30	246
9b	Halls Island	Chester	15	92
9c	Halls Island	Petersburg		61
10	Conduit Road	Hopewell		48
11	Colonial Heights Creek	Chester		75
12	Wallace Creek Area	Sutherland		18
13	Bevils Bridge	Mannboro	10	12
14	East Sappony Creek	Mannboro		11
15	Carver's Branch	Mannboro		102
		Subtotals	614	1616
		Grand Total		2230

Table 5-2. Chickahominy River Basin Wetlands

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Acres Swamp
1	Barrets Point	Surry		29
2	Tomahund Creek	Brandon	230	
3	Gordon Island and Gordon Creek	Brandon and Norge	1990	41
4	Bush Neck	Brandon and Norge	410	
5	Morris Creek	Brandon	522	13
6	Blackstump Creek	Norge	412	
7	Eagle Bottom	Brandon	84	
8	Yarmouth and Shipyard Creek	Norge	594	
9	Creek above Eagle Bottom	Brandon	18	
10	Parson's Island and Old Neck	Brandon	1280	
11	Creek between Shipyard Creek and Hog Neck Creek	Brandon and Norge	96	
12	Hog Neck Creek	Norge	186	
13	Big Marsh Point	Brandon	212	
14	Watts Point	Brandon	45	24
15	Mill Creek	Walkers	66	
16	Diascund Creek	Walkers	100	164
17	Wilcox Neck	Walkers	279	94
18	Turner Neck	Walkers	100	72
19	Matahunk Neck	Walkers	180	80
20	Walkers	Walkers	62	53
21	Johnson Creek	Walkers	97	45
22	Osborn Landing	Walkers		162
23	Binns Bar	Walkers		44
24	Cypress Bank Landing	Walkers		71
25	Big Swamp	Walkers		13
26	Winns Landing	Walkers		74
27	Winns Landing to Holly Landing	Providence Forge		870
28	Stony Run to Schiminoe Creek	Providence Forge		461
29	Schiminoe Creek to Nance Creek			
30	Roxbury to Henrico Co. and Charles City Co. Boundary	Roxbury		1254
31	White Oak Swamp	Roxbury		987
32	Bottoms Bridge Area	Quinton		848
33	Below Grapevine Bridge to Mechanicsville	Seven Pines		687
34	Mechanicsville to above Upham Brook	Richmond		578
		Subtotal	6963	7431
		Grand Total		14394

Table 5-3. James River Basin (proper) Wetlands

(James River Basin Wetlands below the fall line in sequential order from the mouth)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Acres Swamp
1	Hampton Flats	Hampton	13	
2	Hoffler Cr.	Newport News South	171	
3	Streeter Cr.	Newport News South	85	4
4	Frederick College	Newport News South		10
5a	Ragged Isl.	Newport News South	310	
5b	Ragged Isl.	Benns Church	411	
6	James R. Country Club	Mulberry Isl.	10	
7	Blunt Point	Mulberry Isl.	11	
8	Mulberry Isl.	Mulberry Isl. and Yorktown	1275	20
9	Goose Island	Yorktown	11	
10	Lawnes Cr.	Hog Isl. and Bacons Castle	680	
11	Hog Isl.	Yorktown	410	
12	Chippokes Cr.	Hog Isl.	362	36
13a	College Run	Hog Isl.	29	118
13b	College Run	Surry,Va.		95
14	Mill Farm Run	Surry,Va.		15
15	Grove Cr.	Hog Isl.	110	75
16	Blizzards Cr.	Surry,Va.		28
17	Cedar Field Cr.	Surry,Va.		26
18	Crouch Cr.	Surry,Va.	123	186
19	Passmore Cr.	Surry,Va.	295	-
20	Jamestown Isl.	Surry,Va.		10
21	Back River	Surry,Va.	119	-
22	Pitch and Tar Swamp	Surry,Va.	150	-
23	Sandy Bay	Surry,Va.	200	-
24	C.N.H. Parkway	Surry,Va.	18	-
25	Powhatan Cr.	Surry,Va.	235	95
26	Mill Cr.	Surry,Va.	-	8
27	Grays Cr.	Surry,Va.	603	390
28	Black Duck Gut	Surry,Va.	53	25
29	Four Mile Tree	Surry,Va.	-	9
30	Broad Swamp	Surry,Va.	-	66
31	Lake Pashehegh	Surry,Va.	10	-
32	Tidal Flat	Surry,Va.	50	8
33	Mud Marsh	Surry,Va.	78	
34	Barrets Pt.	Surry,Va.	62	
35	Camp Lions	Claremont		34
36	Eastover Area	Claremont		38
37	Dancing Pt.	Claremont	14	93
38	Sunken Meadow Pond	Claremont	32	10
39	Sandy Pt.	Claremont		34
40	Sloop Pt.	Claremont		11

Table 5-3 (cont'd)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Acres Swamp
41	Upper Chippakes Cr.	Claremont	51	58
42	Kennon Marsh	Charles City	410	266
43	Upper Brandon	Charles City	30	-
44	Harrison	Charles City	11	-
45	Willow Hill	Charles City		20
46	Wards Cr.	Charles City	45	-
47	Tyler Cr.	Charles City	15	8
48	Morris Cr.	Charles City		90
49	Mapsico	Charles City	40	15
50	Kittewan Cr.	Charles City	296	148
51	Weyanoke Pt.	Charles City	170	50
52	Hundred Cr.	Charles City	70	100
53	Flowerdew Hundred	Charles City		128
54	Queens Cr.	Charles City	75	97
55	Gunns Run	Charles City	80	65
56	Buckland Cr.	Charles City		85
57	Herring Cr.	Westover	314	310
58	Harrison Lake	Westover		120
59	Powell Cr.	Westover	165	452
60	James R. Isl.	Westover	29	8
61	Chappell Cr.	Westover		110
62	Jenny Cr.	Westover		106
63	Harrison Pt.	Westover	14	15
64	Eppes Cr. and Isl.	Westover		147
65	Bailey Creek	Hopewell	30	309
67	Gravelly Run	Hopewell	20	-
68	Oil Terminal	Hopewell	5	-
69	Eppes Isl.	Hopewell		159
70	Eppes Cr.	Hopewell	38	132
71	Johnsons Cr.	Hopewell	65	200
72	Bermuda Hundred	Hopewell		20
73	Turkey Isl.	Hopewell	90	-
74	Prescue Isl.	Hopewell		600
75	Curles Neck	Hopewell	160	817
76	J. R. Old Channel	Hopewell	47	24
77	J. R. Old Channel	Hopewell	14	50
78	Pike Swamp	Hopewell	30	12
79	Turkey Isl.	Dutch Gap	165.1	175.9
80	Jones Neck	Dutch Gap	85.2	
81	Meadowville Swamp	Dutch Gap		130.4
82	Aiken Swamp	Dutch Gap		22.5
83	Hatcher Isl.	Dutch Gap	17.6	19.6
84	J. R. Farrar Isl.	Chester,Va.	32	28
		Subtotal	8543.9	6689.4
		Grand Total		15233.3

Table 5-4. Lafayette River Basin Wetlands

(James River Basin Wetlands below the fall line in sequential order from the mouth)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Acres Swamp
1	Lawless Pt.	Norfolk North,Va.	3	-
2	Millbrook Rd.	Norfolk North,Va.	3	-
3	Granby H. S.	Norfolk North,Va.	3	-
4	Talbot Park	Norfolk North,Va.	3	-
5	Belvedere Rd.	Norfolk North,Va.	4	-
6	Blake St.	Norfolk North,Va.	3	-
7	Summers Dr.	Norfolk North,Va.	15	-
8	Wayne Cr. and Charters Isl.	Norfolk North,Va.	44	-
9	Lakewood Pt.	Norfolk North,Va.	9	-
10	Lakewood Shores	Norfolk North,Va.	8	-
11	Hancock Ave.	Norfolk South,Va.	4	-
12	Somme Ave.	Norfolk South,Va.	5	-
13	Ballentine Pl.	Norfolk South,Va.	42	-
		Grand Total	146	

Table 5-5. Elizabeth River Basin Wetlands

(James River Basin Wetlands below the fall line in sequential order from the mouth)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Acres Swamp
1	Craney Isl. and Cr.	Norfolk North,Va.	58	-
2	Lake Kingman	Norfolk South,Va.	10	-
Eastern Branch				
3	Broad Cr.	Kempsville	20	-
4	Upper Eastern Branch	Kempsville	120	32
5	Elizabeth River Shores	Kempsville	6	-
6	Indian River	Kempsville	6	-
Southern Branch				
7	Jones Cr.	Norfolk South,Va.	11	-
8	Gilligam Cr.	Norfolk South,Va.	11	-
9	Paradise Cr.	Norfolk South,Va.	62	-
10	Blows Cr.	Norfolk South,Va.	29	-
11	Milldam Cr.	Norfolk South,Va.	71	3
12	St. Julian Cr.	Norfolk South,Va.	26	-
13	Newton Cr.	Norfolk South,Va.	53	13
14	Ind. Waste Pond	Norfolk South,Va.	22	12
15	Hodges Cr.	Norfolk South,Va.	2	-
16	Junction Deep Cr. and S. Branch	Norfolk South,Va.	67	74
17	Deep Creek	Norfolk South,Va.	41	3
18	Mains Creek	Norfolk South,Va.	37	-
19	Millville to Great Bridge	Deep Creek,Va.	560	30
20	Mill Creek	Deep Creek,Va.	70	-
Western Branch				
21	West Norfolk	Norfolk South,Va.	6	-
22	Lilly Cr.	Norfolk South,Va.	10	-
23	Baines Cr.	Norfolk South,Va.	68	-
24	Pinehurst	Norfolk South,Va.	7	-
25	Sterns Cr.	Bowers Hill,Va.	47	-
26	Drum Pt. Cr.	Bowers Hill,Va.	69	-
27	Bailey Cr.	Bowers Hill,Va.	120	-
28	Green Lawn Memorial Park	Bowers Hill,Va.	15	-
29	Goose Cr.	Bowers Hill,Va.	75	-
		Subtotal	1845	167
		Grand Total		2012

Table 5-6. Nansemond River Basin Wetlands
(in sequential order from the river mouth)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Acres Swamp
1	West Creek	Newport News South	95	
2	Cedar Point	Newport News South	36	
3	Bleak Horn	Newport News South	76	
4	Pike Point	Newport News South	2.3	
5	Knotts Creek	Newport News South and Bowers Hill	211	7
6	Knotts Neck and Bennett Creek	Bowers Hill	606	33
7	Bennett Harbor	Chuckatuck	210	
8	Cedar Creek	Chuckatuck	66	
9	Nenita	Chuckatuck	62	
10	Glebe Point	Chuckatuck	51	
11	Shackley Marsh	Chuckatuck	87	
12	Oyster House	Chuckatuck	326	
13	Wilroy Swamp	Chuckatuck	448	
14	Stockley Marsh	Chuckatuck	314	
15	Pumping Station	Chuckatuck	83	
16	Western Branch Marsh	Chuckatuck	115	
17	Abraham Point	Chuckatuck	118	
18	Brock Point	Chuckatuck	115	
19	Thompson Landing	Chuckatuck	162	
20	Pinner Marsh	Chuckatuck	111	
21	Muskrat Bluff	Chuckatuck	216	
22	Willowbrook Marsh	Chuckatuck	136	
		Subtotal	3646.3	40
		Grand Total		3686.3

Table 5-7. Chuckatuck Creek Basin Wetlands
(in sequential order from the river mouth)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Swamp
1	Windall Creek	Benns Church	60	16
2	Smith Neck Cr.	Benns Church	23.4	
3	Brewers Creek	Benns Church	318	
4	Green Swamp Creek	Benns Church	68	
5	Tower Chuckatuck Cr.	Benns Church	374	
		Subtotal	843.4	16
		Grand Total		859.4

Table 5-8. Pagan River Basin Wetlands
(in sequential order from the river mouth)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Swamp
1	Goodwin Point	Mulberry	25	
2	Williams Cr.	Mulberry	408	
3	Jones Cr.	Benns Church	975	
4	Cypress Cr.	Benns Church	768	
		Grand Total	2174	

Table 5-9. Warwick River Basin Wetlands
(in sequential order from the river mouth)

Number	Name	U.S.G.S. Quadrangle	Acres Marsh	Acres Swamp
1	Fishers Creek	Mulberry Isl.	48	
2	Beverly Hills	Mulberry Isl.	30	
3	Deep Creek	Mulberry Isl.	108	
4	Jordan	Mulberry Isl.	12	
5	Young	Mulberry Isl.	62	
6	Holloway	Mulberry Isl.	14	
7	Yank	Mulberry Isl.	42	
8	Lukas Cr.	Mulberry Isl.	220	
9a	Warwick R. Marsh		279	
9b	Warwick R. Marsh	Yorktown	579	
		Grand Total	1394	

Table 6

Minimum Average 7 and 14 Consecutive Day Low Flows at Richmond Gauging Station (USGS, Richmond, Va.)

Probability of Occurrence of Lower Flow	14 days cfs	7 days cfs
0.02	450	378
0.05	550	465
0.10	665	560
0.50	1200	1050
0.90	2200	1950
0.98	3150	2850

V. DISPERSION AND WATER QUALITY MATHEMATICAL MODELS

The principal element of a mathematical model of water quality is essentially a mathematical representation of the water quality cause-and-effect relationships. The mathematical representation for the James River model is the mass-balance equation which describes the fate of a pollutant after being introduced into a water body. The equation consists of terms representing various physical phenomena which act upon a dissolved or suspended substance in a flow field, such as transport by convection, by dispersion, disappearance due to decay or to a sink, and additions due to sources, man-made or natural.

In the microscopic sense, the transport of dissolved substance in a water body is invariably caused by the movement of water, i.e., the convective transport. The number of diffusion or dispersion-type terms included in the mass-balance equation is dictated by the degree of simplification by which the convective velocity is presented. In the regime of continuum mechanics, only the macroscopic velocity of a fluid particle is considered. The transport of a dissolved substance due to thermally agitated random motion of molecules is modeled as a diffusion process termed molecular diffusion.

For a turbulent flow field, a deterministic description of the total velocity field is impossible, so that only the ensemble average of the velocity field may be determined. Therefore, the convective velocity in the mass-balance equation includes only the ensemble average velocity. The transport by turbulent velocity is termed turbulent diffusion. A model of the gradient transport with turbulent eddy diffusivity much larger than molecular diffusivity has been used extensively for turbulent diffusion. Although the concept of eddy diffusivity has been developed rigorously only for restricted classes of turbulent flows (Taylor, 1921; Batchelor, 1949), it has been proved satisfactory for many practical applications. Therefore, the mass-balance equation may be written as

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial z} = \frac{\partial}{\partial x}\left(e_x \frac{\partial c}{\partial x}\right)$$

$$+ \frac{\partial}{\partial y}\left(e_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(e_z \frac{\partial c}{\partial z}\right) + q - p \qquad \text{(V-1)}$$

where t is time, $c(x,y,z,t)$ is the mean concentration of a dissolved substance, u, v and w are the mean velocity components in the x, y and z directions respectively, e_x, e_y, and e_z are the turbulent diffusion coefficients, and q represents sources and p the sinks. The mean quantities are the ensemble mean or time mean over an appropriate time interval. It is impossible to obtain a true ensemble mean in a turbulent flow occurring in nature. However, time average over a period longer than the turbulent time scale while shorter than the time scale of gross variation may serve to approximate an ensemble mean.

Dispersion vs. Diffusion

In principle, equation (V-1) above may be solved for concentration field c (x,y,z,t) as function of time and three spatial dimensions, if the three-dimensional velocity field and turbulent diffusion coefficients are known. In most practical cases, however, solving a time-dependent partial differential equation with three spatial corrdinates is impractically difficult at the present time. Furthermore, the three-dimensional velocity field is equally difficult to calculate and extremely difficult to measure. Because of these difficulties, it is often advantageous to simplify equation (V-1) by reducing the number of spatial coordinates, assuming the water body's geometry permits.

One-Dimensional Dispersion

For a long, narrow water body such as a river in which water flows mainly along a fixed axis, the problem may be simplified by seeking the average concentration over the cross-section normal to the axis. This is achieved by integrating equation (V-1) over a cross section. After integration, equation (V-1) becomes

$$\frac{\partial}{\partial t}(AC) + \frac{\partial}{\partial x}(AUC) + \frac{\partial}{\partial x}\int_A u'c'dA$$

$$= \frac{\partial}{\partial x}\left(A\bar{e}_x \frac{\partial C}{\partial x}\right) + QA - PA \qquad \text{(V-2)}$$

where A is the cross-sectional area, U is the longitudinal velocity averaged over a cross-section, C is the concentration averaged over a cross-section, x is the distance along the axis, u' and c' are the spatial deviations of the velocity component and the concentration respectively from the cross-sectional average, $\bar{e}_x$ is the spatial mean value of the turbulent diffusivity, Q and P are the average sources and sinks within the cross-section, respectively.

The integral $\int_A u'c'\,dA$ represents the mass transport associated with the velocity and concentration variation over the cross section. Taylor (1953, 1954) and Aris (1956) showed that this mass transport may be described approximately by Fickian type diffusion and so it is possible to write

$$\int_A u'c'dA = -AE\,\frac{\partial C}{\partial x} \qquad \text{(V-3)}$$

where E is the dispersion coefficient.

After substituting equation (V-3) into equation (V-2), equation (V-2) may be written as

$$\frac{\partial}{\partial t}(AC) + \frac{\partial}{\partial x}(AUC) = \frac{\partial}{\partial x}\{A(E + \bar{e}_x)\,\frac{\partial C}{\partial x}\} + QA - PA \qquad \text{(V-4)}$$

or, after combining with one-dimensional continuity equation,

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{1}{A}\,\frac{\partial}{\partial x}\{A(E + \bar{e}_x)\,\frac{\partial C}{\partial x}\} + Q - P \qquad \text{(V-5)}$$

where E is usually much larger than $\bar{e}_x$ so that $\bar{e}_x$ may be neglected for most practical applications. The dispersion term with coefficient E is derived mainly from the spatial-average representation of velocity and concentration field, while the coefficients e_x, e_y and e_z are derived from ensemble-average representation. To distinguish the different mechanisms involved, Holley (1969) suggested the terms 'dispersion coefficient' for E and 'diffusion coefficient' for e's. As can be seen from equation (V-3) the dispersion coefficient E is associated with the non-uniformity of the longitudinal velocity within a cross-section. Thus the mechanism behind dispersion is a 'shear effect'.

Equation (V-4), or (V-5), or their equivalent, is the basic framework for a one-dimensional mathematical model of water quality. Before the equation may be solved analytically or numerically, E as well as U and A, have to be calculated or measured independently. Taylor (1953), who examined laminar flow in a circular tube, was the first to determine analytically a value for the dispersion coefficient E. He demonstrated, both analytically and experimentally, that the average concentration of a dissolved substance over the cross-section of a tube was dispersed relative to a plane moving with the mean velocity U as though it obeyed a Fickian type diffusion equation. The dispersion coefficient was found to be

$$E = \frac{a^2\, U^2}{48D} \tag{V-6}$$

where D is the coefficient of molecular diffusion, a is the radius of the tube and U is the mean velocity over a cross-section of the tube.

Taylor (1954), in an analogous treatment, extended this theory to turbulent flow in a pipe. The effective longitudinal dispersion coefficient was found to be 10.1 au_* where u_* is the shear velocity given by $u_* = (\tau_o/\rho)^{\frac{1}{2}}$, τ_o being the shear stress at the wall and ρ, the density of the fluid.

Elder (1959) extended Taylor's theory to steady, uniform flow in a wide open channel. The longitudinal dispersion coefficient was computed to be 5.9 hu_* where h was the depth of the fluid. Bowden (1965) evaluated the dispersion coefficients for various velocity profiles in a channel of uniform depth. He derived the expression

$$E = khU \tag{V-7}$$

with the constant k dependent on the velocity profile.

The dispersion characteristics in natural streams and their dependence on the bulk parameters of the channel was studied by Fischer (1967). He demonstrated that the lateral velocity variation, rather than vertical shear, was the primary dispersive mechanism in natural streams with large width-to-depth ratios.

Two-Dimensional Dispersion

For a water body with two horizontal dimensions of the same order of magnitude, an equation of more than one spatial dimension has to be used to describe the concentration field. Okubo (1968) has demonstrated the shear effect on the spreading of pollutant with a simple kind of shear for a uni-directional mean current in an open sea. In a bay or coastal sea where the depth is much smaller than the horizontal dimensions, the time scale of vertical diffusion is much smaller than the horizontal ones. The depth-mean concentration field will be sufficient for most practical purposes. Without rigorous proof, Taylor's concept of one-dimensional dispersion was used in a two-dimensional case by Marsch & Shankar (1969), Leendertse (1970), and Fischer (1970). They described the depth-mean concentration field with a two-dimensional Fickian-type diffusion equation

$$\frac{\partial \overline{C}}{\partial t} + \overline{U}\frac{\partial \overline{C}}{\partial x} + \overline{V}\frac{\partial \overline{C}}{\partial y} = \frac{1}{h}\frac{\partial}{\partial x}\left(hE_x \frac{\partial \overline{C}}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\left(hE_y \frac{\partial \overline{C}}{\partial y}\right) + \overline{Q} - \overline{P} \qquad \text{(V-8)}$$

where $\overline{C}$, $\overline{U}$, $\overline{V}$, $\overline{Q}$ and $\overline{P}$ are depth-mean concentration, velocity components, sources and sinks respectively, h is the depth of water. Leendertse (1970) assumed that the shear effects due to vertical variation of velocity components were independent and used the one-dimensional formulation of E for E_x and E_y, the horizontal dispersion coefficients in the x and y directions.

<u>Dispersion in an Oscillatory Flow</u>

In a homogeneous estuarine river the convective velocity U of equation (V-4) or (V-5) may include two components: a slowly varying component due to freshwater discharge and a periodic component due to tidal currents. To evaluate the dispersion coefficient, the theories of one-dimensional dispersion in unidirectional flow have to be extended to an oscillatory flow field.

Okubo (1967) compared the shear effect in oscillatory flow to that of steady flow, the magnitude of which equaled the amplitude of the oscillating current. He concluded that if the time required to produce lateral homogeneity by mixing was much longer than the period of oscillation, the shear effect of the oscillating current would be negligible compared to the steady current. If the lateral mixing was accomplished within the period of oscillation, the shear effect produced by the periodic motion became as important as that for steady flow.

Holley, et.al. (1970) examined dispersion in one-dimensional oscillatory flow and its dependence on the parameter T', the ratio between the period of oscillation T and the time scale for cross-sectional mixing T_c. They found that if $T' >> 1$, the quasi-steady approach may be used and the average dispersion coefficient over a tidal cycle, $\langle E \rangle$, can be related to the average hydraulic parameters during the period of oscillation. If $T' < 1$, $\langle E \rangle$ varied approximately as the square of T'. They treated the dispersions due to vertical shear and transverse shear independently. The parameter T_v' was evaluated based on $T_c = T_v$, the time scale of vertical mixing, for the vertical shear effect, and T_t' was evaluated based on $T_c = T_t$, the time scale of transverse mixing, for the transverse shear effect. They observed that for most estuaries T_v' was usually greater than unity but T_t' was much less than unity. As the width of the channel increased, the dispersion due to transverse shear decreased with the square of T_t'. Thus, they concluded that vertical shear was the dominant dispersive mechanism in wide estuaries and that the dispersion coefficient could be approximated by Elder's expression

$$\langle E \rangle = 5.9\ h u_* \tag{V-9}$$

where u_* was the shear velocity related to the tidal velocity averaged over one-half period, and h was the depth.

Assuming that the vertical shear effect is the dominant dispersive mechanism, Harleman (1971) modified Taylor's expression of dispersion coefficient to homogeneous estuarine rivers by writing it in terms of the amplitude of tidal current, and increasing it by a factor of two to account for bends and channel irregularities. Harleman's modification of Taylor's expression is

$$E = 100\ n\ U_t\ R^{5/6}, \tag{V-10}$$

where U_t is the amplitude of tidal current, R is the hydraulic radius and n is the Manning friction coefficient.

Dispersion in Stratified Flow

There is always some degree of density stratification existing in the salt intrusion region of an estuarine river. Density stratification tends to hinder turbulent diffusion in the vertical direction. In cases where vertical diffusion is hindered to such an extent that the time scale of vertical mixing is no longer small compared with longitudinal mixing, the one-dimensional dispersion approximation of the mixing processes ceases to be applicable. The precise degree of stratification which can be treated satisfactorily by a one-dimensional model still remains to be determined.

In addition to the suppression of vertical diffusion, the stratification also tends to increase velocity shear by inducing gravitational circulation. Therefore, according to Taylor's theory, stratification will invariably increase longitudinal dispersion. In a given estuarine river, the degree of stratification, and hence, the longitudinal dispersion coefficient increases with the freshwater discharge. Using steady state models for a reach of the Delaware Estuary, Paulson (1970) demonstrated that the longitudinal dispersion coefficient increased as the freshwater discharge increased.

Thatcher and Harleman (1972) suggested that the longitudinal dispersion coefficient is proportional to local non-dimensional salinity gradient, with the proportionality factor a weak function of the degree of stratification. This assumption that the dispersion coefficient is proportional to longitudinal salinity gradient is questionable, because of the fact that the salinity gradient usually tends to zero, while the dispersion coefficient increase towards the mouth of an estuary.

Dispersion Resulting from Tidal Average

With the dispersion coefficient expressed in terms of available hydraulic and geometric parameters, equation (V-4) or (V-5) may be applied to an estuarine river and solved numerically with a digital computer. In the formulation of numerical computations with finite difference approximation, two distinct types of models may be developed because of the oscillating feature of the convective current U: the short-term model or real-time model and the long-term or slack tide approximation model. The purpose of the analysis and the response time of the system are important criteria in determining the type of model.

In a real-time model the time increment of numerical computation is much smaller than a tidal period, thus the time variation of the tidal component of the convective velocity can be included in the model. The real-time model is used when the response time of the system is short and an equilibrium state is reached quickly. This model is also used when short-term variations of a concentration field are to be investigated.

In a long-term model the time increment of numerical computation is an integral multiple of the tidal period. In this model the convective velocity is the velocity averaged over a tidal period, i.e. the non-tidal component. The convection due to the tidal current is incorporated into the dispersion term. The dispersion coefficient includes the contribution from the transport by the oscillating tidal current as well as the contribution from 'shear effect'. Since the computation time required is less than that for the real-time model, this model is more practical for use in investigation of long term variations, such as seasonal variations, of a concentration field.

Because of the periodicity of the velocity U, equation (V-4) or (V-5) cannot be directly approximated by a finite difference form with a time increment larger than a tidal cycle. The equation has to be averaged over a tidal cycle to construct a long-term model. Okubo (1964) has made a rigorous derivation of the mass-balance equation for the concentration field averaged over tidal cycle. He arrived at the equation

$$\frac{\partial \langle S \rangle}{\partial t} + U_f \frac{\partial \langle S \rangle}{\partial x} = \frac{1}{\langle A \rangle} \frac{\partial}{\partial x} \left(\langle A \rangle E_a \frac{\partial \langle S \rangle}{\partial x} \right)$$

$$+ \langle Q \rangle - \langle P \rangle \qquad \text{(V-11)}$$

where $U_f = \frac{Q_f}{\langle A \rangle}$,

$\langle\ \rangle$ designates a quantity averaged over tidal cycle, Q_f is freshwater discharge, and E_a is the longitudinal dispersion coefficient.

For many practical applications, the significant information is the maximum or minimum concentration of a dissolved or suspended substance within a tidal cycle. An equation describing the concentration field at a particular phase of tidal cycle is more appropriate. Orzech, et.al. (1972) derived equations similar to equation (V-11) for the concentration field at high and low water slacks, with different dispersion coefficients. They stressed the significant contribution of the term $\langle u''c'' \rangle$ to the longitudinal dispersion, where u" is the deviation of velocity from tidal average value and c" is the deviation of concentration from the value at high or low water slack. This contribution was termed as 'phase effect' by Fischer (1972a). Fischer (1972b) made an attempt to investigate various mechanisms involved in the longitudinal dispersion of a long-term model. He used data from the Mersey Estuary and concluded that the most important mechanism is transverse circulation, or transverse shear effect. However, he arbitrarily neglected the phase effect.

Discussion and Conclusions

The division of the transport mechanism into convection and dispersion is done artificially for mathematical convenience. The dispersion term in a mass-balance equation results from the representation of the convective velocity with average value. The mechanisms involved in the dispersion term depend on the way in which the convective velocity is represented. The dispersion term may include either of the 'shear effect', i.e. the dispersion resulting from spatial average of the velocity, or the 'phase effect', i.e. the dispersion resulting from temporal average, or both.

The water quality model of the James River estuary developed herein is a one-dimensional, real-time non-steady state model. The convective velocity is the mean velocity averaged over cross-section and thus, includes the time-varying tidal current. The dispersion mechanism is mainly the 'shear effect', which is small compared with the convection by tidal current in case the stratification is weak (Harleman, 1971). The dispersion coefficient may be estimated satisfactorily from hydraulic and geometric parameters. In the case where the stratification is strong, the complexities of estuarine circulation defy rigorous analysis. No satisfactory analytical method has been developed for predicting the dispersion coefficient in or determining the degree of stratification under which the one-dimensional model is applicable. Empirical relationships are frequently resorted to.

Our model for salt intrusion in the James River Estuary is a long-term model. The process of time averaging utilized introduces the additional complexity of 'phase effect'. The expression of convective velocity includes the freshwater component only. The transport of material by tidal current is modeled into the dispersion term and, thus, transport by dispersion is no longer small compared with that by convection. Satisfactory theory for analytical estimation of the dispersion coefficient due to 'phase effect' is still lacking. The current approach to the solution of this problem is empirical and observational. Field data of concentration distribution of natural or artificially introduced tracer are utilized in order to obtain some useful estimates of the dispersion coefficient.

VI. IMPLICIT-SCHEME WATER QUALITY MODELS

A. Y. Kuo

A. Mass Balance within a Volume Element of an Estuary

In an estuarine river such as the James where the longitudinal dimension is much larger than the vertical and lateral dimensions, the longitudinal distribution of a dissolved substance is much more variable than those of the other two. To facilitate the numerical computation of water quality parameters in such tidal systems, the river may be subdivided into a number of volume elements, called reaches, by a series of lateral transects along the river. The concentration of a dissolved substance may be represented by an average value within the volume element. Changes in the amounts of a dissolved substance in a particular reach or segment may be due to:

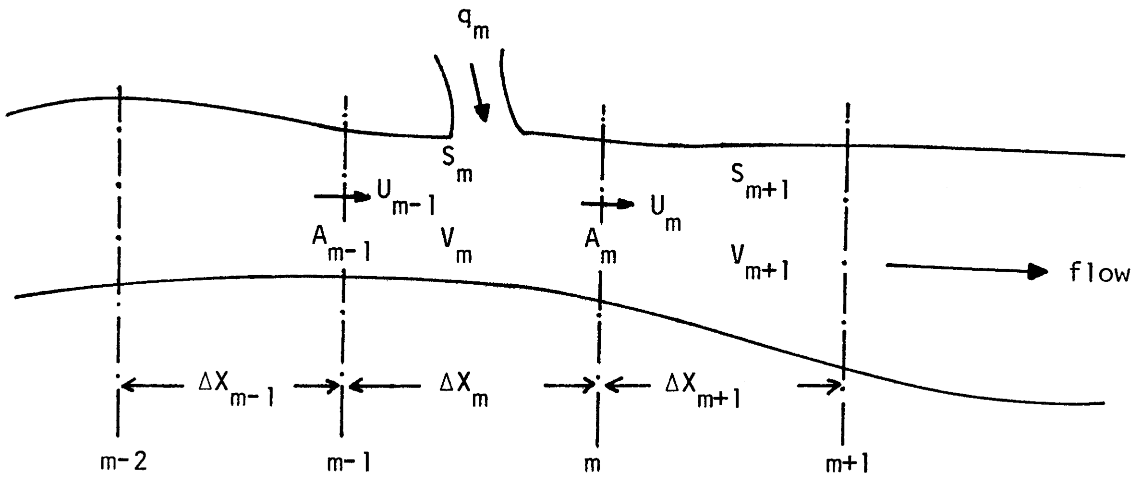
(1) advection and dispersion which transport materials into or out of the reach through the end transects,

(2) decay of the substance within the reach,

(3) addition due to sources of the substance within the reach.

The dissolved substance may be salts, oxygen or a biochemically degradable material, or any one of many other soluble materials.

An equation may be formulated for the mass balance of a dissolved substance in a volume element by expressing these mechanisms mathematically. Considering the mth reach of the river bounded by the (m-1)th and mth transects as shown in the sketch below:



the time rate of change of water volume may be expressed as:

$$\frac{\partial V_m}{\partial t} = (AU)_{m-1} - (AU)_m + q_m \tag{VI-1}$$

where

t = time,

V_m = the volume of water between the mth and (m-1)th transects,

$(AU)_m$ = $A_m U_m$, the flow rate through the mth transect,

A_m = the cross-sectional area of the mth transect,

U_m = the average velocity through the mth transect,

q_m = the rate of lateral inflow into the mth reach.

The time rate of change of total dissolved salt within the reach may be expressed as

$$\frac{\partial}{\partial t}(S_m V_m) = (AUS)_{m-1} - (AUS)_m + \left(AE\frac{\partial S}{\partial x}\right)_m$$

$$- \left(AE\frac{\partial S}{\partial x}\right)_{m-1} + q_m So_m \qquad \text{(VI-2)}$$

where

S_m = the average salinity of the reach,

$(AUS)_m$ = the advective flux of salt through the mth transect,

$\left(AE\frac{\partial S}{\partial x}\right)_m$ = the dispersive flux of salt through the mth transect,

E = dispersion coefficient,

x = distance along the axis of the river,

So_m = the average salinity of the lateral inflow.

Similarly, the time rate of change of total dissolved BOD (biochemical oxygen demand) and DO (dissolved oxygen) may be expressed as

$$\frac{\partial}{\partial t}(B_m V_m) = (AUB)_{m-1} - (AUB)_m + \left(AE\frac{\partial B}{\partial x}\right)_m \qquad \text{(VI-3)}$$

$$- \left(AE\frac{\partial B}{\partial x}\right)_{m-1} + q_m Bo_m - k_1 B_m V_m + Bs_m$$

$$\frac{\partial}{\partial t}(C_m V_m) = (AUC)_{m-1} - (AUC)_m + \left(AE\frac{\partial C}{\partial x}\right)_m$$

$$- \left(AE\frac{\partial C}{\partial x}\right)_{m-1} + q_m\, Co_m - k_1 B_m V_m$$

$$+ k_2 V_m\,(C_s - C_m) + Sy_m V_m \qquad \text{(VI-4)}$$

where

B_m = the average BOD concentration of the mth reach,

Bo_m = the BOD concentration of the lateral inflow,

k_1 = the deoxygenation coefficient,

Bs_m = the BOD source in the mth reach,

C_m = the average DO concentration of the mth reach,

Co_m = the DO concentration of lateral inflow,

k_2 = the reaeration coefficient,

C_s = the saturated oxygen concentration,

Sy_m = the source and sink of DO due to algal photosynthesis and respiration.

In equations (VI-2), (VI-3), and (VI-4), the advective flux through a transect, for example, the mth, is the product of the cross-sectional area A_m, the average velocity U_m, and the substance concentration in that water passing through the transect. Since concentrations are assigned to the volume element, those at the transects must be estimated. The salinity is a monotonic function of longitudinal distance, therefore the 'weighted average' of concentrations at adjacent reaches may be used, i.e.

$$(S)_{m-1} = \frac{S_{m-1} \cdot \Delta X_m + S_m \cdot \Delta X_{m-1}}{\Delta X_{m-1} + \Delta X_m} \qquad \text{(VI-5)}$$

$$(S)_m = \frac{S_m \cdot \Delta X_{m+1} + S_{m+1} \cdot \Delta X_m}{\Delta X_m + \Delta X_{m+1}} \qquad \text{(VI-6)}$$

where $(S)_{m-1}$ and $(S)_m$ designate the salinity of water passing through the (m-1)th and mth transects respectively. Since there may be some oxygen sags or local maximum BOD concentration along an estuarine river, it is more appropriate, in the cases of BOD and DO, to approximate the concentration at a transect to be that of the volume element from which the water arrives, i.e.

$$(B)_{m-1} = \begin{cases} B_{m-1} & \text{if } U_{m-1} \geq 0 \\ B_m, & \text{if } U_{m-1} < 0 \end{cases} \tag{VI-7}$$

$$(B)_m = \begin{cases} B_m & \text{if } U_m \geq 0 \\ B_{m+1}, & \text{if } U_m < 0 \end{cases} \tag{VI-8}$$

and

$$(C)_{m-1} = \begin{cases} C_{m-1} & \text{if } U_{m-1} \geq 0 \\ C_m, & \text{if } U_{m-1} < 0 \end{cases} \tag{VI-9}$$

$$(C)_m = \begin{cases} C_m & \text{if } U_m \geq 0 \\ C_{m+1} & \text{if } U_m < 0 \end{cases} \tag{VI-10}$$

The diffusive flux through a transect is proportional to the concentration gradient, which may be approximated by the ratio of difference between the concentrations in adjacent reaches to the distance between the centers of the reaches, i.e.

$$\left(\frac{\partial F}{\partial x}\right)_{m-1} = \frac{F_m - F_{m-1}}{\dfrac{\Delta X_{m-1} + \Delta X_m}{2}} \tag{VI-11}$$

$$\left(\frac{\partial F}{\partial x}\right)_m = \frac{F_{m+1} - F_m}{\dfrac{\Delta X_m + \Delta X_{m+1}}{2}} \tag{VI-12}$$

where F designates salt, BOD, or DO concentration.

Substituting equations (VI-5), (VI-6), (VI-11) and (VI-12) into equation (VI-2), and simplifying the result with the aid of equation (VI-1), the mass balance of salt may be expressed as

$$\begin{aligned} \frac{\partial S_m}{\partial t} = {} & \frac{A_{m-1}}{V_m} \cdot \frac{S_{m-1} - S_m}{\Delta X_{m-1} + \Delta X_m} (\Delta X_m \cdot U_{m-1} + 2E_{m-1}) \\ & - \frac{A_m}{V_m} \cdot \frac{S_{m+1} - S_m}{\Delta X_m + \Delta X_{m+1}} (\Delta X_m \cdot U_m - 2E_m) \\ & + \frac{q_m}{V_m} (So_m - S_m) \end{aligned} \tag{VI-13}$$

Similarly, with equations (VI-1), (VI-7), (VI-8), (VI-11) and (VI-12), equation (VI-3) may be simplified to

$$\begin{aligned} \frac{\partial B_m}{\partial t} = {} & \frac{A_{m-1}}{V_m} \left\{U_{m-1}(B_i - B_m) + 2E_{m-1} \cdot \frac{B_{m-1} - B_m}{\Delta X_{m-1} + \Delta X_m}\right\} \\ & - \frac{A_m}{V_m} \left\{U_m(B_j - B_m) - 2E_m \cdot \frac{B_{m+1} - B_m}{\Delta X_m + \Delta X_{m+1}}\right\} \\ & - k_1 B_m + \frac{q_m}{V_m} (Bo_m - B_m) + \frac{Bs_m}{V_m} \end{aligned} \tag{VI-14}$$

and, with equations (VI-1), (VI-9), (VI-10), (VI-11) and (VI-12), equation (VI-4) may be simplified to

$$\frac{\partial C_m}{\partial t} = \frac{A_{m-1}}{V_m} \{U_{m-1}(C_i - C_m) + 2E_{m-1} \frac{C_{m-1} - C_m}{\Delta X_{m-1} + \Delta X_m}\}$$

$$- \frac{A_m}{V_m} \{U_m(C_j - C_m) - 2E_m \frac{C_{m+1} - C_m}{\Delta X_m + \Delta X_{m+1}} \}$$

$$- k_1 B_m + k_2(C_s - C_m) + \frac{q_m}{V_m} (Co_m - C_m) + Sy_m \tag{VI-15}$$

where

$$i = \begin{cases} m-1 & \text{if } U_{m-1} \geq 0 \\ m, & \text{if } U_{m-1} < 0 \end{cases}$$

$$j = \begin{cases} m & \text{if } U_m \geq 0 \\ m+1, & \text{if } U_m < 0 \end{cases}$$

B. "Real Time" Model for Salinity, DO and BOD

Finite Difference Approximation in Time Domain

With proper initial and boundary conditions, equations (VI-13), (VI-14) and (VI-15) may be integrated with respect to time to obtain the temporal variations of salinity, DO and BOD concentrations within each reach of the estuary. In solving these equations with a digital computer, they are integrated numerically over successive finite time intervals. At each integration step over a time increment, the various parameters, such as velocities, dispersion coefficients, etc., should assume representative values during this particular time interval. The velocity in an estuarine river oscillates with a period of 12.4 hours. It is apparent that a mathematical model with a time increment greater than a tidal cycle cannot describe the temporal variation of velocity induced by tidal fluctuation. Only a model with a time increment much smaller than a tidal cycle can describe the temporal variation of tidal velocity properly. The selection of the time increment will depend on the response time of the system and the purpose of the model.

Since BOD has a deoxygenation coefficient, k_1, of order of 10^{-1} per day, i.e., it has a characteristic lifetime on the order of ten days. The concentration of BOD will reach a new state of equilibrium in the order of ten days after a significant change of BOD producing factors occurs. The reaeration coefficient for DO concentration is on the order of 10^{-1} per day. Therefore, even if the model is to determine long-term (for example, seasonal) variations of the DO and BOD concentrations, it needs to be run for a simulated time on the order of ten days only for each set of input parameters corresponding to each seasonal condition, to arrive at the equilibrium concentration fields for that season. It is not necessary to run the model with simulated time continuously from season to season throughout the year. Thus,one can afford to have the time increment of the numerical computation be much smaller than a tidal cycle, and, therefore, the temporal variation of the tidal velocity may be included in the model. This is called a "real time" model. The salinity is included in this model for the purpose of verifying the dispersion coefficients and serving as a parameter for determining the saturated oxygen concentration.

An implicit scheme is used to formulate the finite difference forms in time domain for equations (VI-13), (VI-14) and (VI-15). Except for the terms involving lateral inflow, the right hand sides of the equations are expressed in terms of salinity or concentrations at the end of a time step as well as that at the beginning of the time step. The equations are approximated as follows:

$$\frac{S_m' - S_m}{\Delta t} = \frac{1}{2} \frac{A_{m-1}'}{V_m'} \frac{S_{m-1}' - S_m'}{\Delta x_{m-1} + \Delta x_m} (\Delta x_m U_{m-1}' + 2E_{m-1}')$$

$$+ \frac{1}{2} \frac{A_{m-1}}{V_m} \frac{S_{m-1} - S_m}{\Delta x_{m-1} + \Delta x_m} (\Delta x_m U_{m-1} + 2E_{m-1})$$

$$- \frac{1}{2} \frac{A_m'}{V_m'} \frac{S_{m+1}' - S_m'}{\Delta x_m + \Delta x_{m+1}} (\Delta x_m U_m' - 2E_m')$$

$$- \frac{1}{2} \frac{A_m}{V_m} \frac{S_{m+1} - S_m}{\Delta x_m + \Delta x_{m+1}} (\Delta x_m U_m - 2E_m)$$

$$+ \frac{q_m}{V_m} (So_m - S_m) \qquad \text{(VI-16)}$$

$$\frac{B_m' - B_m}{\Delta t} = \frac{1}{2}\,\frac{A_{m-1}}{V_m}\,\{U_{m-1}(B_i - B_m) + 2E_{m-1}\,\frac{B_{m-1} - B_m}{\Delta x_{m-1} + \Delta x_m}\}$$

$$+ \frac{1}{2}\,\frac{A_{m-1}'}{V_m'}\,\{U_{m-1}'(B_k' - B_m) + 2E_{m-1}'\,\frac{B_{m-1}' - B_m'}{\Delta x_{m-1} + \Delta x_m}\}$$

$$- \frac{1}{2}\,\frac{A_m}{V_m}\,\{U_m(B_j - B_m) - 2E_m\,\frac{B_{m+1} - B_m}{\Delta x_m + \Delta x_{m+1}}\}$$

$$- \frac{1}{2}\,\frac{A_m'}{V_m'}\,\{U_m'(B_\ell' - B_m') - 2E_m'\,\frac{B_{m+1}' - B_m'}{\Delta x_m + \Delta x_{m+1}}\}$$

$$- \frac{1}{2}\,(k_1 B_m + k_1' B_m') + \frac{q_m}{V_m}\,(Bo_m - B_m) + \frac{Bs_m}{V_m} \qquad \text{(VI-17)}$$

$$\frac{C_m' - C_m}{\Delta t} = \frac{1}{2}\,\frac{A_{m-1}}{V_m}\,\{U_{m-1}(C_i - C_m) + 2E_{m-1}\,\frac{C_{m-1} - C_m}{\Delta x_{m-1} + \Delta x_m}\}$$

$$+ \frac{1}{2}\,\frac{A_{m-1}'}{V_m'}\,\{U_{m-1}'(C_k' - C_m') + 2E_{m-1}'\,\frac{C_{m-1}' - C_m'}{\Delta x_{m-1} + \Delta x_m}\}$$

$$- \frac{1}{2}\,\frac{A_m}{V_m}\,\{U_m(C_j - C_m) - 2E_m\,\frac{C_{m+1} - C_m}{\Delta x_m + \Delta x_{m+1}}\}$$

$$- \frac{1}{2}\,\frac{A_m'}{V_m'}\,\{U_m'(C_\ell' - C_m') - 2E_m'\,\frac{C_{m+1}' - C_m'}{\Delta x_m + \Delta x_{m+1}}\}$$

$$- \frac{1}{2}\,(k_1 B_m + k_1' B_m') + \frac{1}{2}\,k_2\,(C_s - C_m)$$

$$+ \frac{1}{2}\,k_2'(C_s' - C_m') + \frac{q_m}{V_m}\,(Co_m - C_m) + Sy_m$$

(VI-18)

where the subscripts

$$k = \begin{cases} m-1 & \text{if } U_{m-1}' \geq 0 \\ m, & \text{if } U_{m-1}' < 0 \end{cases}$$

$$\ell = \begin{cases} m & \text{if } U_m' \geq 0 \\ m+1, & \text{if } U_m' < 0 \end{cases}$$

In an estuarine river, the volume of a reach and the cross-sectional areas of the two transects bounding the reach will fluctuate almost in phase with tide. Since Δx_m is constant with respect to time, the cross-sectional areas A_m and A_{m-1} will increase or decrease with the reach volume V_m. Furthermore, the fluctuations of A_{m-1}, A_m and V_m are all small compared with their respective average values. It is reasonable to assume that the quantities $\frac{A_{m-1}}{V_m}$ and $\frac{A_m}{V_m}$ are independent of time and let

$$R1_m = \frac{A_{m-1}}{V_m} = \text{constant}$$

$$R2_m = \frac{A_m}{V_m} = \text{constant}$$

Regrouping the coefficients of S_{m-1}', S_m' and S_{m+1}', equation (VI-16) may be written as

$$S_m' = -a_m S_{m+1}' + b_m S_{m-1}' + c_m \qquad \text{(VI-19)}$$

where

$$a_m = R2_m \cdot \delta_m (\tfrac{1}{2}\Delta x_m \cdot U_m' - E_m')/d_m$$

$$b_m = R1_m \cdot \delta_{m-1}(\tfrac{1}{2}\Delta x_m \cdot U_{m-1}' + E_{m-1}')/d_m$$

$$c_m = \{S_m + R1_m \cdot \delta_{m-1}(S_{m-1} - S_m)(\tfrac{1}{2}\Delta x_m \cdot U_{m-1} + E_{m-1})$$

$$- R2_m \cdot \delta_m (S_{m+1} - S_m)(\tfrac{1}{2}\Delta x_m U_m - E_m)$$

$$+ \frac{q_m}{V_m}(So_m - S_m) \cdot \Delta t\}/d_m$$

$$d_m = 1 + R1_m \cdot \delta_{m-1}(\tfrac{1}{2}\Delta x_m \cdot U_{m-1}' + E_{m-1}')$$

$$- R2_m \cdot \delta_m (\tfrac{1}{2}\Delta x_m \cdot U_m' - E_m')$$

$$\delta_m = \frac{\Delta t}{\Delta x_m + \Delta x_{m+1}}$$

Equations (VI-17) and (VI-18) may also be written in the form of equation (VI-19) with

$$a_m = (\tfrac{1}{2}\Delta t \cdot \beta \cdot R2_m \cdot U_m' - R2_m \cdot \delta_m \cdot E_m')/d_m$$

$$b_m = (\tfrac{1}{2}\Delta t \cdot \alpha \cdot R1_m \cdot U_{m-1}' + R1_m \cdot \delta_{m-1} \cdot E_{m-1}')/d_m$$

$$c_m = \{B_m + \frac{\Delta t}{2} \cdot R1_m \cdot U_{m-1}(B_i - B_m) + R1_m \cdot \delta_{m-1} \cdot E_{m-1}(B_{m-1} - B_m)$$

$$- \frac{\Delta t}{2} \cdot R2_m \cdot U_m (B_j - B_m) + R2_m \cdot \delta_m E_m (B_{m+1} - B_m)$$

$$- \frac{\Delta t}{2} k_1 B_m + \frac{q_m}{V_m} \cdot \Delta t (Bo_m - B_m) + \frac{Bs_m}{V_m} . \Delta t\}/d_m$$

$$d_m = 1 + \frac{\Delta t}{2} \cdot \alpha \cdot R1_m \cdot U_{m-1}' + R1_m \cdot \delta_{m-1} \cdot E_{m-1}'$$

$$- \frac{\Delta t}{2} \cdot \beta \cdot R2_m \cdot U_m' + R2_m \, \delta_m \cdot E_m' + \frac{\Delta t}{2} k_1'$$

for the equation for BOD, and with

$$a_m = (\frac{\Delta t}{2} .\beta.R2_m.U_m' - R2_m.\delta_m.E_m')/d_m$$

$$b_m = (\frac{\Delta t}{2} .\alpha.R1_m.U_{m-1}' + R1_m.\delta_{m-1}.E_{m-1}')/d_m$$

$$c_m = \{C_m + \frac{\Delta t}{2} .R1_m.U_{m-1}(C_i - C_m) + R1_m.\delta_{m-1}.E_{m-1}$$

$$(C_{m-1} - C_m) - \frac{\Delta t}{2} .R2_m.U_m(C_j - C_m) + R2_m.\delta_m.E_m.$$

$$(C_{m+1} - C_m) - \frac{\Delta t}{2}(k_1.B_m + k_1'.B_m') + \frac{\Delta t}{2} .k_2(C_s - C_m)$$

$$+ \frac{\Delta t}{2} .k_2'.C_s' + \frac{q_m}{V_m} .\Delta t(Co_m - C_m) + Sy_m.\Delta t\}/d_m$$

$$d_m = 1 + \frac{\Delta t}{2} .\alpha.R1_m.U_{m-1} + R1_m.\delta_{m-1}.E_{m-1}' - \frac{\Delta t}{2} .\beta.R2_m.U_m'$$

$$+ R2_m.\delta_m.E_m' + \frac{\Delta t}{2} .k_2'$$

for the equation for DO, where

$$a = \begin{cases} 0 & \text{if } U_{m-1}' < 0 \\ 1\ , & \text{if } U_{m-1}' \geq 0 \end{cases}$$

$$\beta = \begin{cases} 0 & \text{if } U_m' \geq 0 \\ 1\ , & \text{if } U_m' < 0 \end{cases}$$

<u>Elimination Process</u> Because of advective and dispersive transport across the transects bounding each end of a particular reach of the estuarine river, concentrations in one reach will depend on the concentrations in two adjacent reaches. This interdependence of concentrations at neighboring reaches is manifested in equation (VI-19).

Therefore, equation (VI-19) cannot be solved for S_m' at the mth reach by itself. Equations must be written for every reach in the estuarine river and solved for the concentrations in every reach simultaneously.

Suppose that the total length of estuarine river to be modeled is divided into N reaches. (N-2) equations will be obtained by writing equation (VI-19) for m = ML+1 to m = MU-1, where the MLth and MUth reaches are the most upstream and downstream ones, respectively. Since there are (N-2) equations for N unknowns, two boundary conditions must be specified. The principal operation of numerical computations in the model is then to compute the concentrations in each reach at time $t_o + \Delta t$ with a given initial concentration field at time t_o and appropriate boundary conditions. The computed concentration field at $t_o + \Delta t$ will then be used as the initial condition to compute the concentration field at time $t_o + 2\Delta t$, and so forth. Each computation cycle will advance the time by the increment of Δt. Within each computation cycle, the (N-2) simultaneous equations are solved by an elimination method.

Taking the equation for salinity as an example, S_{ML+1}' may be expressed in terms of S_{ML+2}' through equation (VI-19) with m - ML+1, and boundary condition S_{ML}' given, i.e.

$$S_{ML+1} = - a_{ML+1}S_{ML+2}' + b_{ML+1}S_{ML}' + C_{ML+1} \tag{VI-20}$$

where the only unknown on the right hand side of the equation is S_{ML+2}'. Equation (VI-20) may, in turn, be substituted back into equation (VI-19) with $m = ML+2$, and thus one arrives at an expression for S_{ML+2}' in terms of S_{ML+3}'. In general, there exists the following relation

$$S_m' = - P_m S_{m+1}' + O_m \qquad \text{(VI-21)}$$

where the recursion coefficients P_m and O_m may be calculated from the upstream boundary condition S_{ML}'.

With subscript m-1, equation (VI-21) becomes

$$S_{m-1}' = -P_{m-1} S_m' + O_{m-1}$$

Substituting this expression for S_{m-1}' in equation (VI-19), it becomes

$$S_m' = -a_m S_{m+1}' + b_m(-P_{m-1} S_m' + O_{m-1}) + c_m$$

or

$$S_m' = - \frac{a_m}{1 + b_m \cdot P_{m-1}} S_{m+1}' + \frac{b_m O_{m-1} + c_m}{1 + b_m \cdot P_{m-1}} \qquad \text{(VI-22)}$$

The comparison between equations (VI-21) and (VI-22) gives

$$\left.\begin{aligned} P_m &= \frac{a_m}{1 + b_m \cdot P_{m-1}} \\ O_m &= \frac{b_m \cdot O_{m-1} + c_m}{1 + b_m \cdot P_{m-1}} \end{aligned}\right\} \qquad \text{(VI-23)}$$

Since S_{ML}' is a known quantity, the comparison between equation (VI-20) and (VI-21) with $m = ML+1$ gives

$$-P_{ML+1} = a_{ML+1}$$

$$O_{ML+1} = b_{ML+1} \cdot S'_{ML} + c_{ML+1}$$

and thus

$$P_{ML} = 0, \; O_{ML} = S_{ML}'$$

In summary, the recursion coefficients and equation are

$$P_{ML} = 0, \; O_{ML} = S_{ML}'$$

$$\left.\begin{aligned} P_m &= \frac{a_m}{1 + b_m \cdot P_{m-1}} \\ O_m &= \frac{c_m + b_m \cdot O_{m-1}}{1 + b_m \cdot P_{m-1}} \end{aligned}\right\} \qquad \text{(VI-23)}$$

and

$$S_m' = -P_m S_{m+1}' + O_m, \qquad \text{(VI-21)}$$

with m = ML+1, ML+2, ---, MU-1.

The order of numerical computations is

(1) Calculate the recursion coefficients by applying equations (VI-23) repeatedly with m = ML+1, ML+2, ---, MU-1, and

(2) With S_{MU}' given as the downstream boundary condition, the salinity of the interior reaches is calculated by applying equation (VI-21) repeatedly with m = MU-1, MU-2, ---, ML+1.

<u>Evaluation of Parameters</u>

(1) Velocity U: In an estuarine river, the current

velocity may be divided into two parts,

$$U(x,t) = U_f(x,t) + U_t(x,t) \qquad \text{(VI-24)}$$

where U_f is the non-tidal component due to freshwater discharge and U_t is the oscillating tidal component. In this model, the tidal current is approximated by a sinusoidal function of time with period T and phase f(x),

$$U_t(x,t) = U_T(x)\sin\{\frac{2\pi}{T} t + f(x)\} \qquad \text{(VI-25)}$$

where U_T is the amplitude. $U_T(x)$ and f(x) are obtained from field measurements. The non-tidal component U_f is calculated by the equation

$$U_f(x,t) = \frac{Q(x,t)}{G(x,t)} \qquad \text{(VI-26)}$$

where Q(x,t) is the freshwater discharge from a drainage area upstream of the transect located at distance x; this is estimated from the record of a stream gauge station located upstream of the tidal limit, assuming freshwater discharge to be proportional to drainage area. G(x,t) is the cross-sectional area of the transect and is estimated by

$$G(x,t) = A(x)\{1 + \frac{Q(x,t)}{Q_T(x)}\}^{\mu} \qquad \text{(VI-27)}$$

where A(x) is the cross-sectional area below mean sea level, $Q_T(x)$ is the average tidal discharge and μ is a constant less than unity.

(2) Dispersion Coefficient E: The dominant mechanism of longitudinal dispersion is the interaction between turbulent

diffusion and shearing current. Taylor's (1954) formulation of one-dimensional dispersion has been successfully modified and extended to tidal rivers (Holley, et.al., 1970; Harleman, 1971). The dispersion coefficient in a tidal river may be expressed as

$$E = \nu n|U|R^{5/6} \qquad \text{(VI-28)}$$

where n is Manning's friction coefficient, $|U|$ is the absolute value of velocity, R is hydraulic radius, and ν is a constant on the order of 100. It is known that the presence of density stratification due to salinity intrusion enhances the vertical shear while suppressing the turbulence, and therefore increases the dispersion coefficient. Equation (VI-28) is modified to

$$E = \nu n|U|R^{5/6}(1 + \nu' S) \qquad \text{(VI-29)}$$

where ν' is a constant and S is the salinity. ν' is adjusted until the model results agree satisfactorily with the salinity distribution measured during the field operation in summer of 1971.

(3) Reaeration Coefficient k_2: O'Connor and Dobbins (1956) presented a theoretical derivation of the reaeration coefficient, in which fundamental turbulence parameters were taken into account. They derived the following formula

$$(k_2)_{20} = \frac{(D_c U)^{1/2}}{H^{3/2}} \qquad \text{(VI-30)}$$

where D_c is the molecular diffusivity of oxygen in water, U and H are the cross-sectional mean velocity and depth respectively, and $(k_2)_{20}$ is the reaeration coefficient at $20^\circ C$. This formula has been shown to give a satisfactory estimate of k_2 for a reach of river with cross-sectional mean depth and velocity more or less uniform throughout the reach. For a case like the James River in which the cross-section in some reaches varies greatly, there is no reason to expect a satisfactory estimate from the formula if U and H at the two bounding transects of the reach are used. Therefore, equation (VI-30) is modified as stated in the following paragraph.

Assuming that the O'Connor and Dobbins formula is valid locally then

$$f = k_2 h = \frac{(D_c u)^{\frac{1}{2}}}{h^{\frac{1}{2}}} \qquad \text{(VI-31)}$$

where f is the exchange coefficient, i.e., the exchange rate of oxygen through unit water surface area, u is the local depth-mean velocity and h is local depth. The total exchange rate of oxygen through the water surface over a reach is

$$M = \int_\sigma f(C_s - C)\,d\sigma \qquad \text{(VI-32)}$$

where σ is the total surface area over a reach. By definition of k_2,

$$M = (k_2)_{20} V(C_s - C) \qquad \text{(VI-33)}$$

thus ,

$$(k_2)_{20} = \frac{D_c^{\frac{1}{2}}}{V} \int_\sigma \frac{u^{\frac{1}{2}}}{h^{\frac{1}{2}}} d\sigma = D_c^{\frac{1}{2}} \left\langle \frac{u^{\frac{1}{2}}}{h^{\frac{1}{2}}} \right\rangle \frac{\sigma}{V}$$

$$= D_c^{\frac{1}{2}} \left\langle \frac{u^{\frac{1}{2}}}{h^{\frac{1}{2}}} \right\rangle \frac{1}{\langle h \rangle} \qquad \text{(VI-34)}$$

where < > means the average over area σ. Since the velocity data are available only at the end transects of a reach, no true $\left\langle \frac{u^{\frac{1}{2}}}{h^{\frac{1}{2}}} \right\rangle$ may be estimated. In this model, the average value of $\frac{U^{\frac{1}{2}}}{H^{\frac{1}{2}}}$ at the two end-transects are used while <h> is adjusted to an effective depth which is chosen between <h> and the average H of end-transects.

To adjust k_2 for temperatures other than 20°C, Elmore and West's (1961) formula is used

$$k_2 = (k_2)_{20} \cdot 1.024^{(\theta - 20)} \qquad \text{(VI-35)}$$

where θ is the water temperature in centigrade degrees.

(4) Photosynthesis and Respiration Sy: The amount of oxygen produced by photosynthesis varies with the intensity of sunlight and the density of plant population. In addition, at night, the same plants extract oxygen from the water for respiration. This oxygen source and sink is represented by a sinusoidal function of time with a period of one day. The amplitudes of the function are allowed to vary from reach to reach and an array is provided in the computer program for input data of the amplitudes in mg/ℓ/day. If more complete information is available, the functional form of this oxygen

source and sink may be refined.

The amplitudes of photosynthesis and respiration are set to zero at every reach for the 1971 summer verification run. Since the field data at different reaches were collected over a time span of 20 days, the data only represent typical conditions in the summer. The phase difference between tidal fluctuation and photosynthesis-respiration shifts from day to day. There is no way to fix the phase difference in the model while sumulating every reach at the same time. Furthermore, no diurnal fluctuation of DO concentration is observed in any set of the data and, thus, the photosynthesis and respiration may be assumed to be negligible.

(5) Deoxygenation Coefficient k_1: The value of k_1 depends on water temperature. In this model, k_1 is taken to be 0.2/day at 20^{o}C. The formula for correction to other temperatures is the same as that used in the model for Upper York River System (Hyer, et.al. 1971).

(6) Saturated Oxygen Content C_s: The saturated oxygen content depends on the temperature and salinity. C_s is calculated by the same method as the model for Upper York System (Hyer, et.al. 1971).

Boundary Conditions

(1) Upstream Boundary Conditions: The uppermost reach is located immediately downstream of the fall line near Richmond. This is far beyond the salt intrusion limit even at the time of extreme low freshwater discharge. For this

reach, the salinity is kept in the model at the value of 0.1, the value assumed for freshwater.

This reach receives the domestic and industrial waste discharge from the metropolitan area around Richmond. The BOD concentration is calculated as

$$BOD_{ML} = \frac{BSOT}{62.4 \cdot QQ \cdot 86400} \cdot 10^6 + BODS_{ML1} \qquad \text{(VI-36)}$$

where BOD_{ML} is the BOD concentration, in ppm, at the most upstream reach, the MLth reach; BSOT is the total BOD load in pounds per day; QQ is the freshwater discharge; and $BODS_{ML1}$ is the background BOD concentration at location upstream of Richmond. $BODS_{ML1}$ is about 1 to 3 ppm for normal situations.

An additional reach is added upstream of the fall line to facilitate the boundary condition for DO. This reach is assumed to be located upstream of all the waste discharge points in the Richmond area and its DO concentration is not affected by the waste discharges. The DO concentration at this additional reach is set at 85% of saturated oxygen content, which is a conservative value in relatively unpolluted streams.

(2) Downstream Boundary Conditions: The flow field and the boundary geometry of the estuary in Hampton Roads preclude using the one-dimensional approximation for this part of the estuary. Therefore, the most downstream reach, the MUth reach, of the present model is set around the James River Bridge. An additional reach is added

downstream of it for the purpose of specifying the boundary conditions.

A technique combining linear extrapolation and semi-explicit scheme is used to estimate the salinity boundary condition at the additional reach. This technique has been used for the upper Rappahannock River model (Fang, et.al., 1972).

For the verification of the model with 1971 summer survey data, the BOD boundary condition is set at 4.0 ppm, the observed value downstream of the James River Bridge. This value has to be estimated for other situations.

The DO boundary condition is set to be 85% of saturated oxygen content, the observed value downstream of the James River Bridge.

Computation Procedures

The following are the principal steps in the computer program:

(1) Read the geometric, hydraulic and water quality parameters of the estuary,

(2) Re-arrange the data to fit the computation scheme,

(3) Calculate the parameters for every reach or transect at the beginning of computation,

(4) Calculate the parameters for every reach or transect at the end of each time step,

(5) Compute a_m, b_m, c_m, and d_m of equation (VI-19) and P_m, O_m of equation (VI-23) for the salt balance equation,

(6) Compute salinity at the end of each time step by equation (VI-21),

(7) Repeat (5) and (6) for BOD and DO,

(8) Shift the parameters and concentration fields at the end of each time step to the beginning of the next time step,

(9) Repeat (4) to (8), and

(10) Print the concentration fields at selected times.

Manual for Program User

The program user should change the following input data to suit the conditions of a particular run.

Main Program

(1) TMAX: the number of tidal cycles the program is to be run; in general, 40 tidal cycles will be sufficient to reach an equilibrium state.

(2) NRNM: the number of freshwater discharges under which the program is to be run, $NRNM \geq 1$.

(3) DNB: the number of hours from 0600 to computation starting time; DNB is to take into account the phase of diurnal variation in photosynthesis and respiration.

(4) TB: the number of hours from low water slack at the most upstream transect to computation starting time; TB may be set to zero for most cases.

Input Subroutine

(1) TITLE: a title describing the particular run of the program.

(2) data group number 2.

NS: the number of discharge data to be read, NS = NRNM.

NAME: a description of the discharge data.

DISCH(I): the freshwater discharge, in cfs, near Richmond.

(3) data group number 3

NS: number of times the calculated concentration fields are to be printed.

TT(I): number of tidal cycles after computation starts at which the concentration fields are to be printed, I = 1,NS. All the numbers should be integral multiple of 0.04 and TT(NS) should be equal to TMAX.

(4) data group number 4

CB(I): initial salinity, in ppt, at each reach, I = 1,24.

(5) data group number 5

BODB(I): initial BOD concentrations, in ppm, at each reach, I = 1,24. The first two data in this group will not be used in the computations and may be assigned arbitrarily.

(6) data group number 6

DOB(I): initial DO concentrations, in ppm, at each reach, I = 1,24. The first data will not be used in the computations and may be assigned arbitrarily.

(7) data group number 7

BODD(I): distributed BOD sources, in ppm/day, including all the BOD sources except discharges from sewage treatment plants and industrial effluents, I = 1,24. The distributed BOD sources were verified with the 1971 field data; they should not be modified unless conditions known to change.

(8) data group number 8

BSOT(I): BOD sources from the discharge of sewage treatment plants and industrial effluents, in pounds per day, I = 1,24.

(9) data group number 9

TEMP(I): water temperature, in centigrade, at each reach, I = 1,24.

(10) data group number 10

SY(I): amplitude of photosynthesis and respiration, in ppm per day, at each reach, I = 1,24.

(11) data group number 13

DOS(I): DO concentration of lateral inflow, in ppm, I = 1, 24.

(12) data group number 14

BODS(I): BOD concentration of lateral inflow, in ppm, I = 1, 24.

(13) data for each additional run with different conditions (need to be furnished only if NRNM $\geq$ 2)

(a) TITLE: a title describing this particular condition.

(b) All of the data groups for which the conditions require different values from previous run. The data groups having the values same as the previous run need not appear again.

(c) a data card read 99 to signal the end of data for a particular running condition.

The program user should not change the input data which are not mentioned above. The program will print out all of the input data and the calculated concentration fields at the times specified in data group number 3.

The section of the James River from the fall line to the James River Bridge at Newport News is divided into 23 reaches by 24 transects. The input data should be assigned according to the reaches. Figure 6 is a map showing the locations of the reaches and transects. Table 7 gives the distance, in statute miles, of transects from the river mouth at Old Point Comfort. The major contributors of BOD sources at each reach are also given in the table.

C. "Slack Tide Approximation Model" for Salt Intrusion

Salinity variation in an estuarine river is mainly governed by the freshwater discharge, which varies with a time scale on the order of several months. Furthermore, the salinity responds very slowly to decreasing freshwater discharge. Therefore, the salinity distribution never stays at an equilibrium state for prolonged periods. Accordingly, it is necessary to run a mathematical model with simulated time continuously from season to season in order to predict the long-term variations of salinity intrusion. Hence, a model with time increment of numerical computation shorter than a tidal cycle is not practical. A model with 'slack tide approximation' is more suitable for describing the long term variation of salinity intrusion. In this model, the time increment is an integral multiple of a tidal cycle and the salinity assumes the value at high

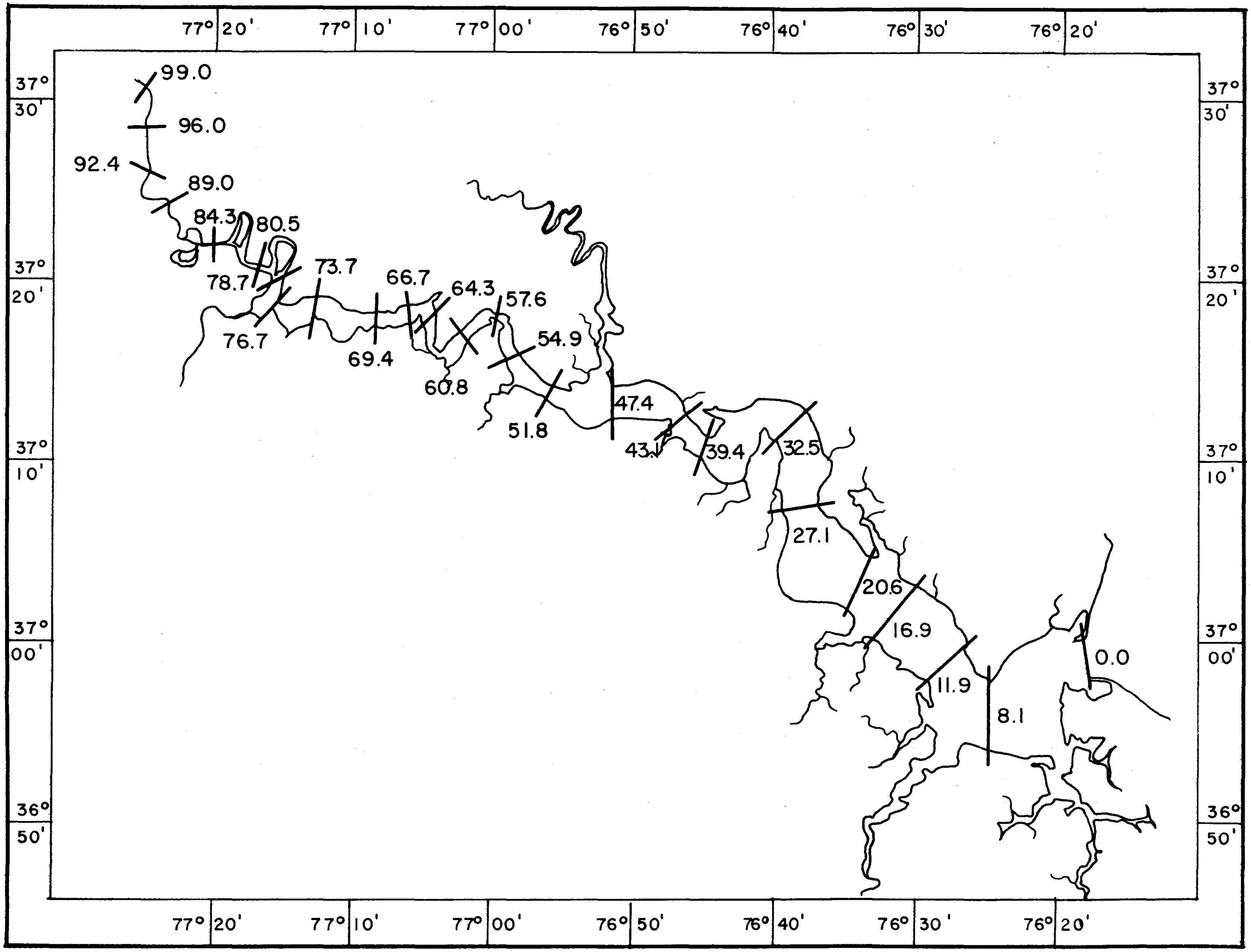

77° 20'
77° 10'
77° 00'
76° 50'
76° 40'
76° 30'
76° 20'
37° 30'
37° 20'
37° 10'
37° 00'
36° 50'
99.0
96.0
92.4
89.0
84.3
80.5
78.7
76.7
73.7
69.4
66.7
64.3
60.8
57.6
54.9
51.8
47.4
43.1
39.4
32.5
27.1
20.6
16.9
11.9
8.1
0.0

Table 7

Identification of Reaches

Transect No.	Distance from River Mouth	Reach no.	Major BOD Sources
1	99.0		
		2	Richmond STP, Federal Board & Paper, Standard Paper, Henrico County STP
2	96.0		
		3	Deep Water Terminal STP, E.I. DuPont Co.
3	92.4		
		4	Chesterfield County STP
4	89.0		
		5	
5	84.3		
		6	American Tobacco
6	80.5		
		7	
7	78.6		
		8	Petersburg STP, Colonial Heights STP
8	76.7		
		9	Hopewell STP, Fort Lee STP, Firestone Co., Allied Chemical Co., Continental Can Co., Hercules Powder Co.
9	73.7		
		10	
10	69.4		
		11	
11	66.7		
		12	
12	64.3		
		13	
13	60.8		
		14	
14	57.6		
		15	
15	54.9		
		16	
16	51.8		
		17	
17	47.4		
		18	
18	43.1		
		19	

Table 7 (cont'd)

Transect No.	Distance from River Mouth	Reach no.	Major BOD Sources
19	39.3		
		20	
20	32.5		
		21	Dow Chemical Co.
21	27.1		
		22	Fort Eustis
22	20.6		
		23	HRSDC James R., Smithfield Packing, Smithfield Ham & Prod.
23	16.9		
		24	
24	11.9		

water slack. The advective velocity is the current velocity averaged over tidal cycles, i.e., the velocity due to freshwater discharge and is given by equation (VI-26). The transport of salt by the oscillating tidal currents is incorporated into the dispersion term as 'phase effect', resulting in a dispersion coefficient an order of magnitude larger than that used in the 'real time' model.

The contribution of 'phase effect' to the dispersion coefficient has been discussed in the report on the upper Rappahannock River Model (Fang, et.al., 1972). To account for the long term variation of freshwater discharge, the dispersion by 'shear effect' is modified to include its dependence on the freshwater flow. In a given estuarine river, the increase of freshwater discharge tends to enhance the vertical stratification, which, in turn, suppresses the vertical turbulent diffusion. In addition to the suppression of vertical diffusion, the stratification also tends to increase velocity shear. Therefore, according to Taylor's theory, the increase of freshwater discharge will increase the dispersion by 'shear effect'. Using steady-state models for a reach of the Delaware Estuary, Paulson (1970) demonstrated that the dispersion coefficient increased roughly with the square root of freshwater discharge over the very limited range of freshwater discharge available to him. This square root dependence is adopted for the James River model and found to be satisfactory except at times of very high freshwater discharge. A comprehensive theory of the dependence of 'shear effect' on the freshwater discharge is still to be developed.

The numerical technique used for solving the mass balance equation is essentially the same as that of 'real time' model. The James River Estuary is divided into 23 reaches for the model under consideration as it was in the 'real time' model. The finite difference form of the mass balance equation of salt is written for each reach with each time increment an integral multiple of tidal cycle. The set of simultaneous equations are solved with the same elimination process.

Manual for Program User

The program user should change the following input data to suit the conditions of a particular run.

Main Program:

(1) ITMAX: the number of days the program is to be run.

(2) NRNM: the number of conditions with which the program is to be run.

INPUT Subroutine:

(1) TITLE: a title describing the particular run of the program.

(2) data group number 2

NS: number of freshwater discharges to be read. NS = ITMAX + 63

NAME: a description of the discharge data.

DISCH(I): daily freshwater discharge, in cfs, at the gauging station near Richmond; the daily discharge data are needed for the period simulated and also for the 62 days preceding that.

(3) data group number 3

NS: number of dates on which the computed results are to be printed.

ITT(I): number of days after computation starts on which the outputs are to be printed. ITT(NS) should be equal to ITMAX.

(4) data group number 4

CB(I): initial salinity, in ppt, at each reach, I = 1,24.

(5) data for each additional run with different conditions. (need to be furnished only if NRNM$\geq$2).

(a) TITLE: a title describing this particular condition.

(b) ML = 2, MU = 24.

(c) all of the data groups for which the conditions require different values from previous runs. The data groups having values the same as the previous run do not need to appear again.

(d) a data card reading 99 to signal the end of data for a particular running condition.

The program user should not alter the input data which are not mentioned above. The program will print out the input data, and the predicted salinity on dates specified in data group number 3.

D. Model Verification

The 'real time' model is run with a freshwater discharge value at Richmond being 6700 cfs, which is the average value over the period from 20 June to 30 June, 1971. The model outputs are compared with the salinity and DO data collected during the period 20 June to 26 July, 1971. The field data were not collected simultaneously along the estuary; they were collected at several transects at a time. The field surveys were started at upstream transects and progressed downstream. Therefore, (allowing some travelling time for freshwater discharge), the 6700 cfs can be considered as the average freshwater discharge to which the data correspond.

Figure 7 shows the comparison of salinity data and model outputs. The overall DO distributions are compared in Figure 8 with average DO plotted as a function of distance along the river. Each data point represents the average value over the cross-section and sampling period. In most cases, there were 9 data points in a transect measured hourly over a period of 3 to 4 days. The calculated DO

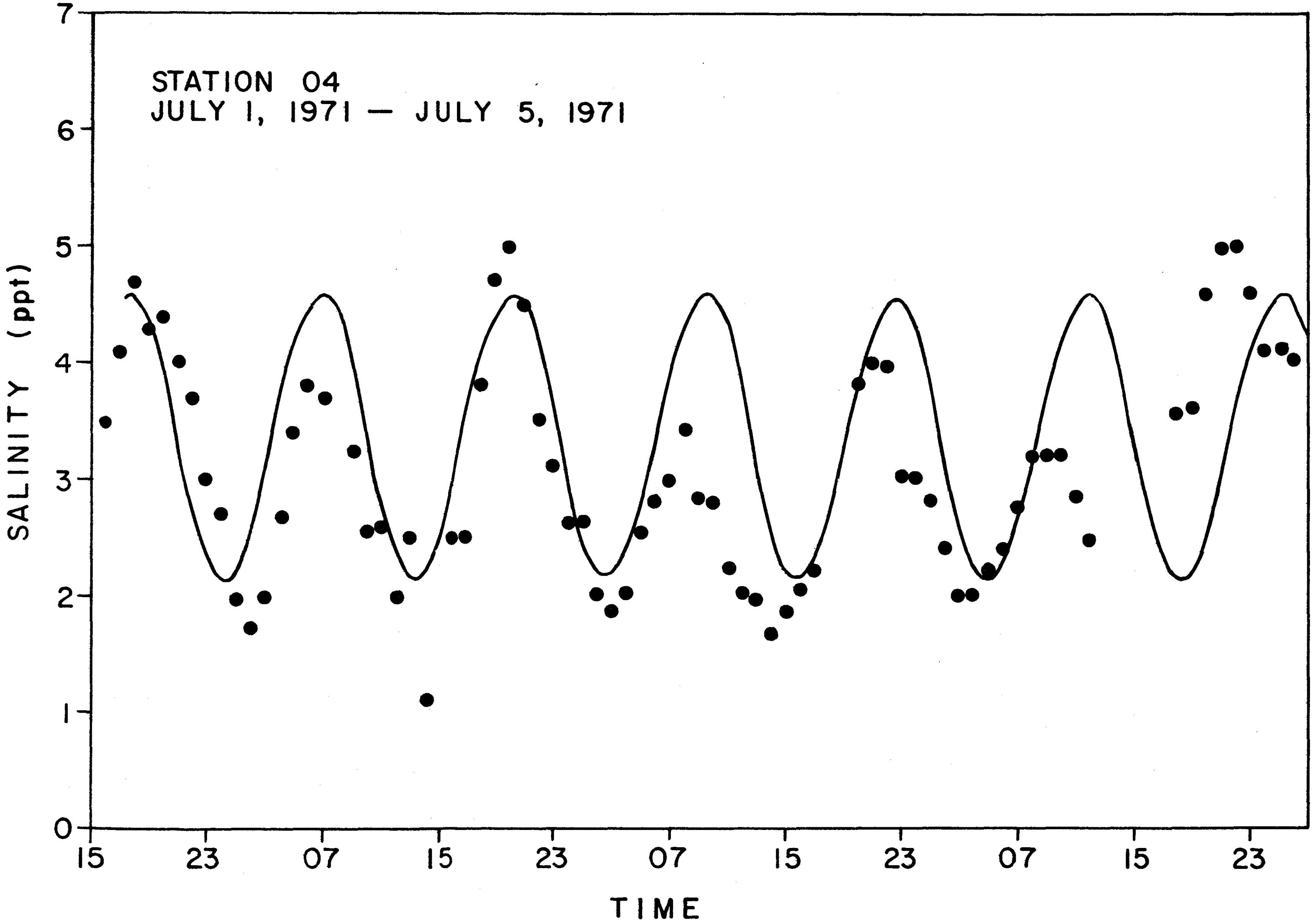


FIGURE 7. COMPARISON OF SALINITY DATA (POINTS) AND MODEL OUTPUT (CURVE).

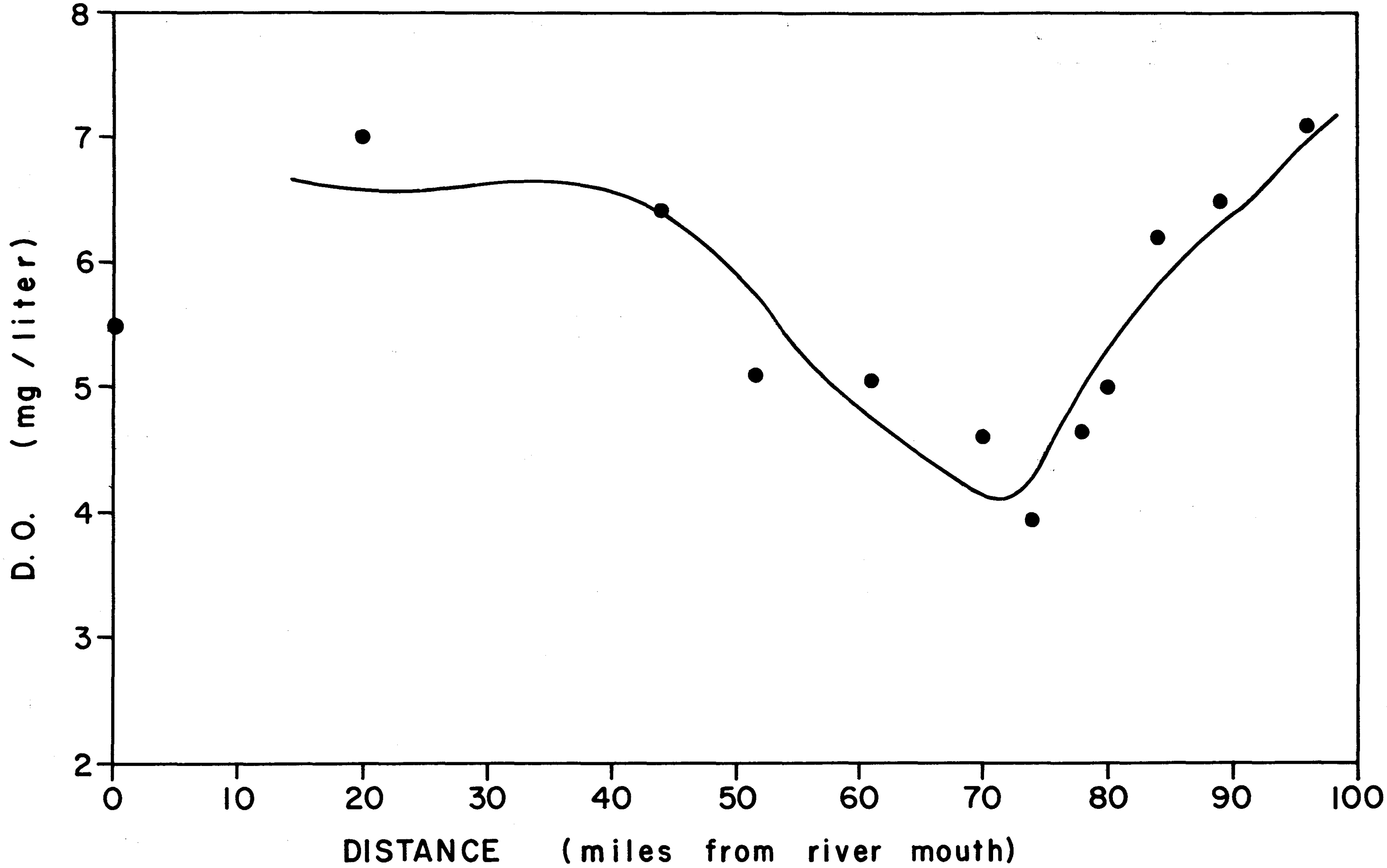


FIGURE 8. COMPARISON OF DO DATA WITH MODEL OUTPUT.

concentration at each reach is averaged over a tidal cycle and presented with a faired curve. The standard deviation of field data from model results is 0.37 mg/liter, which is about 6.7% of the average value. The DO sag exists at a short distance downstream of Hopewell, where the heavy BOD loads from industrial and domestic wastes are introduced into the river.

The temporal variations of DO concentration at given transects are shown in figures 9 to 19. The model predicts the average DO concentration in volume elements. The concentrations at transects are obtained by interpolation and plotted as faired curves. As shown in the figures, while the values of average DO predicted by the model agree reasonable well with those of field data at most of the transects, the field data have much larger time variation. The major factor contributing to this discrepancy in time variability is believed to be the effect of photosynthesis and respiration of plants. Since the amount of dissolved oxygen contributed by photosynthesis and consumed by respiration cannot be predicted because it varies from time to time and, from place to place, the present model does not include the effect of this process on oxygen balance. Furthermore, for the purpose of meeting the water quality standard, the photosynthesis cannot be counted on as a reliable source of oxygen.

Figure 20 shows the salinity distributions predicted by the 'slack tide approximation' model and the field data from slack water runs at high water slack. The slack water run data of 1 September, 1971 were used as the initial conditions of the model. Very high freshwater discharge occurred around 28 October. Attempts to model the recovery phase of salt intrusion after the very high freshwater discharge failed to give satisfactory results in comparison with the available field data on 3 December 1971. Further studies on the dispersion characteristics in stratified flow are necessary to extend the applicability of the model to very high freshwater flow condition.

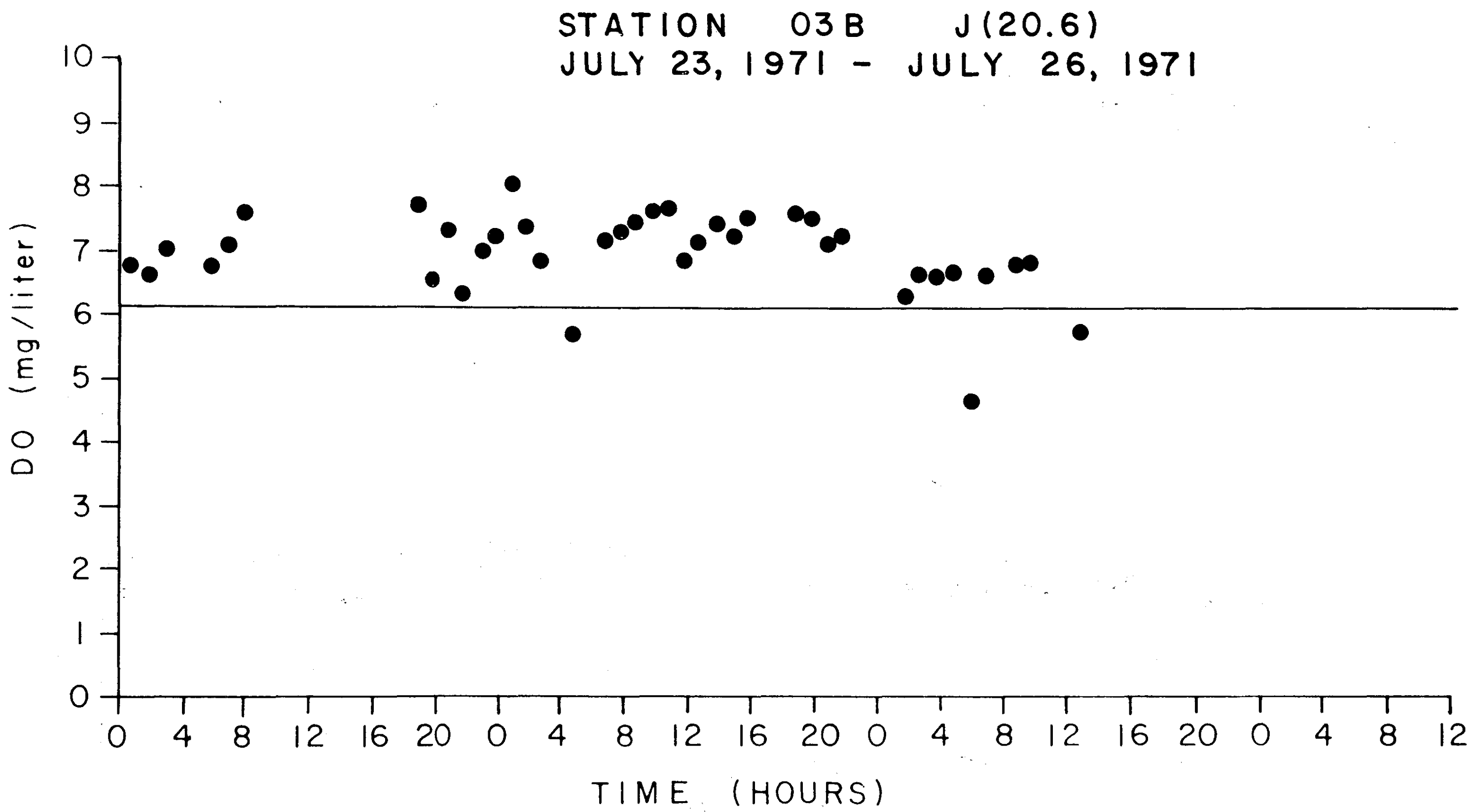


FIGURE 9. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 20.6.

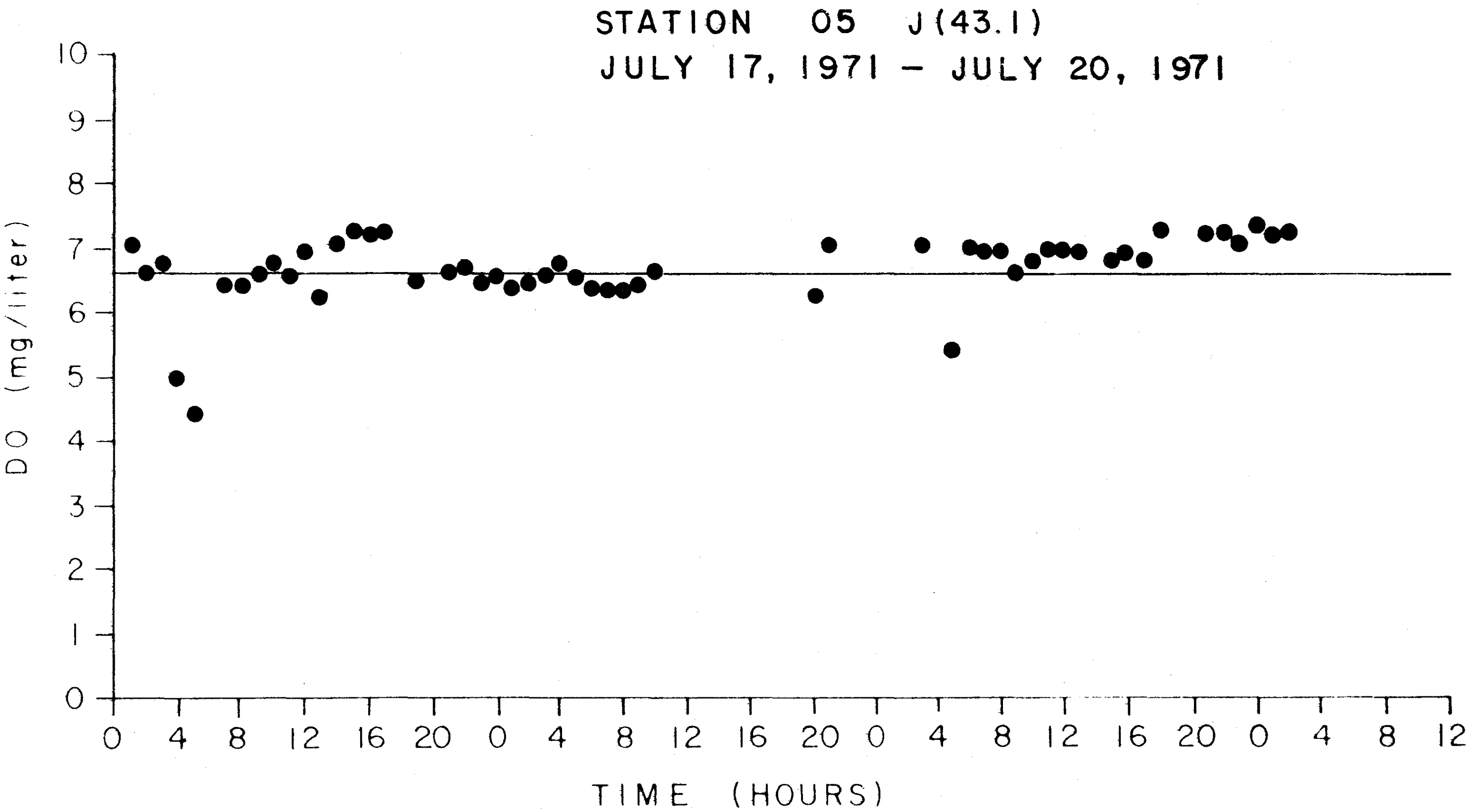


FIGURE 10. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 43.1.

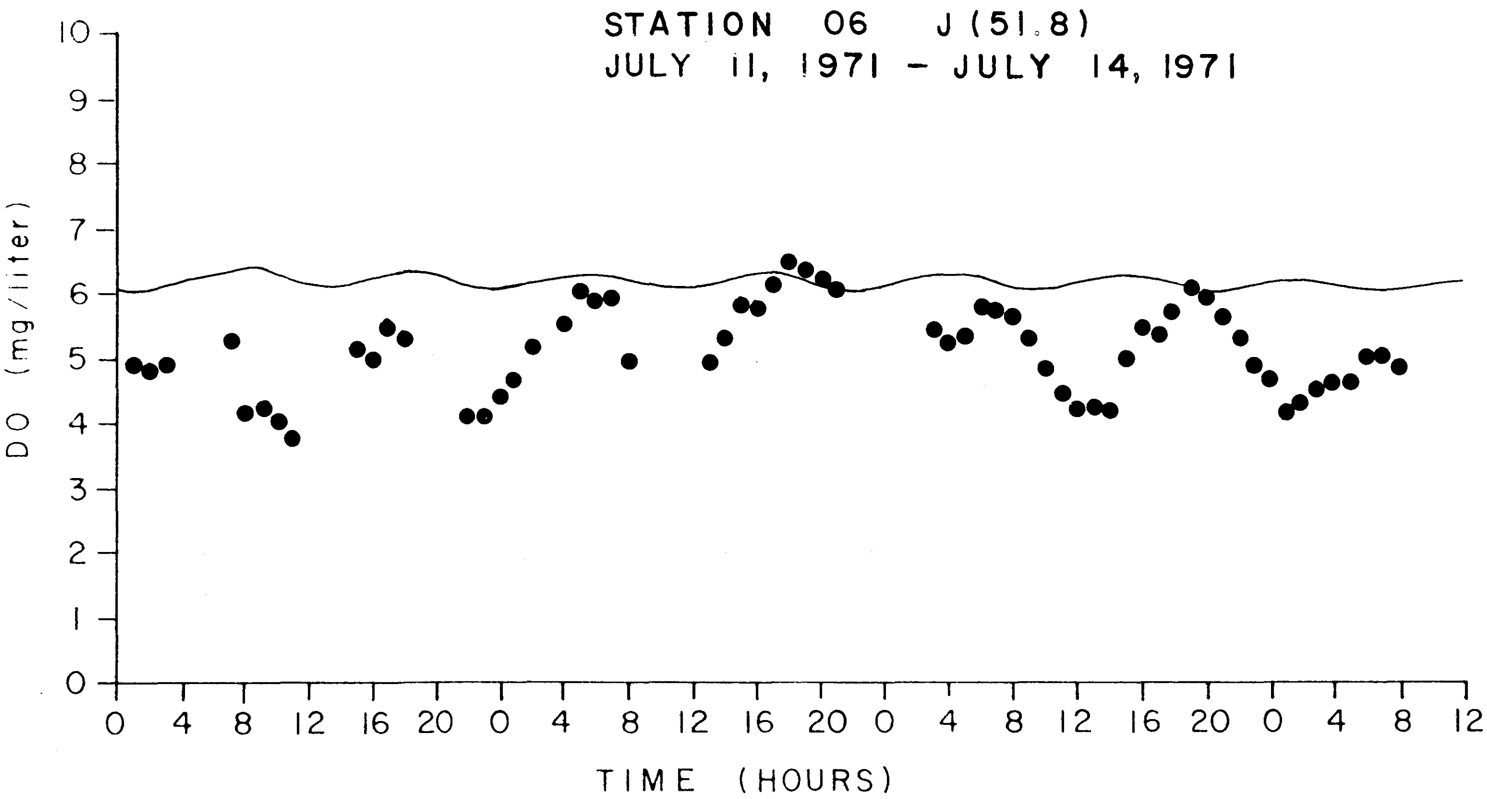


FIGURE 11. VARIATION OF DO WITH TIME, MODEL RESULTS AND FIELD DATA AT JAMES RIVER MILE 51.8.

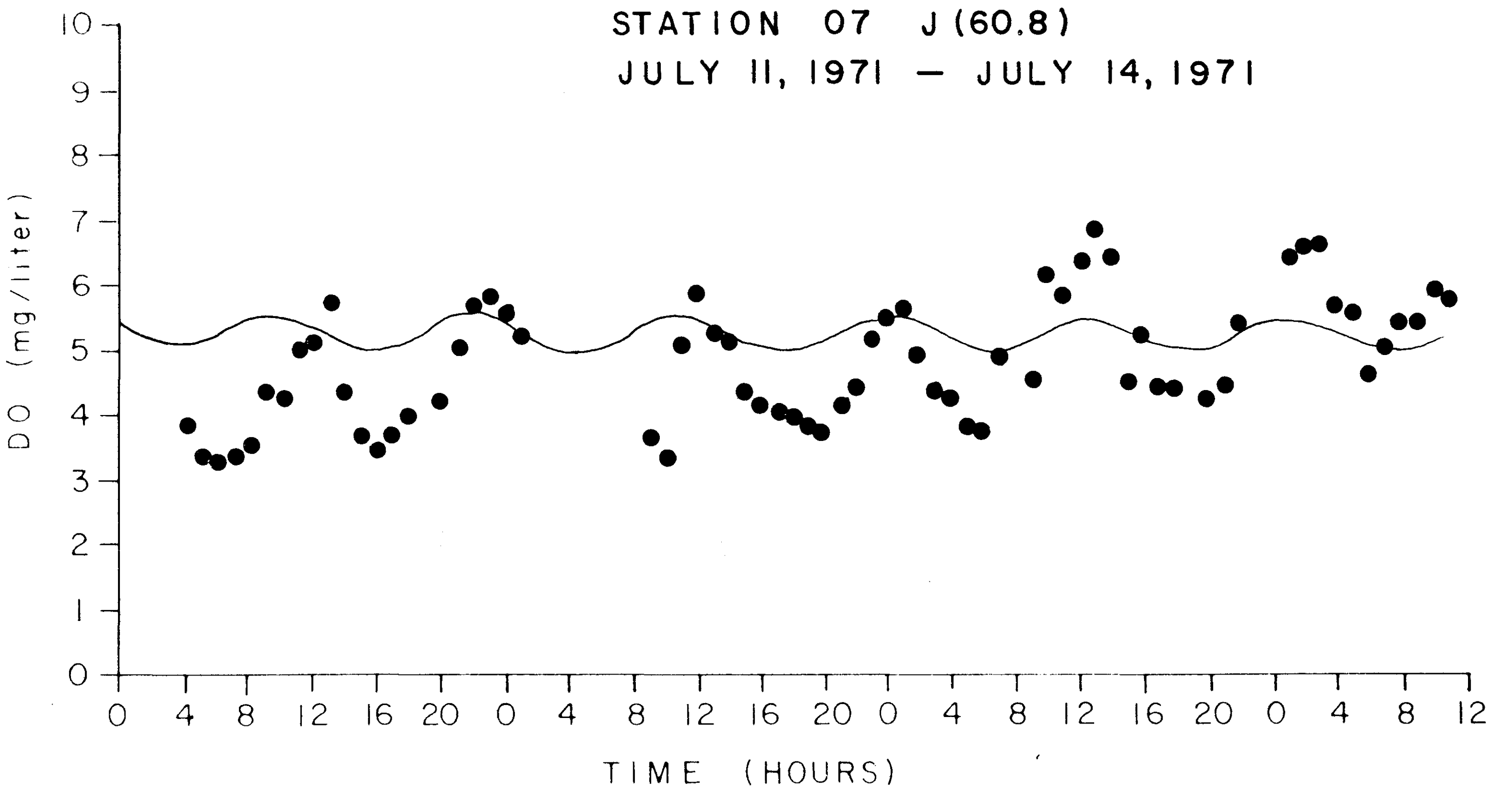


FIGURE 12. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 60.8.

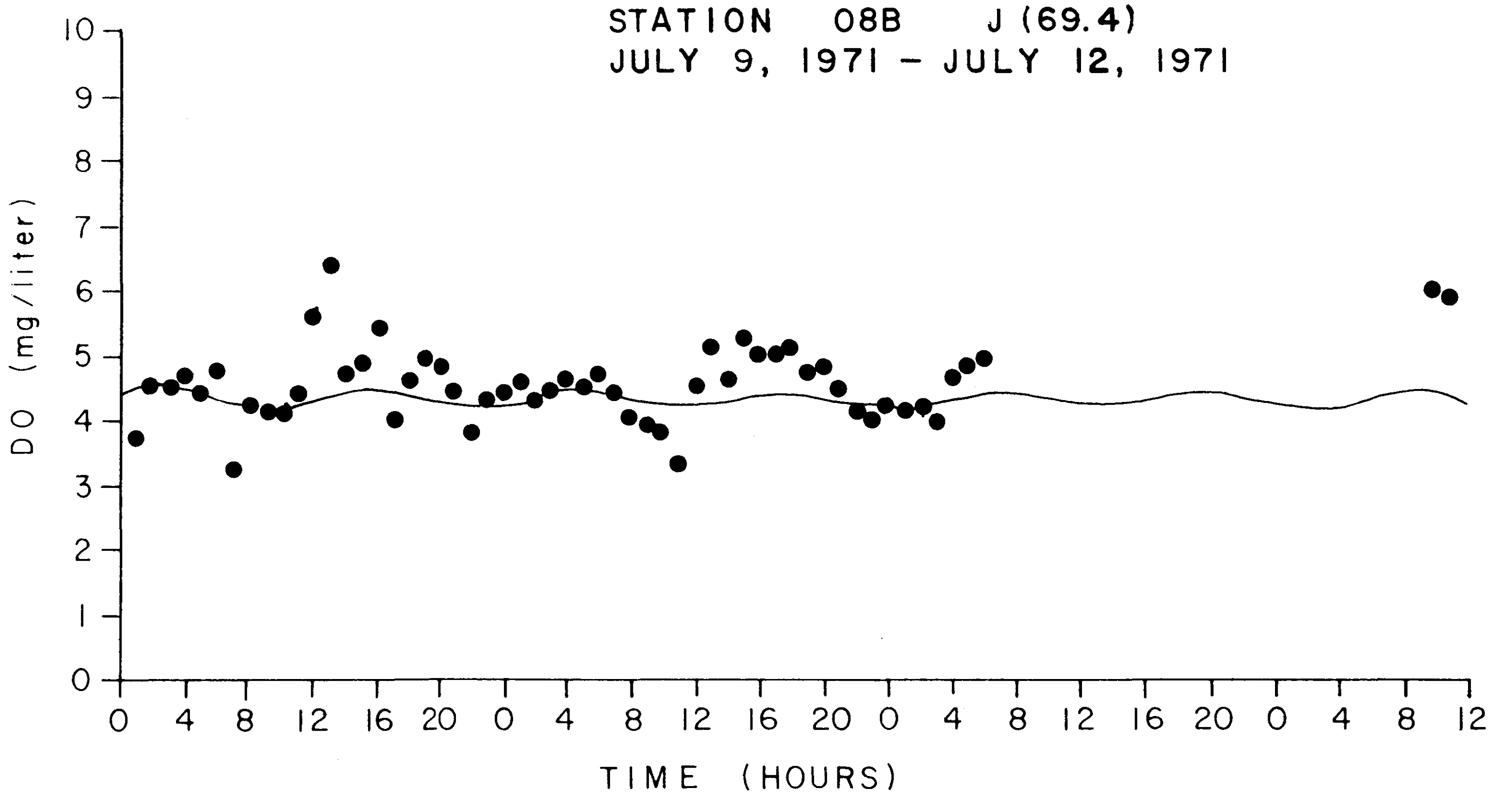


FIGURE 13. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 69.4.

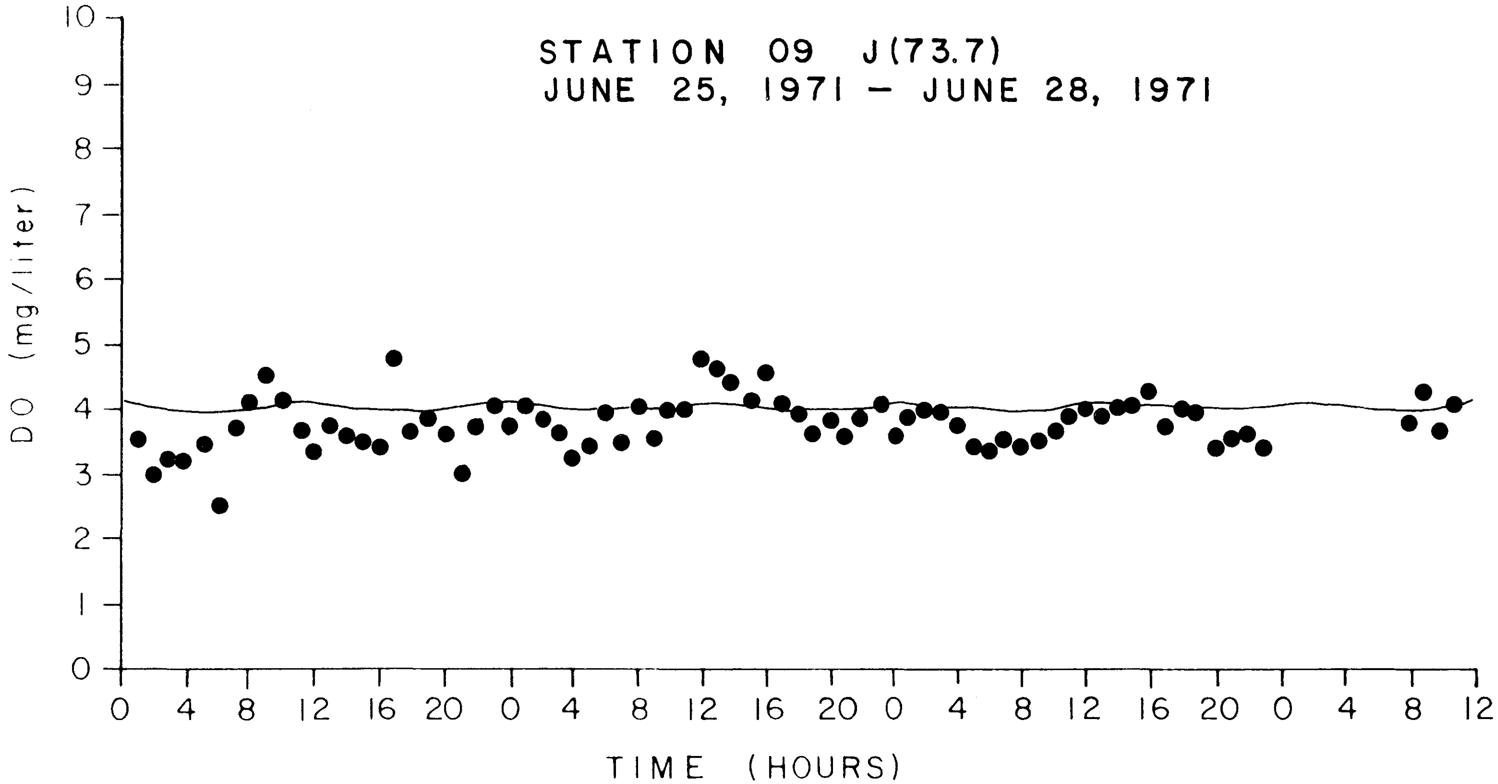


FIGURE 14. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 73.7.

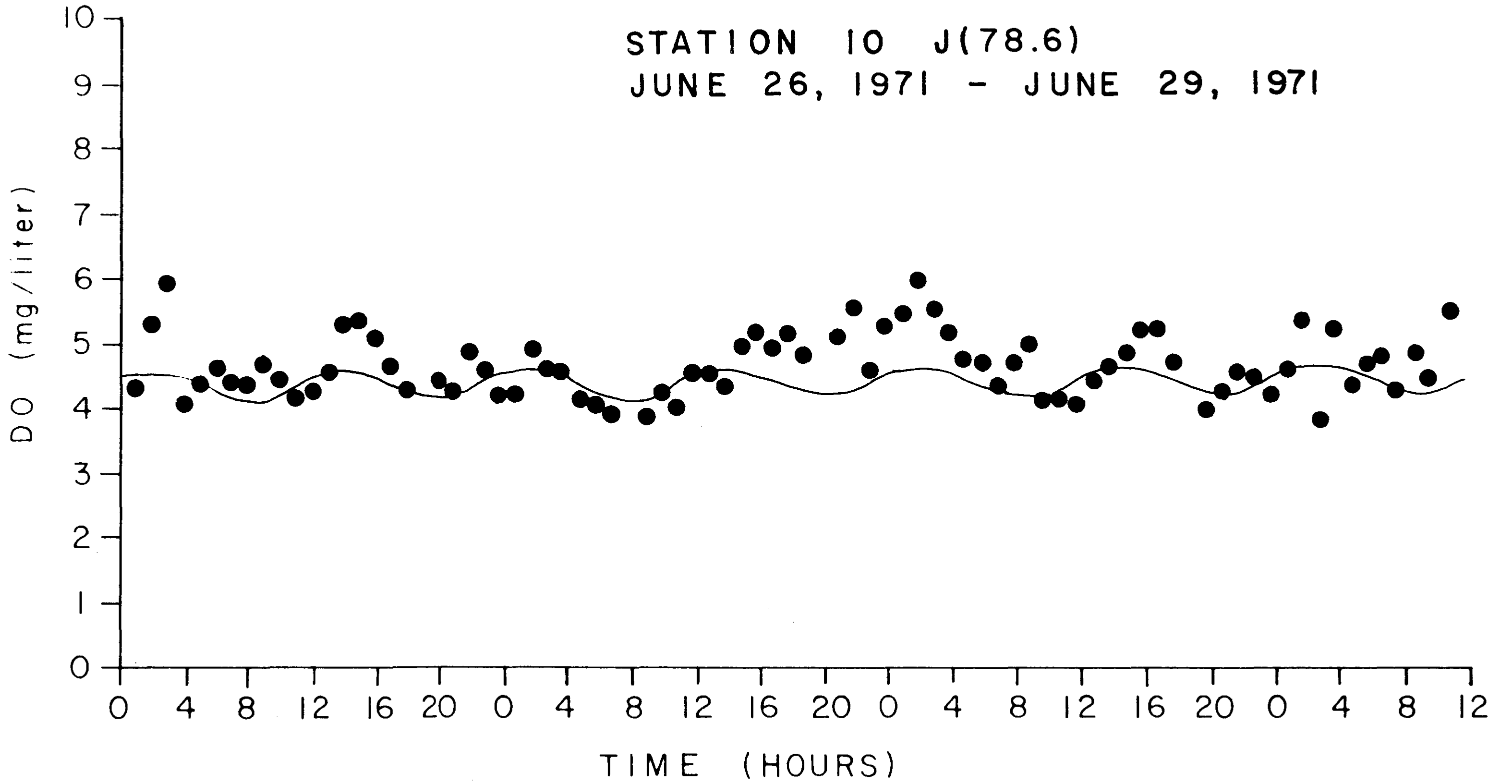


FIGURE 15. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 78.6.

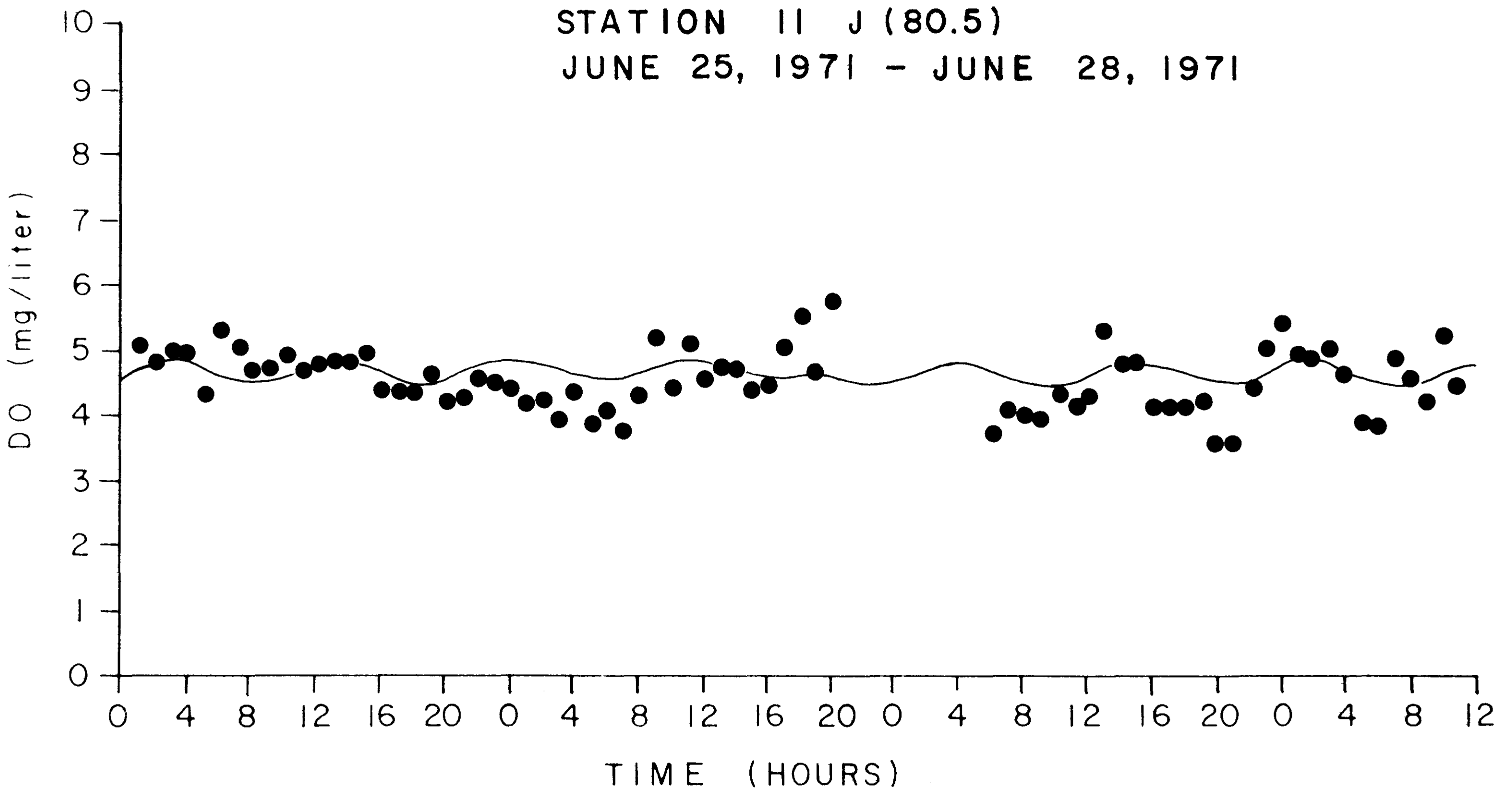


FIGURE 16. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 80.5.

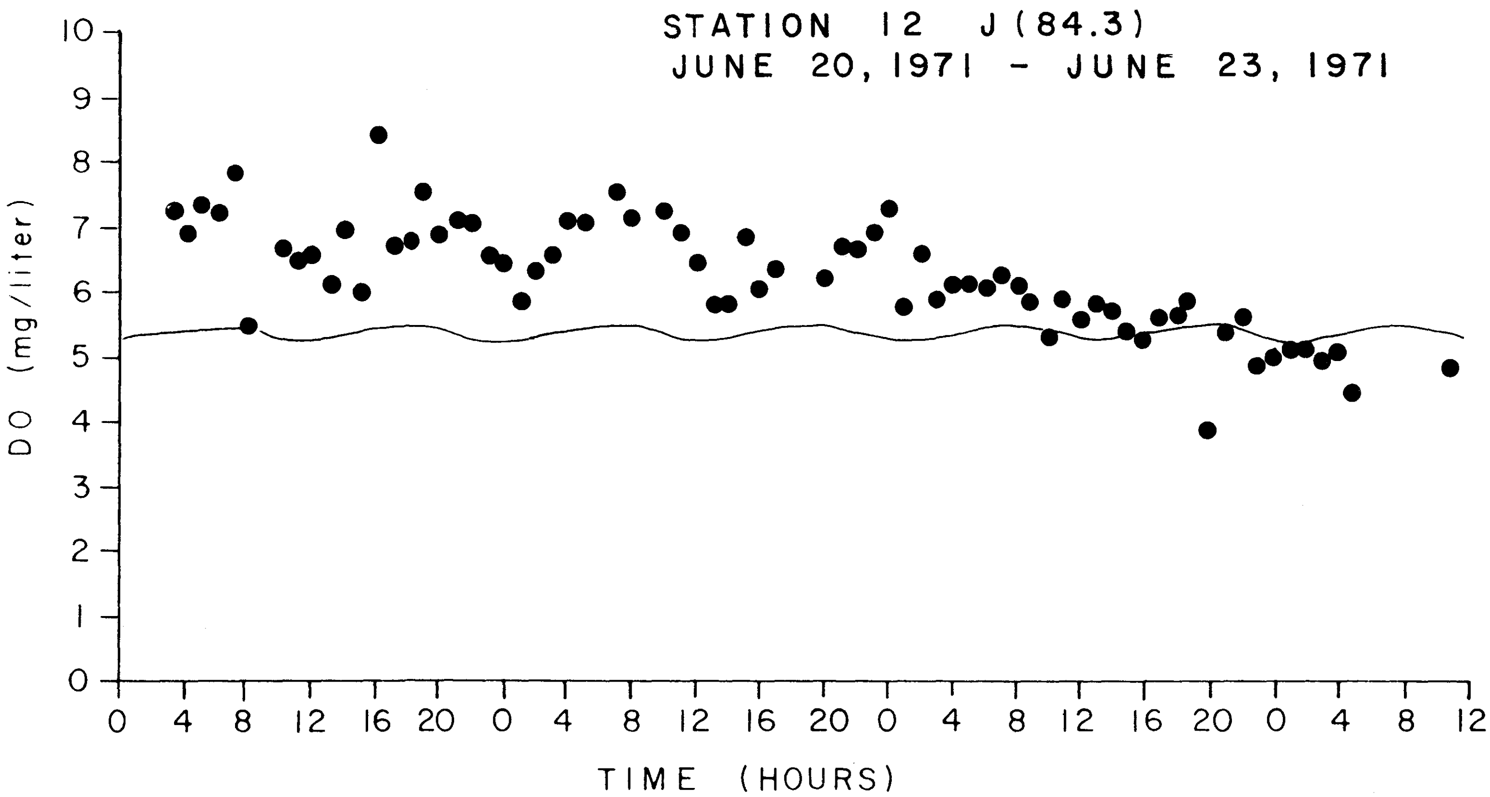


FIGURE 17. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 84.3.

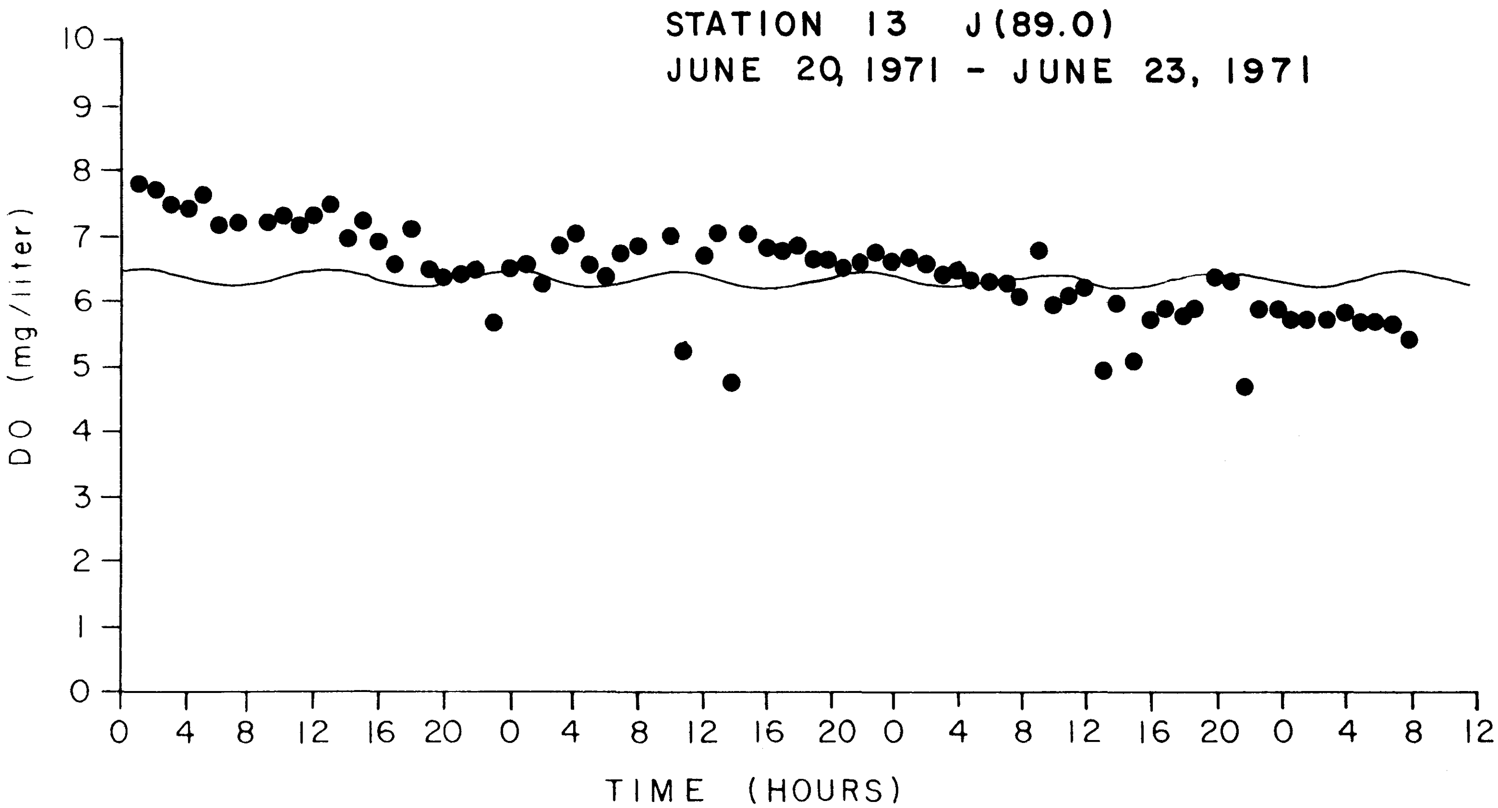


FIGURE 18. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 89.0.

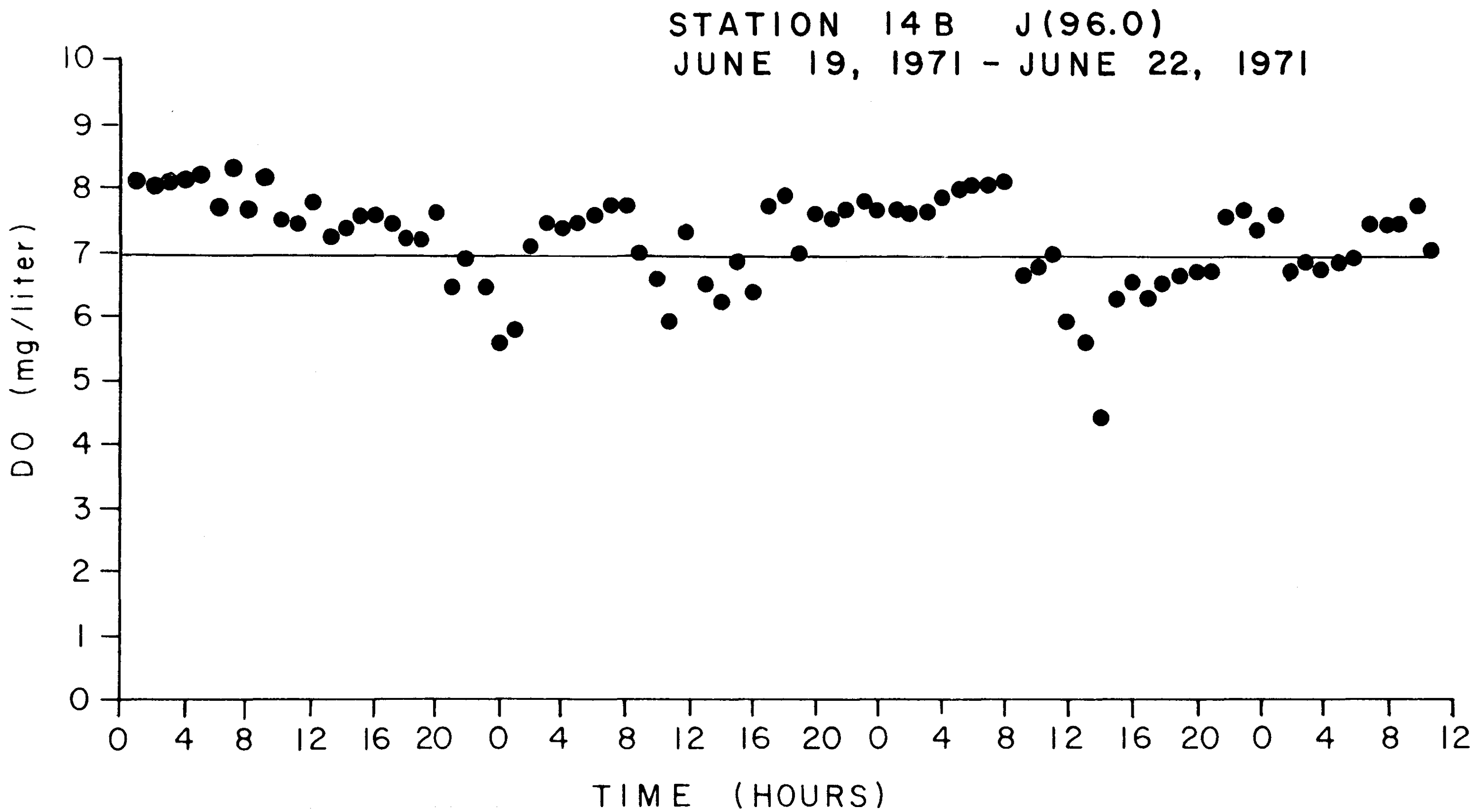


FIGURE 19. VARIATION OF DO WITH TIME, MODEL RESULTS AND OBSERVED VALUES AT JAMES RIVER MILE 96.0.

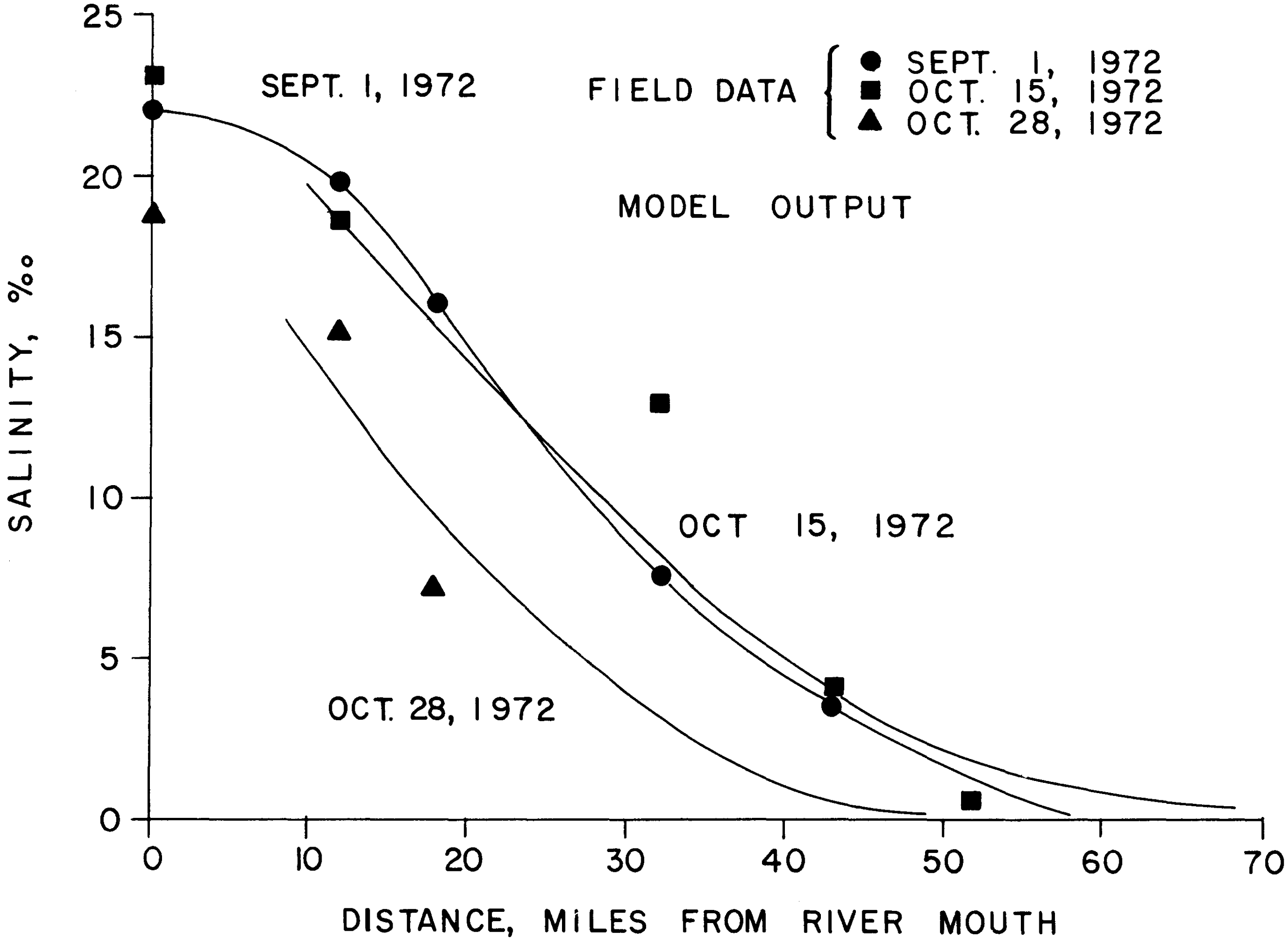


FIGURE 20. COMPARISON OF THE SALINITY DISTRIBUTION, USING THE 'SLACK TIDE APPROXIMATION' MODEL.

VII. EXPLICIT-SCHEME WATER QUALITY MODELS

P. V. Hyer

I. Salinity Model

i. Description

A. Purpose of model - The explicit-scheme salinity model is designed to predict high-water slack salinity distribution as a function of time over a period of several months. The model is non-tidal (Thomann type), balancing river discharge against mixing represented by a dispersion coefficient. The model treats the estuary as a series of segments, each segment exchanging mass with its neighbors by dispersion and advection. In this way the problem of salinity distribution reduces to a set of equations, one for each segment of the estuary.

B. Finite difference equations - The rate of change of salinity in the ith segment of the estuary is related to the salinity in the segment and in the two neighboring segments. The equation for the segment is as follows:

$$\frac{\partial S_i}{\partial t} = \frac{Q_i}{V_i}\{S_{i-1}(1-\phi_i) + S_i\phi_i\}$$

$$- \frac{Q_{i+1}}{V_i}\{S_i(1-\phi_{i+1}) + S_{i+1}\phi_{i+1}\}$$

$$+ \frac{2E_iA_i}{V_i(L_{i-1}+L_i)}(S_{i-1} - S_i)$$

$$+ \frac{2E_{i+1}A_{i+1}}{V_i(L_i+L_{i+1})}(S_{i+1} - S_i)$$

where Q_i is the net advective flow (non-tidal) into the ith reach from upstream and Q_{i+1} is the outward flow across the downstream interface. The cross-sectional areas are A_i and A_{i+1} respectively and the dispersion coefficients are E_i and E_{i+1} respectively. The length of the ith reach is L_i, so that $(L_{i-1} + L_i)/2$ is the distance from the center of one reach to the center of the next.

The interpolation factor ϕ_i is computed in the program to allow the model to describe adequately both the far upstream reaches, where the mass flux across the interface is determined by the upstream reach and the fully estuarine regime, where the interfacial value of salinity is the average of the salinities at the two adjacent reaches. This is accomplished by setting:

$$\phi_i = \frac{2E_iA_i}{(L_{i-1}+L_i)Q_i} \leq 0.5$$

$$\phi_i = 0.5 \text{ otherwise}$$

ii. Evaluation of Parameters

A model is merely a set of equations whose result can be no better than the data input to the model. Every parameter used in the model must be determined empirically. (It is assumed that the model is appropriate and that the necessary parameters can be determined). The geometric data have been described elsewhere in this report. The other important inputs are dispersion coefficient and freshwater discharge.

A. Dispersion coefficient - Turbulent mixing because of tidal motion is treated in this model by means of a dispersion coefficient, which is mathematically analogous to a molecular diffusion coefficient, but much larger in magnitude. In the fresh-water region, the dispersion coefficient is calculated according to the modified Taylor's equation for open-channel flow.

$$E = 77n\ QA^{-1}R^{5/6}$$

where Q is the magnitude of the tidal current, A is the mean cross-sectional area, R is the hydraulic radius and n is the Manning Roughness.

In saline regions the dispersion coefficient is much greater because the salt itself, by its effect on the density distribution, generates a motion resulting in mixing. The dispersion coefficient for the saline regime is calculated from field data assuming a quasi-steady salinity distribution:

$$E = \frac{QS}{A\frac{\partial S}{\partial x}}$$

where Q is the fresh-water discharge and S is salinity at HWS. The computed values of dispersion coefficient are shown in table 8.

B. Fresh-water discharge - The Virginia Water Control Board maintains gauging stations on the James River and Kanawha Canal near Richmond, Va. These are the recorded

Table 8

Calculated Dispersion Coefficients
for Explicit Scheme Salinity Model

Transect	River Mile	$E(ft^2/sec)$	$E(mi^2/day)$
J14	83.4	62.	0.19
J13	77.3	82.	0.25
J12	73.2	79.	0.25
J11	69.9	82.	0.25
J10	68.3	54.	0.17
J09	64.0	52.	0.16
J08	60.3	98.	0.30
J07	52.8	130.	0.40
J06	45.0	109.	0.34
J05	37.4	1300.	4.0
J04	28.2	1330.	4.1
J03	17.9	2290.	7.1
J02	10.3	7630.	23.7
J01	0.0	14300.	44.4

flows used as input to the model. Besides inflow from upstream, each segment has a lateral inflow of surface water contributed by the land draining directly into that segment or its tributaries. This lateral inflow is calculated automatically in the model by assuming hydrologic homogeneity over the drainage basin and calculating the lateral inflow from the incremental drainage area and the gauged flow. Ground water contributions to fresh water flow are not considered.

iii. Verification

The salinity model was verified according to data from VIMS slack water runs for summer and fall of 1971. High water slack runs occurred September 1, October 15, October 28 and December 3, 1971. Initial conditions were taken from the summer field study and the initial date for the computer run was July 22. Because the flow varied rapidly between October 15 and October 28, it was necessary to use five-day average flows in the verification.

The verification results for each of the four slack water runs are shown in figures 21 through 24.

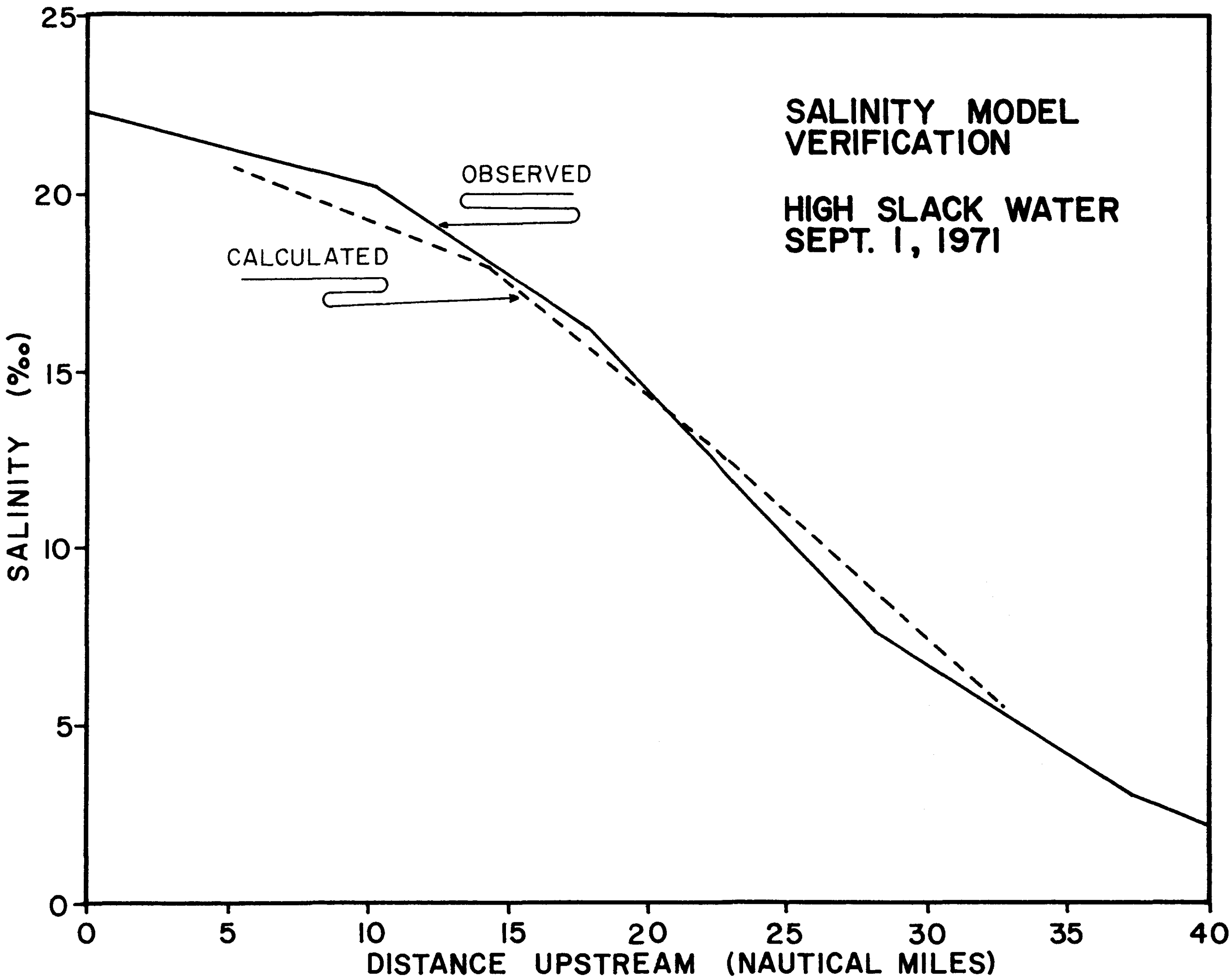


FIGURE 21. SALINITY MODEL VERIFICATION I (EXPLICIT-SCHEME).

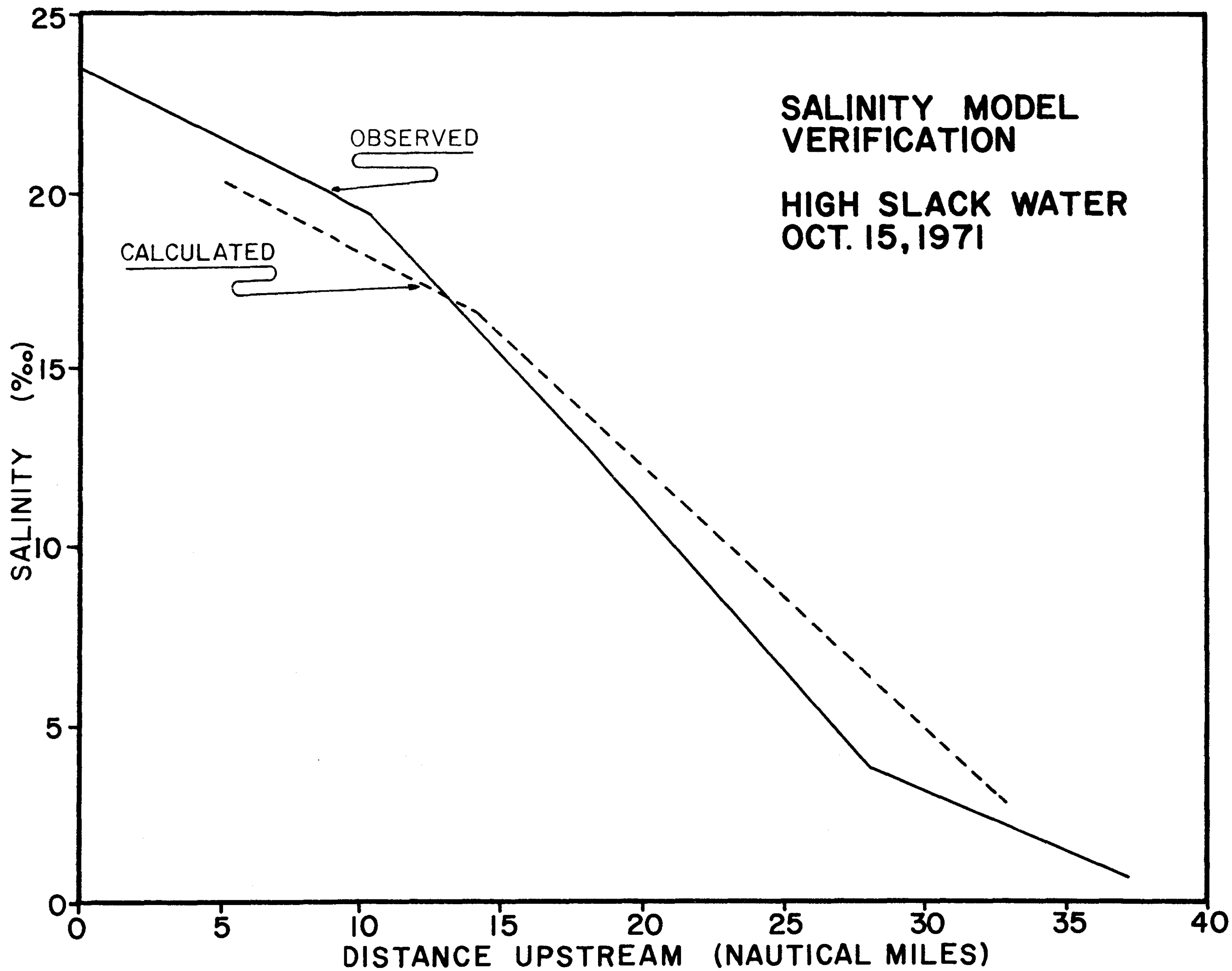


FIGURE 22. SALINITY MODEL VERIFICATION II (EXPLICIT-SCHEME).

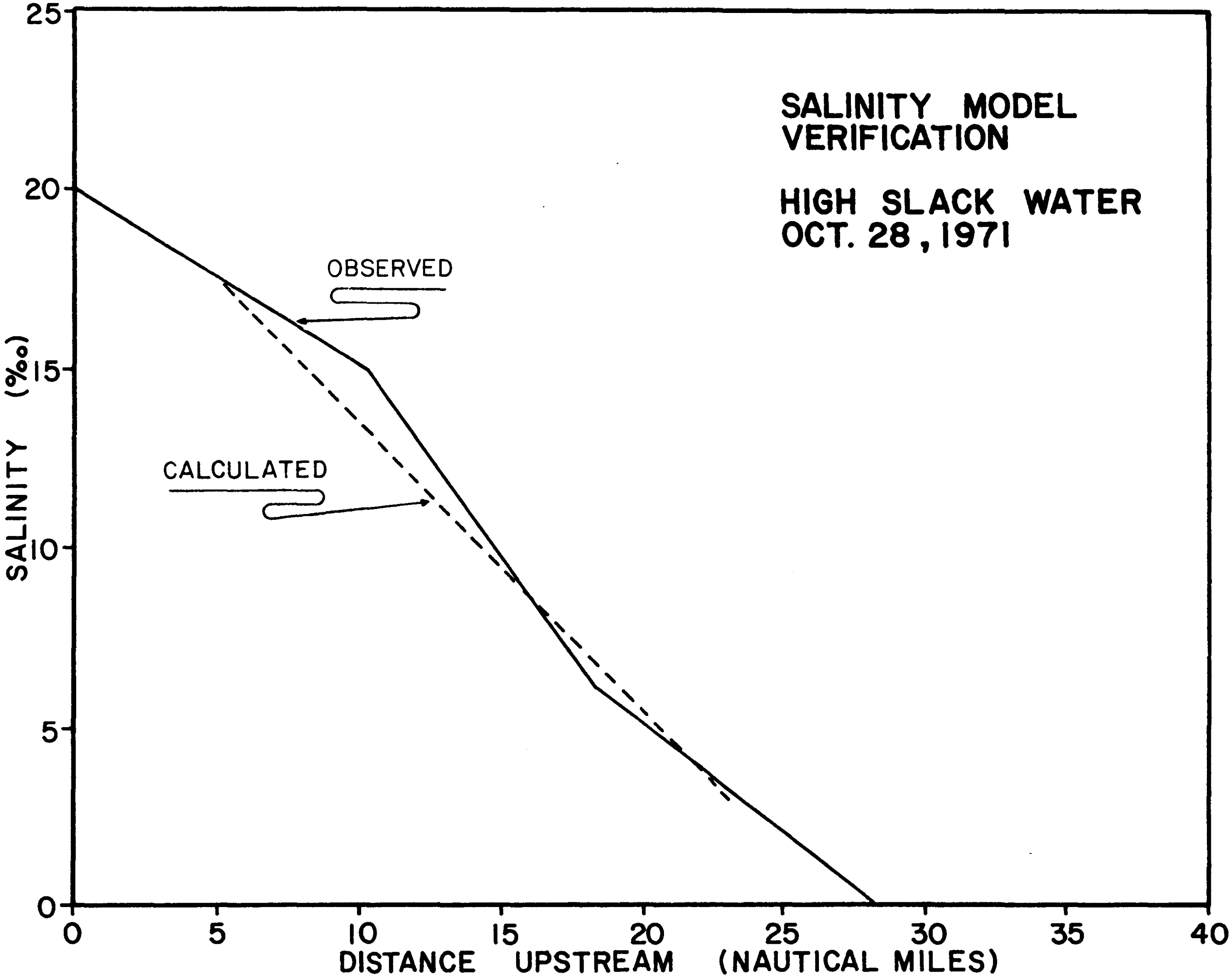


FIGURE 23. SALINITY MODEL VERIFICATION III (EXPLICIT-SCHEME).

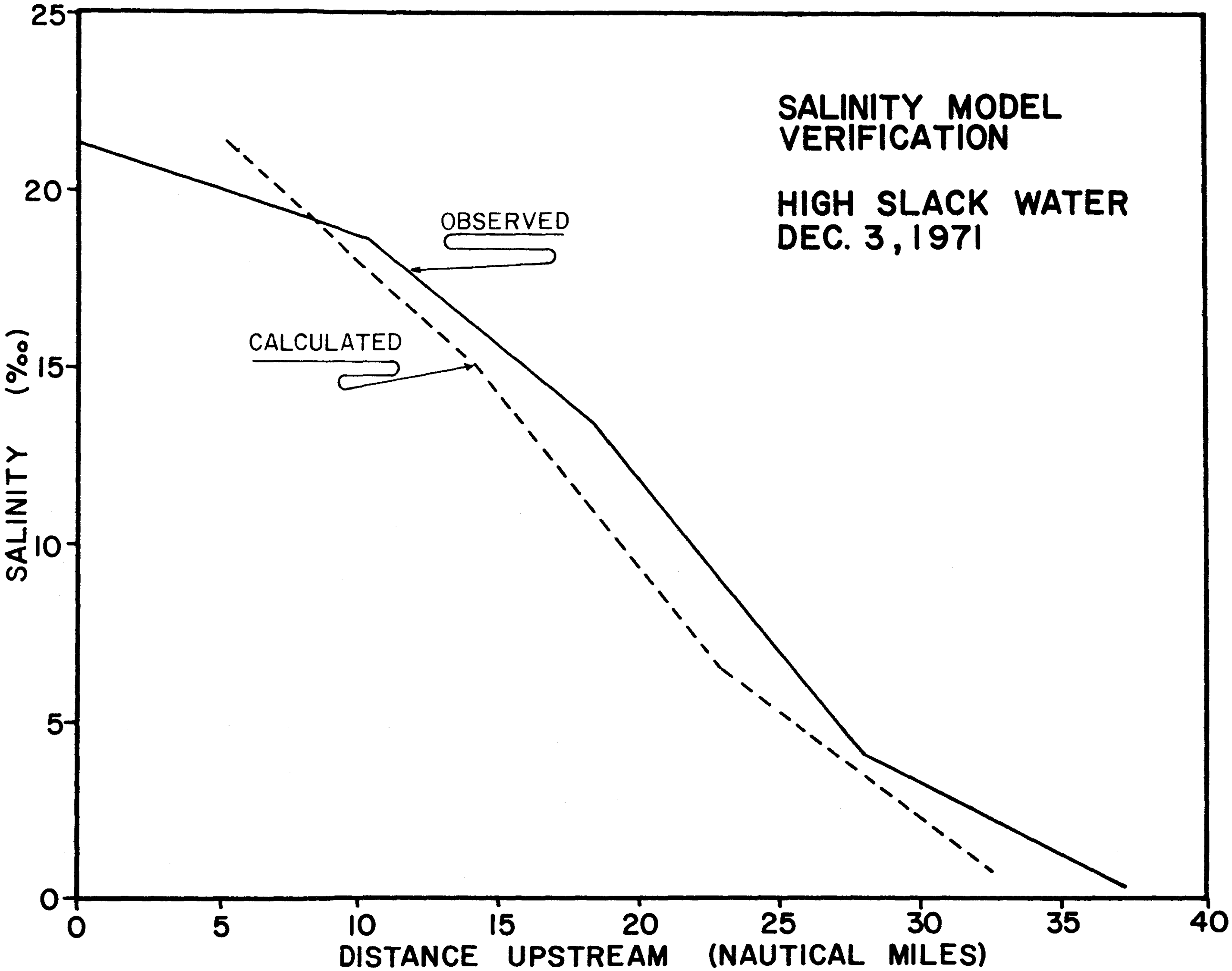


FIGURE 24. SALINITY MODEL VERIFICATION IV (EXPLICIT-SCHEME).

II. Dissolved Oxygen Model

i. Description

A. Purpose of model - the explicit-scheme dissolved oxygen model is designed to predict dissolved oxygen and biochemical oxygen demand levels for a tidal estuary over periods of one to two weeks. The model is real-time, including tidal motion. Advection and dispersion are included in the model. The model includes terms for BOD and benthic demand loadings, and terms for biochemical decay and atmospheric reaeration. Finite-difference equations are used for both BOD and DO in a set of reaches.

B. Finite-difference equations - for each segment there is a pair of equations, one for dissolved oxygen and the other for BOD. These equations relate the rate of change of concentration in the reach to the advective and dispersive contributions across the ends of the reach and the source and sink terms in the reach. The finite-difference equations are:

$$\frac{\partial C_i}{\partial t} = \left(\frac{Q_i(1-\phi_i)}{V_i(t)} + \frac{2E_iA_i}{V_i(t)(L_{i-1}+L_i)} \right)(C_{i-1} - C_i)$$

$$+ \left(\frac{Q_{i+1}\phi_{i+1}}{V_i(t)} - \frac{2E_{i+1}A_{i+1}}{V_i(t)(L_i+L_{i+1})} \right)(C_i - C_{i+1})$$

$$- R_1L_i + k_2\ (C_{si} - C_i) + \frac{P_i}{V_i(t)}$$

$$\frac{\partial L_i}{\partial t} = \left(\frac{Q_i(1-\phi_i)}{V_i(t)} + \frac{2E_iA_i}{V_i(t)(L_{i-1}+L_i)}\right)(L_{i-1}-L_i)$$

$$+ \left(\frac{Q_{i+1}\phi_{i+1}}{V_i(t)} - \frac{2E_{i+1}A_{i+1}}{V_i(t)(L_i+L_{i+1})}\right)(L_i - L_{i+1})$$

$$- k_1L_i + \frac{J_i}{V_i(t)}$$

where

C_i = dissolved oxygen concentration

L_i = BOD concentration

Q_i = inflow into ith reach from upstream, including alternating tidal flow

Q_{i+1} = flow from ith reach to i+1th reach, including alternating tidal flow

$V_i(t)$ = volume of ith reach, including variation of volume over the tidal cycle

E_i = dispersion coefficient between i-1th reach and ith reach

A_i = cross-sectional area between i-1th reach and ith reach

L_i = length of ith reach

ϕ_i = interpolation factor in advective term. Generally ϕ_i = 0.4 on ebb; 0.6 on flood.

J_i = BOD loading

P_i = Primary oxygen term. Positive for source, negative for sink.

k_1 = BOD decay coefficient.

k_2 = atmospheric reaeration coefficient.

ii. Evaluation of parameters - All the parameters used in the model must be determined from field experience. The parameters can be divided into hydraulic, sanitary and geometric.

A. Hydraulic parameters - Tidal flow is included in this model. The tidal flux is assumed sinusoidal and the current amplitude has been determined from the velocity measurements made using the Braincon current meter records. The tidal flow at a given time is computed within the program using the input tidal current amplitude, cross-section area and a sinusoidal function of the tidal stage.

The dispersion coefficient is not highly important in this model. Sensitivity tests performed in the model of the Upper York System indicate that dispersion coefficients of five percent those used in the non-tidal model adequately describe the shape of the sag region.

B. Sanitary parameters - the BOD loadings were determined from the records of the Water Control Board and the Hampton Roads Sanitation District. Consideration was limited to sources of greater than two hundred pounds per day. The Water Control Board supplied data for industrial sources and sewage treatment plants from Richmond to Williamsburg. Hampton Roads Sanitation District supplied records for its own facilities. In the case of treatment plants, the average loadings for July 1971 were used. Williamsburg STP was not included since it had not yet come on line at that time.

A benthic demand loading of 60,000 lbs/day has been included for Hopewell to include the oxygen demand exerted by bottom deposits. This term is exerted immediately on the dissolved oxygen, i.e. it is not included as a source of BOD but as a sink term in the DO equation.

An immediate demand loading of 60,000 lbs/day was included for Hopewell since the industrial wastes for this area include some volatile, rapidly-oxidizing components. This figure is about sixty percent of the ultimate BOD for this complex.

For reaeration, the O'Connor-Dobbins formula was used

$$k_2 = \left(\frac{Du}{H^3}\right)^{\frac{1}{2}} \theta^{T-20}$$

, where D is the molecular diffusion coefficient, U is the tidal current amplitude and H is the hydraulic depth. The temperature correction factor is 1.024.

The decay coefficient used was

$$k_1 = 0.2\nu^{T-20}, \quad \text{where } \nu = 1.047$$

C. Geometrical Data - VIMS personnel conducted a bathymetric survey in Spring, 1971 and Spring, 1972, taking cross-sectional depth profiles at 25 transects using a Raytheon sonic depth recorder. While this survey was in operation, several temporary tide gauges were in operation. These gauges were surveyed to obtain their level with respect to mean sea level (1929 Datum Plane). Consequently, the cross-sectional areas themselves could be corrected to mean sea level. Volume data were obtained from CBI, Special Report No. 20 entitled "Volumetric, Great and Tidal Statistics of the Chesapeake Bay Estuary and its Tributaries" by W. B. Cronin. This report gave cumulative estuarine volume at mean tide level for each five kilometers of distance upstream. The actual volume between VIMS transects was found by interpolation. This report also tabulated water surface area at mean sea level. Hence the mean depth for a given volume was calculated as the volume divided by the surface area. Lateral inflow was calculated from the incremental drainage area as reported by Seitz in CBI Special Report No. 19, assuming hydrologic homogeneity. Finally reach lengths were determined from navigation charts published by the U.S.C. & G.S.

iii. Verification and Sensitivity

A. Verification

A water quality model of a particular estuary must have particular inputs from that estuary and must also be shown to predict the behavior of that estuary. This demonstration is known as model verification. The James River water quality model was verified using the data from the intensive field project of the summer of 1971. These time series were of the appropriate length and type for verifying the model, i.e. were real-time series covering several tidal cycles.

The fresh-water discharge was held constant at the flow rate for the last ten days of June, 1971. The waste loading for the Richmond-Hopewell area were obtained from the Virginia Water Control Board, expressed as 5-day BOD's. These were converted to ultimate by multiplying by a factor 1.5. Besides the reported loadings, the verification included background BOD loadings corresponding to estimates of agricultural runoff, etc., in reaches 3, 4, 5 & 6. These loadings correspond exactly to the background BOD used in this report by Kuo. Hampton Roads Sanitation District supplied discharge loading records for July, 1971. Table 9 shows the reported loadings and estimated background loading used in the verification. The water temperature was set at a constant value for each reach obtained from a time average of the field data.

The field data themselves were also used to obtain boundary conditions. Dissolved oxygen concentration was set at 85% of saturation upstream of Richmond. The actual boundary condition was adjusted from this value slightly by the BOD entering the river from Richmond. The upstream boundary condition on BOD was determined from the loading contributed by Richmond and the fresh-water discharge into the first reach. For the flows prevailing, the boundary condition was 2.1 ppm. The downstream boundary condition on DO was set at 70% saturation including the effect of 20 ppt salinity on the saturation concentration. The downstream BOD boundary condition was set at 4.0 parts per million..

The model verification run was for several days beginning at low water slack and including tidal motion.

Table 9

James River Loadings Used in Explicit Model

Reach	Limits, river miles	Reported Loading (lb/day ult.)	Background Loading (lb/day ult.)	Geographical Location
		98000		Richmond
1	83.4 - 77.3	5540		
2	77.3 - 73.2	-		
3	73.2 - 69.9	1900	75600	
4	69.9 - 68.3	-	67300	
5	68.3 - 66.6	16400	78600	Appomattox River
6	66.6 - 64.0	182000	74600	Hopewell
7	64.0 - 60.3			
8	60.3 - 57.9			
9	57.9 - 55.8			
10	55.8 - 52.8			
11	52.8 - 50.0			
12	50.0 - 45.0			
13	45.0 - 41.2			
14	41.2 - 37.4			
15	37.4 - 28.2			
16	28.2 - 17.9	4900		Hampton Roads
17	17.9 - 10.3	10800		"
18	10.3 - 7.0	1900		"
19	7.0 - 0.0	12700		"

The field observations were approached as a quasi-steady limit by the verification run. Figure 25 shows the time average of the field data compared to the model results for high- and low-water slack times. The average of the results at the two slack times is also shown. Figure 26 shows the distribution of maximum and minimum model results. These are plotted with the 90% confidence limits of the field data. The bars are indicative of the variance of the samples, rather than the variance of the intra-tidal mean value.

B. Sensitivity

Some computer runs were made to test the sensitivity of the model to variations in certain inputs. In particular the effects of variations in temperature, freshwater discharge, BOD loading and decay coefficient were studied. A summary of the results for high water slack are given in figures 27 & 28, showing the deviations of HWS DO from the verification run under various changes in input. Note that while an increase in temperature increases the reaeration rate, this effect is overridden by the increase in decay coefficient and depression of saturation concentration caused by an increase in temperature. Also shown is the result of increasing the load coming from Bailey's Creek (the bulk of the Hopewell loading) by 50%. Similar curves are also shown for alleviating water conditions by the

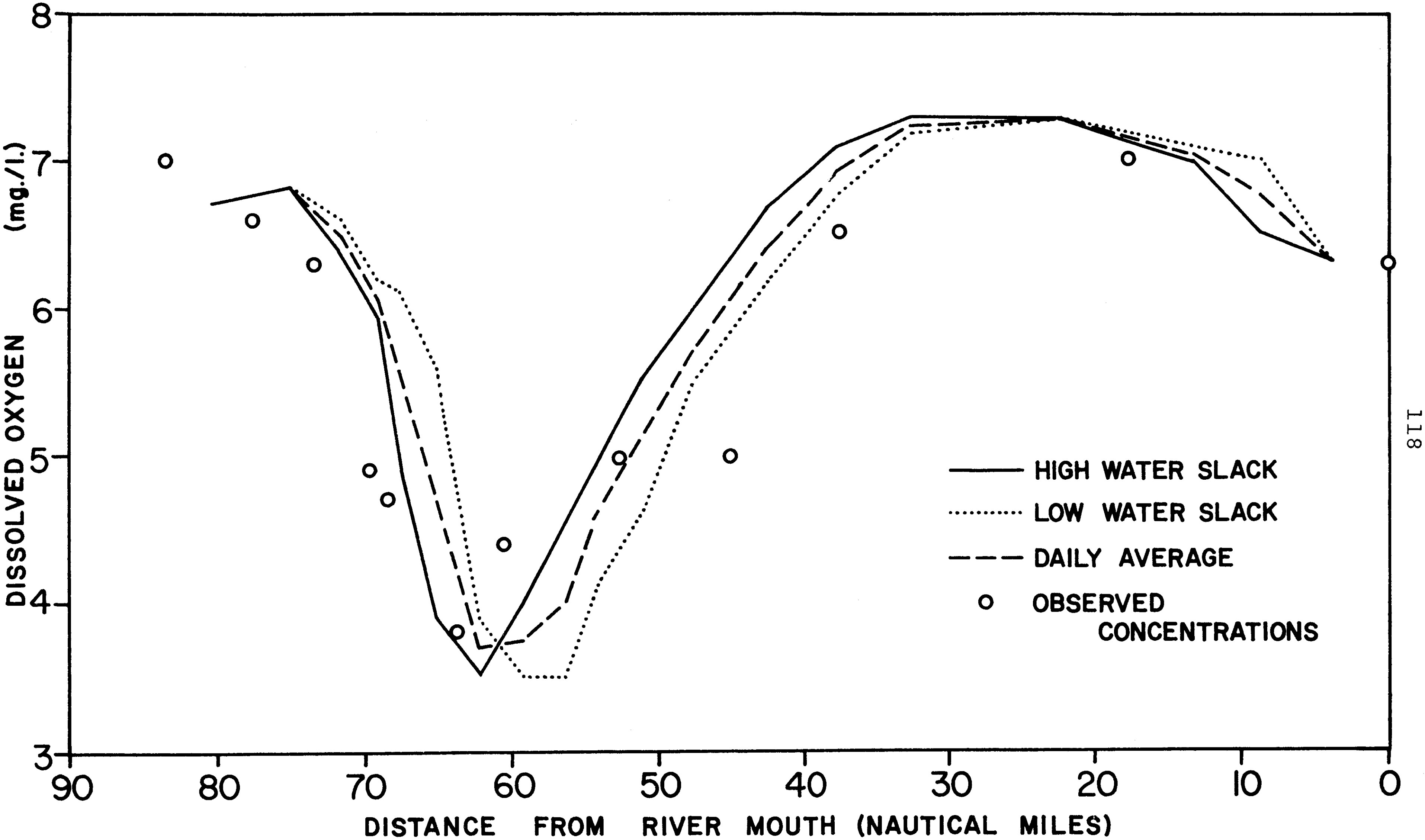


FIGURE 25. COMPARISON OF DO DISTRIBUTION ALONG THE JAMES ESTUARY (EXPLICIT SCHEME MODEL).

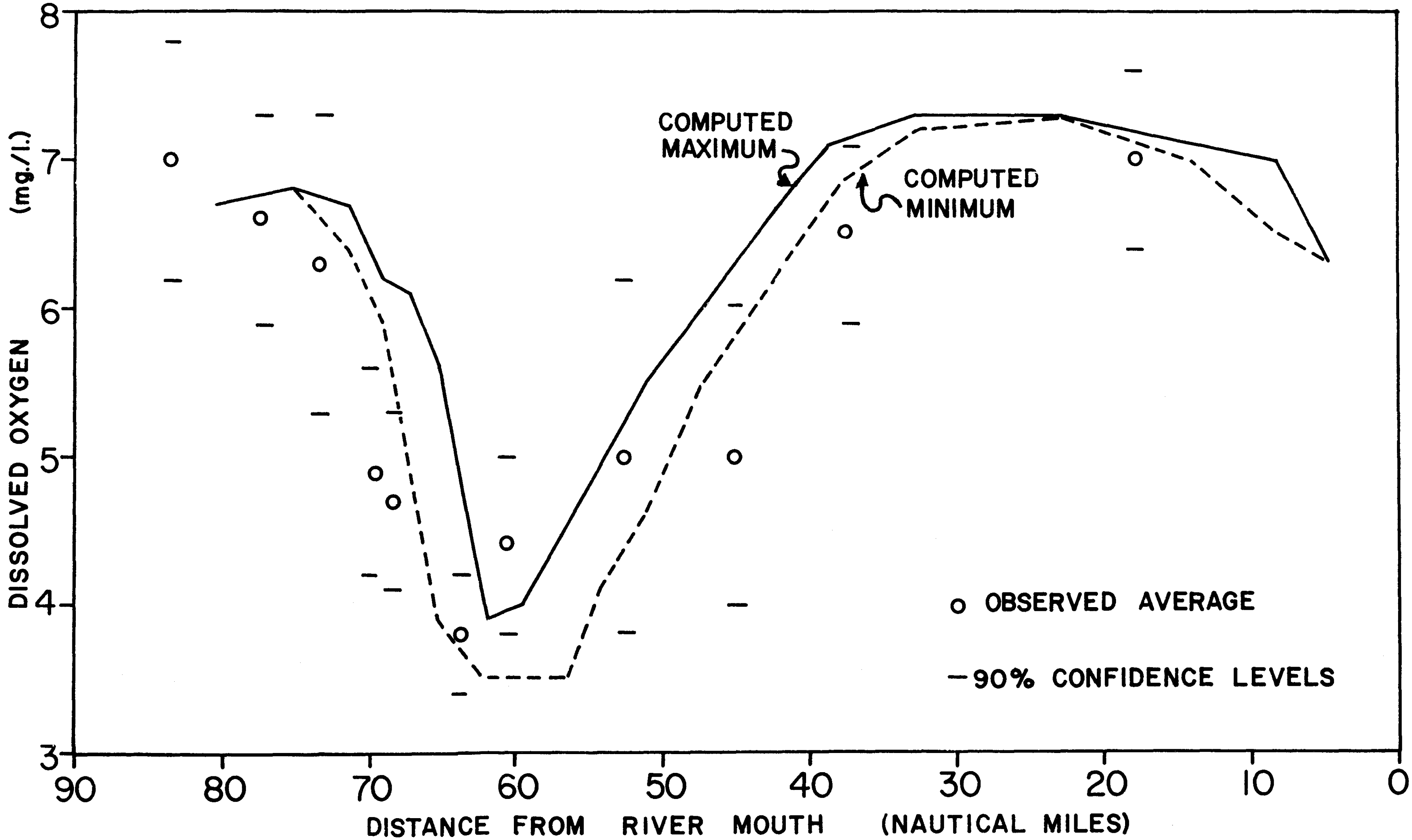


FIGURE 26. COMPUTED DO VARIATION ALONG THE JAMES ESTUARY.

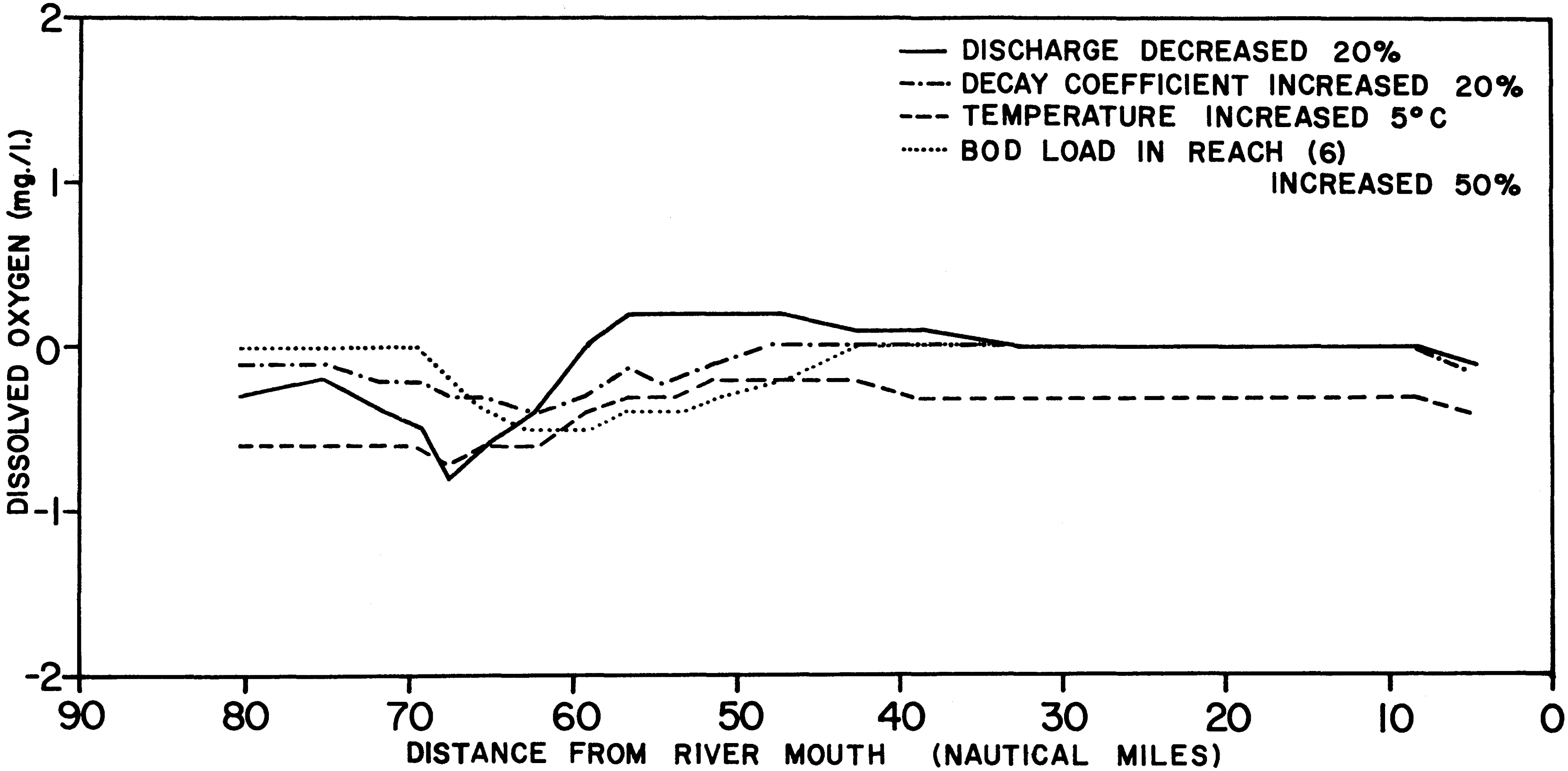


FIGURE 27. DEVIATION OF HIGH WATER SLACK DO DISTRIBUTION UNDER VARIOUS CHANGES IN INPUT.

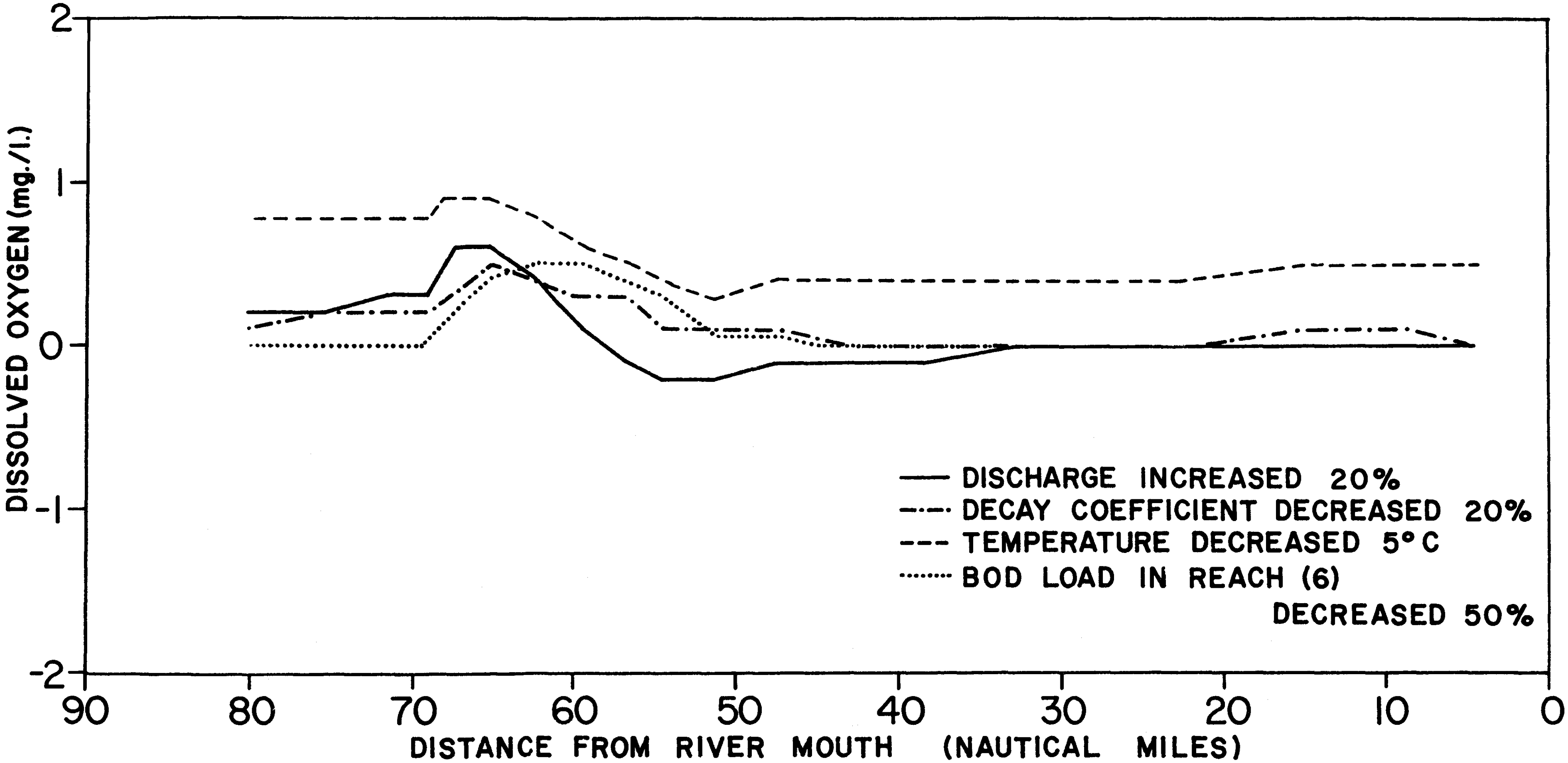


FIGURE 28. DEVIATION OF HIGH WATER SLACK DO DISTRIBUTION UNDER VARIOUS CHANGES IN INPUT.

same degree, i.e. lowering temperature, etc. Note that reduced fresh water flow produces worsened conditions for a certain distance (a deepened sag) followed by comparatively better conditions (faster recovery).

III. User's Manual for Explicit-Scheme Water-Quality Models

The salinity and dissolved oxygen models have been written in FORTRAN IV. They are run on the IBM 360-50 at the Cooperative Computer Center located at the College of William and Mary, but the language is simple enough to make the program operable on other computers. This manual concerns the arrangement of data placed behind the source program.

1. Sectioning of the River System

For computational purposes, the estuary has been divided into a number of reaches. Computations are performed using sectional average values of the system parameters and dependent variables. Some parameters having to do with exchange between sections are defined between reaches. These terms are generally identified by the number of the farther downstream of the two sections.

2. Namelist inputs

For reading data into the program, the "namelist" system is used. A full explanation of this system is to be found in the manual <u>IBM System 360 - Fortran IV Language</u> (File No. 5360-25; Form No. C28-6515-4). Input by namelist saves the program user the trouble of casting his data into a rigid format. To set the variable X equal to 3, for example, the programmer would merely punch "X - 3." If the variable Y has dimension 3, he would set the three members of the array equal to 4, 5, & 6 respectively by punching "Y = 4., 5., 6.," remembering to put a comma after each number.

The beginning of a namelist, say CONTRL, would be announced by a card punched with "&CONTRL" beginning in column 2. The namelist must end with the characters "&END." There must be no punch in column 1 on any card. It is not necessary to specify all the variables belonging to a particular namelist.

Besides fixed and floating point variables, it is possible to read in logical and hollerith variables.

3. Data arrangement

The input data deck begins with three cards for the title page of the output, enabling the user to identify this particular run. They constitute no particular problem. Next come a series of four namelists: CONTRL, MODEL, INITL, & TIMDEP.

A. Namelist CONTRL

This set of data is concerned with inputs to set up and operate the model. These are:

NSECT: number of reaches (NSECTS is not an acceptable alternative);

ERLALL: maximum allowable integration error in BOD or salinity. Dimensioned 3 but only first number of array necessary;

ERCALL: maximum allowable integration error in DO (DO model only). Dimensioned 3 but only first number of array necessary;

NSTEPS: determines initial integration step size;

LNAME: alternative name for single-variable conservative substance (salinity model only). Input twelve hollerith characters.

CFQ: conversion factor for river discharge;

CFK: conversion factor for dispersion coefficient;

CFAREA: conversion factor for cross-section areas;

CFVOL: conversion factor for reach volumes;

CFH: conversion factor for average depth of reach (redundant in salinity model);

CFJ: conversion factor for BOD loading in DO model and salinity loading in salinity model;

CFP: conversion factor for immediate oxygen source or demand (DO model only);

CFU: conversion factor for tidal current amplitude (DO model only);

FIXED: logical input for specifying fixed or variable step size integration. "FIXED=T" for fixed step size "FIXED=F" for variable step size.

BOUND: Specified type of boundary condition. For temperature-dependent boundary condition, "BOUND=1". For specified time-dependent boundary condition "BOUND=2" (DO model only);

DEXPOL: redundant input in DO model;

CFLGTH: conversion factor for reach length.

B. Namelist MODEL

This data set inputs the physical data which do not depend explicitely on time. These are:

THETA: Temperature correction factor for reaeration coefficient (DO model only);

D: Molecular diffusion coefficient for reaeration coefficient (DO model only). Units square feet per second);

A: Decay coefficient at 20C (DO model only). Units reciprocal days;

B: Redundant input to DO model;

PK: Redundant input to DO model;

NU: Temperature correction factor for decay coefficient;

CQO, CQ1, CQ2, CQ3: Redundant inputs to DO model;

XLO: Constant term in temperature-dependent expression for upstream BOD boundary condition (DO model only). Must end in zero. Units parts per million;

YLO: Constant term in temperature-dependent expression for downstream BOD boundary condition (DO model only). Must end in zero. Units parts per million;

XCO: Constant term in temperature-dependent expression for upstream DO boundary condition (DO model only). Must end in zero. Units parts per million;

YCO: Constant term in temperature-dependent expression for downstream DO boundary condition (DO model only). Must end in zero. Units parts per million;

XL: Power-series coefficients for temperature-dependent upstream BOD boundary condition. Up to fifth power possible (DO model only);

YL: Power-series coefficients for temperature-dependent downstream BOD boundary coefficient. Up to fifth power possible (DO model only);

XC: Power-series coefficients for temperature-dependent upstream DO boundary condition. Up to fifth power possible (DO model only);

YC: Power-series coefficients for temperature-dependent downstream DO boundary condition. Up to fifth power possible (DO model only);

CSO: Constant term in polynomial expression for saturation concentration of DO is a function of salinity and temperature (DO model only). Must end in zero. Units parts per million;

CS: Coefficients of polynomial expression for saturation concentration of DO as a function of salinity and temperature (DO model only). The expression used is:

```
C(saturation) = CSO+CS(1)*S
+CS(2)*T + CS(3)*S*S + CS(4)*S*T + CS(5)*T*T
```

LENGTH: Array of lengths of reaches, arranged in sequential order. Number of entries must equal NSECT. Units feet;

LLOWER: Length of imaginary reach downstream of last reach. Units feet;

LUPPER: Length of imaginary reach upstream of first reach. Units feet;

X,Y,Z: Redundant entries in DO model;

AREA: Array of cross-sectional areas between reaches, starting upstream of the first reach. Since area downstream of last reach must be included, the number of entries must exceed NSECT by 1. Units square feet;

H: Array of mean depths of reaches arranged in sequential order. Number of entries must equal NSECT. Redundant in salinity model. Units feet;

K: Array of dispersion coefficients. Numbering the same as that of AREA. Units square feet per second;

SALT: Array of maximum salinity values used in DO model for computing saturation concentration of DO. Units parts per thousand;

VOL: Array of reach volumes. Numbering the same as that of H. Units cubic feet;

DRAER: Array of basin drainage areas feeding into the respective reaches. Numbering same as that of H. Units square miles;

AGAGE: Drainage area upstream of stream gauging station determining fresh-water discharge. Units square miles;

AHEAD: Drainage area draining into river between flow gauge and first reach. Units square miles;

PHAMP: Array of photosynthesis amplitudes. Numbering same as that of H. Option bypassed by putting in array of zeros. Units parts per million;

C. Namelist INITL

This data set consists of initial values for those independent variables which may change with time. These are:

U: Tidal current amplitude array for the respective reaches (DO model only). Numbering same as that of H. Units feet per second;

J: Array of BOD loadings in DO model or salinity loadings in salinity model. Units pounds per day. Numbering same as that of H;

P: Array of immediate oxygen demand (if negative) or source of oxygen (if positive). Units pounds per day. Numbering same as that of H (DO model only);

C: Array of initial values of DO in DO model only. Units parts per million. Numbering same as that of H;

L: Array of initial values of BOD in DO model or salinity in salinity model. Units for BOD parts per million. Units for salinity parts per thousand. Numbering same as that of H;

TEMP: Array of input temperatures (DO model only). Temperature in degrees centigrade. Numbering same as that of H;

MILTIM: Time of day, given in military time. Fixed-point input;

DATE: Array with three members, for month, day and year in that order. Fixed-point numbers;

MONTH: Month, equivalent to DATE(1);

DAY: Day, equivalent to DATE(2);

YEAR: Year, equivalent to DATE(3);

CUPP: Upstream boundary condition on DO (DO model only) in parts per million. Must be specified if "BOUND=2" option is specified.

CLOW: Downstream boundary condition on DO (DO model only) in parts per million. Must be specified if "BOUND=2" option is specified;

LUPP: Upstream boundary condition on BOD, in parts per million, or salinity in parts per thousand. In DO model, LUPP must be specified if "BOUND=2" option has been chosen;

LLOW: Downstream boundary condition on BOD, in parts per million, or salinity in parts per thousand. In DO model, LLOW must be specified if "BOUND=2" option has been chosen;

QGAGE: Fresh water discharge at the gauging station, in cubic feet per second;

QPASS: Fresh water discharge at the gauging station minus hypothetical impoundments, if any. Units cubic feet per second. If natural flow condition used, QGAGE & QPASS will be identical.

JUPP: BOD loading immediately upstream of first reach, if any, expressed in pounds per day. If omitted, a default value of zero is used.

D. Namelist TIMDEP

This data set specifies the values of the independent variables at the end of some period of time. If any entry is omitted from the list, its value is kept the same as it was in INITL. The namelist may be repeated indefinitely, but each repetition must have a new and later time (MILTIM, DATE) than the preceding one. The entries are the same as those of INITL except as follows:

C&L: may not be specified;

PRINT: A logical array for specifying added printout. For both models, "PRINT(1)=T" causes the printing out of the hydraulic and geometric conditions, while "PRINT(3)=T" causes printing out of the integration history. For the DO model, "PRINT(4)=T" causes printing of the decay and reaeration coefficients. For the salinity model, "PRINT(4)=T" causes printing of current values of the dispersion coefficient. (The dispersion coefficient may be modified by an increase in salinity).

RECYCL: When this logical entry is encountered, the program transfers control to the main program to begin a new program. The TIMDEP namelist containing RECYCL must be followed by the three title cards signalling announcing the next job.

VIII. COMPARISON OF JAMES RIVER MATHEMATICAL MODELS

Water quality models vary widely in sophistication. The more factors that are included in a model, the more realistic are its predictions. However, the cost and effort of operating the model go up with the number of variables included. The planner must choose, among the gamut of models available, the simplest model that gives him accurate answers to his questions. He has to find an "optimum" point in the trade-off between realism and cost of operation. Below is an itemization of the various factors that could be included in a water quality model, with comments as to usefulness of each particular feature. Following that is a section describing various particular feature. Following that is a section describing various particular models.

Model features

i. Time dependence. There are three options available in estuarine modeling:

a. steady-state. In this kind of model one calculates a static situation on the basis of steady inputs and parameters. The first models developed were steady-state. Unfortunately,an estuary never actually achieves a steady state.

b. time-dependent non-tidal. In this approach the answers are treated as time dependent functions of variable input parameters. However, tidal motion is not included in the model. Instead an artificial dispersion coefficient is used to simulate the tidally-induced mixing. Such a model operates with a time scale on the order of days or longer, and gives no information on the back-and-forth transport of constituents within a tidal cycle.

c. Real time. A real-time model includes oscillatory tidal motion. Thus the intra-tidal transport is modeled and the tidally-induced mixing is simulated directly, rather than through the agency of an artificial dispersion coefficient.

ii. Longitudinal variability

a. Cross-sectional area. Since the cross-sectional area of an estuary may vary by a factor of fifty from fall line to mouth, this is an important feature to be included in estuarine models if they are to represent real conditions.

b. Length of volume elements. There are two advantages to having the ability to specify and deal with variable reach lengths in a model. First, verification data transects will rarely be equi-spaced (when hydraulic measurements are being taken, it is especially important to avoid placing transects near river bends because of variability induced in the measurements by transverse circulation). Second, one then has the option to make reaches shorter near points where the concentration gradient is likely to be high, thus making it possible to model a sharp curve closely while avoiding the increased running time resulting from a great number of reaches.

c. Volume elements. The volume element size must be consistent with the cross-sectional and reach lengths used.

iii. Multiple loadings. A typical estuary will have multiple sources of BOD. These loads will overlap as they spread out in the estuary and the resulting DO sags will also overlap. An estuarine model should, therefore, accomodate multiple sources of BOD.

iv. Multiple components. Dissolved oxygen was the first water quality index and remains the most important. However, as other water quality parameters are accepted and indices and laboratory analysis become more straightforward, there will be a move to model these.

The present state-of-the-art treats DO and carbonaceous BOD as a linked pair of components. The next logical step is the inclusion of nitrogenous BOD. This advance, however, presents some difficulties. First, the laboratory procedures for determining nitrogenous BOD are more difficult than those for carbonaceous. Second, the mathematical treatment of nitrogenous BOD should be different from that for carbonaceous. Hydroscience (1969) points out that low DO values near a source tend to suppress the nitrification process, so that the center of nitrogenous demand is shifted downstream. The distance shifted depends indirectly on the carbonaceous loading. Modeling and verifying this phenomenon are not straightforward.

Bottom demand and photosynthesis-respiration are occasionally important in estuaries and are useful features to have built into an estuarine model for inclusion at a later date when verification data becomes available.

v. Multiple dimensions. Real processes occur in three spatial dimensions plus time, real pollutants vary laterally and vertically as well as along the estuarine axis. Because of this complexity and the difficulty of describing it in detail, the modeler must do some averaging to begin to simulate any aspect of natural events. First, he is averaging out a whole spectrum of time and space scales by use of time steps and finite-difference spatial expressions. To bring the problem to manageable size, he must also average over one or more spatial dimensions.

The real issue in going to more than one dimension is whether the improvement in realism of the model justifies the increased modeling effort and run time. Because of the greatly increased effort required to include extra dimensions, more than one dimension is to be avoided unless the one-dimensional model is proven to be deficient for the particular case which one must examine and make recommendations or decisions on.

Pritchard's (1969) two-layer approach is of interest for those instances where the parameter being studied is notably stratified, because it is in these cases only that vertical averaging gives bad results. In other cases, it is safe to average vertically even though Pritchard's picture of the circulation may be correct.

The same comment applies to broad reaches. If the cross-stream average is no longer representative of any particular point in the reach, then one must do some cross-stream subdividing to maintain similitude. The Dynamic Estuary Model (DEM) by Feigner & Harris (1970) and the Harleman Model (Dailey & Harleman, 1972) can be considered 1+ dimensional. They enable a largely one-dimensional approach to be applied to complex channel systems with several branches. The DEM can be used to model broad reaches by treating them as a cluster of closely-spaced lagoons or junctions connected by very short, wide channels. It is not clear, however, that the mathematical approach is valid in that limit. Furthermore, the model might introduce some artificial flow known to be absent in the real estuary. An example would be cases where two junctions have a large intersecting area but are known to have little interacting flow.

vi. Dynamic modeling. It seems desirable ultimately to have a completely verified working model of the circulation of every estuary which is under development or management, to use as an input to a water quality model. This entails, however, the expense of verifying and operating the dynamic model. One approach (Feigner & Harris, 1970; Dailey & Harleman, 1972) is to run the circulation model to a quasi-steady state and then store the result on tape to use as input to the water quality model. However, Leendertse (Tracor, 1971, p. 298) states that implicit computation methods make it just as fast to calculate the tidal currents as to read them from a magnetic tape.

vii. Stochastic modeling. There are two sources of uncertainty in a model prediction. First, the data used for verification have some uncertainty. Second, the input parameters have some uncertainty. If by "stochastic model", one means a model which would translate these uncertainties into confidence limits around the prediction, such a model has never been made. The state-of-the-art in water quality modeling has not advanced to this point.

Nor has data-gathering capability advanced sufficiently. Constructing and verifying such a model would entail specifying the variance of each input parameter, as well as the variance of the water quality data being simulated.

More commonly, stochastic refers to models utilizing statistical relationships rather than mechanistic ones. This type of model is constructed by analyzing large amounts of data to produce a set of statistical formulae relating known parameters, such as waste loading and river flow, to such unknowns as dissolved oxygen concentration. Given a set of conditions (called the input), the model predicts the most probable result (called the output). The set of coefficients relating input to output is called the transfer function. Loucks (1969) showed how such a model could be used to relate river flow to reservoir storage.

Again, large volumes of data are needed to construct and verify such models. It is still in the realm of basic research, far from active service in planning.

Particular Models

Models which have been developed, adapted or proposed for use in studies and management development in the James River are described below.

i. EPA Models. The Annapolis Field Office of the EPA has developed a pair of water-quality models for use in fluvial streams and estuaries. These models have been partially calibrated to the James River. They are commonly referred to as Crim models after the chief author (Crim & Lovelace, 1973). The first of these is a one-dimensional steady-state mathematical model (referred to as AUTO-SS) for predicting 3 components: DO, carbonaceous BOD & nitrogenous BOD. However, the nitrogenous BOD term is treated in the same manner as carbonaceous, *viz* strictly a first order decay process. The model allows for variations in channel geometry, dispersion coefficient and lateral inflow; it also may be programmed for water withdrawals and outfalls as well as waste discharges at any point along the stream. Besides carbonaceous and nitrogenous oxygen demand and atmospheric reaeration, the model may include net photosynthesis and respiration and benthic demand.

The other Crim model is time-dependent (referred to as AUTO-QD) but otherwise based on the same assumptions. This model includes mean flow but not tidal current. None of the program inputs can be varied within a run. However, runs can be batched so that the final configuration for one run becomes the starting situation for the next run. All the reaches in the Crim models must be the same length.

ii. VIMS Models. The Virginia Institute of Marine Science has developed two water-quality models for the study of estuaries. These are real-time models (also referred as non-steady state models, tidal-time models, or intra-tidal models) for the study of DO & BOD, although different components may be modeled with reprogramming. Both models include tidal motion, achieved by including a sinusoidal observed tidal current in the advective term. Both models allow for variation with distance of cross-sectional area and elemental volumes and lengths. Both include inflow of water and BOD.

The explicit-scheme model was developed from the DECS-III model, but includes the tidal-motion feature mentioned above. In addition to BOD loadings, it allows for immediate or benthal oxygen demands.

The implicit-scheme model integrates the mass-balance equation according to an implicit integration scheme, thus achieving larger time steps than are possible with an explicit scheme.

The VIMS models have been verified for DO for the James from Richmond to Newport News.

iii. Hydroscience, Inc. Models. Some early DO modeling of portions of the James River were performed by Hydroscience, Inc. The first (O'Connor, 1963) employed an analytic approach, i.e. used explicit mathematical functions to express the solution. The model was steady-state, non-dispersive and concerned with only two sources of BOD, namely Richmond and the DuPont Spruance plant. Longitudinal variations of channel geometry or fresh water flow were not included.

A later study (O'Connor, 1965) was done for the Hopewell portion. This model followed the same approach as the first, but included a dispersion term to simulate the effects of tidal advection and mixing.

iv. VPI Stochastic Models. A stochastic model has been reported on by Krutchkoff (1967) and its use in the James has been proposed. The starting assumptions and analytical approach of this model are those of the steady-state analytical models, i.e. steady-state, without longitudinal variation of cross-sectional area or fresh-water discharge, but including a dispersion coefficient. The model gives as output the deterministic model result, which is interpreted as a most probable DO distribution. The model also predicts a variance about that distribution. Unfortunately, variance of the output is nowhere explicitely or implicitely related to variance of inputs. It rests instead on a parameter Δ which cannot be determined *a priori* but must instead be arrived at somehow from the scatter of the data. This difficulty has been pointed out and discussed by Di Toro, Thomann & O'Connor (1968). In the author's opinion it is inaccurate to call such a model "stochastic".

v. Dailey & Harleman Estuarine Model. A time-dependent water-quality model has been developed by Dailey & Harleman of MIT (1972). This model is a branch-and-channel dynamic model with separate hydraulic and water quality parts.

This MIT model uses an implicit integration scheme. It also distinguishes between the center part of a channel cross-section which passes momentum and stores water and the stagnant shoals which merely store water. By this reasoning the top width is divided into a "core" part and a "storage" part. Another refinement is inclusion of a density-effect term in the momentum equation. The MIT model allows a comprehensive tidal forcing function, consisting of a succession from mean tide to spring or neap time and back again.

The water quality portion of the model handles DO, BOD, salinity and temperature, these being the four most studies water quality indices. Other components can be modeled with some reprogramming. This model allows for BOD sources at each mesh point. This model handles the downstream boundary condition in a special way. The constituent flux ebbing from the farthest downstream reach is independent of the boundary condition. This feature agrees with one's notion of the way real estuaries behave when emptying into much larger bodies of water. The boundary condition is applied on the flooding tide, but the degree of re-intake of flushed contaminant must be determined empirically.

The Harleman model has not been used for the James River, but it has been used to simulate a dye study in the James River Hydraulic model. This dye study was conducted in 1968 by the EPA to study assimilation capacity from Richmond to Hopewell. Direct application to the prototype is difficult because of the lack of scaling similitude of the dispersion coefficient.

Two-Layer Models - Pritchard has refined and elaborated the early discoveries of Stommel & Farmer (1953) concerning estuarine circulation. Briefly, since the surface layer becomes increasingly salty in the direction of net flow, there must be a compensating salt flux upstream near the bottom of the estuary. As an improvement over one-dimensional non-tidal models, in which this mixing is forced through an artificial dispersion coefficient, Pritchard (1969) has proposed a two-layer circulation model. Salinity would be used as a natural tracer to determine the magnitudes of the flows in each layer and of the inter-layer exchanges. These coefficients could then be used to study the spread of any other substance. This approach has been used for a study of the flushing of Baltimore Harbor

(Wilson, 1970) but has not yet been applied to the James. However, one must model more than flushing in a study of DO & BOD, for example. The sources and bio-chemical processes cannot be ignored for these quantities.

Summary

A highly advanced model is not necessarily the best one to use for development or management. The accepted state-of-the-art in model application lags the model development state of the art in time, because model innovations must be widely understood and tested in a number of applications before they will be accepted for use. Suppose, for example, that a disputed model result leads to litigation. The testimony and counter-testimony of modeling experts will focus on how widely understood and accepted the model is, as well as how suitable it is for the purpose and how firm are its theoretical underpinnings.

Most of the previously described models can be considered under development and not yet at the stage of actual use. These include dynamic models, stochastic models and multi-layered models.

The degree of sophistication of models in use advances according to the needs of planners. At the present time there is a need for time-dependent intra-tidal models, because of the range of questions that can be answered using the time-dependent approach.

Some examples are:

a. determination of the minimum dissolved oxygen encountered within a tidal cycle.

b. determination of the effects of periodic discharges, for example, a BOD source that emits on ebb tide only.

c. determination of the effects of aperiodic discharges such as storm runoff.

d. determination of location of minimum dissolved oxygen or maximum BOD as a function of time within the tidal cycle.

While the intra-tidal model can also perform steady-state predictions, a steady-state model cannot produce intra-tidal predictions. Either kind of model can be used for estimating time-average water quality resulting from seasonally prevailing conditions, but the intra-tidal model has additional capability.

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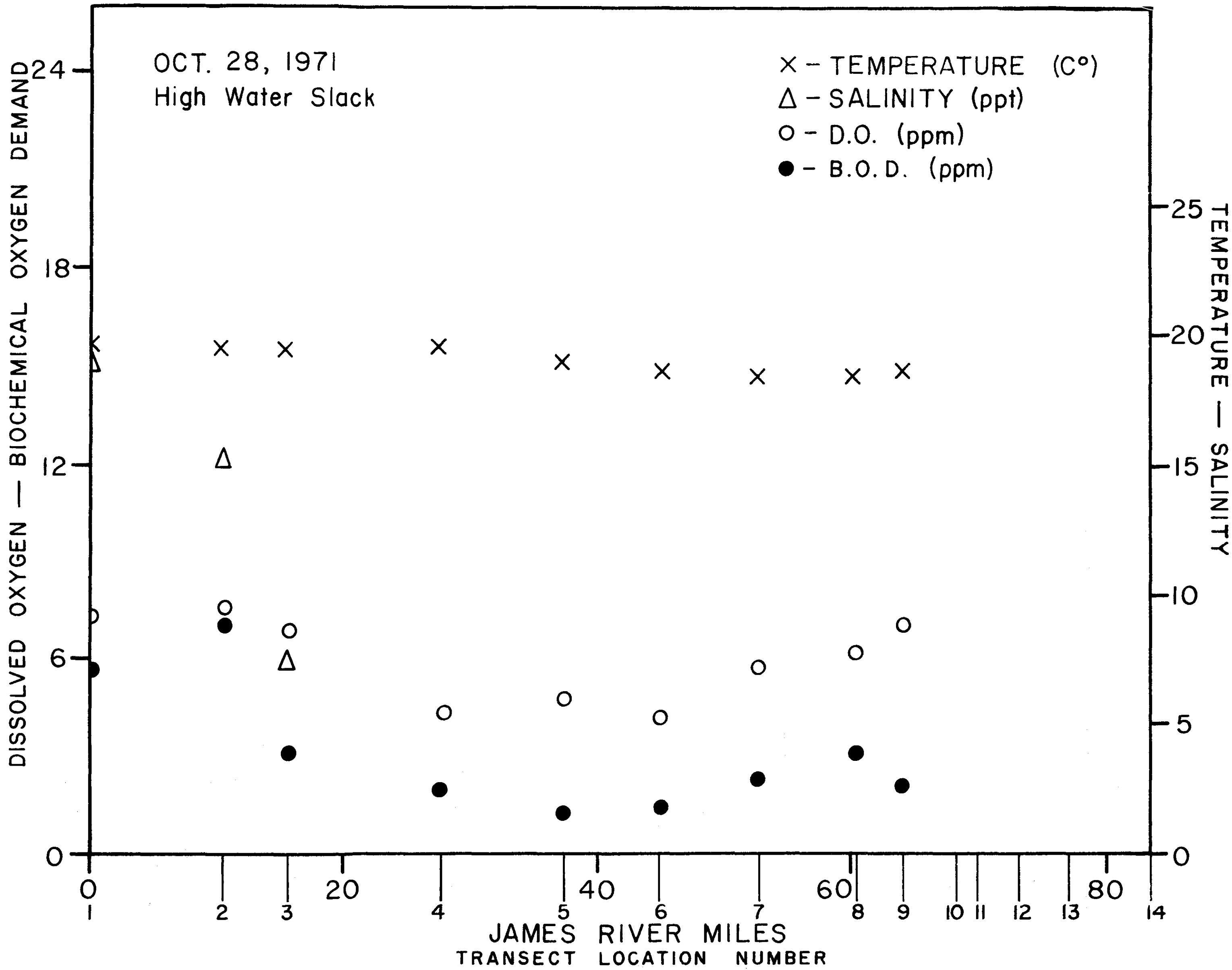
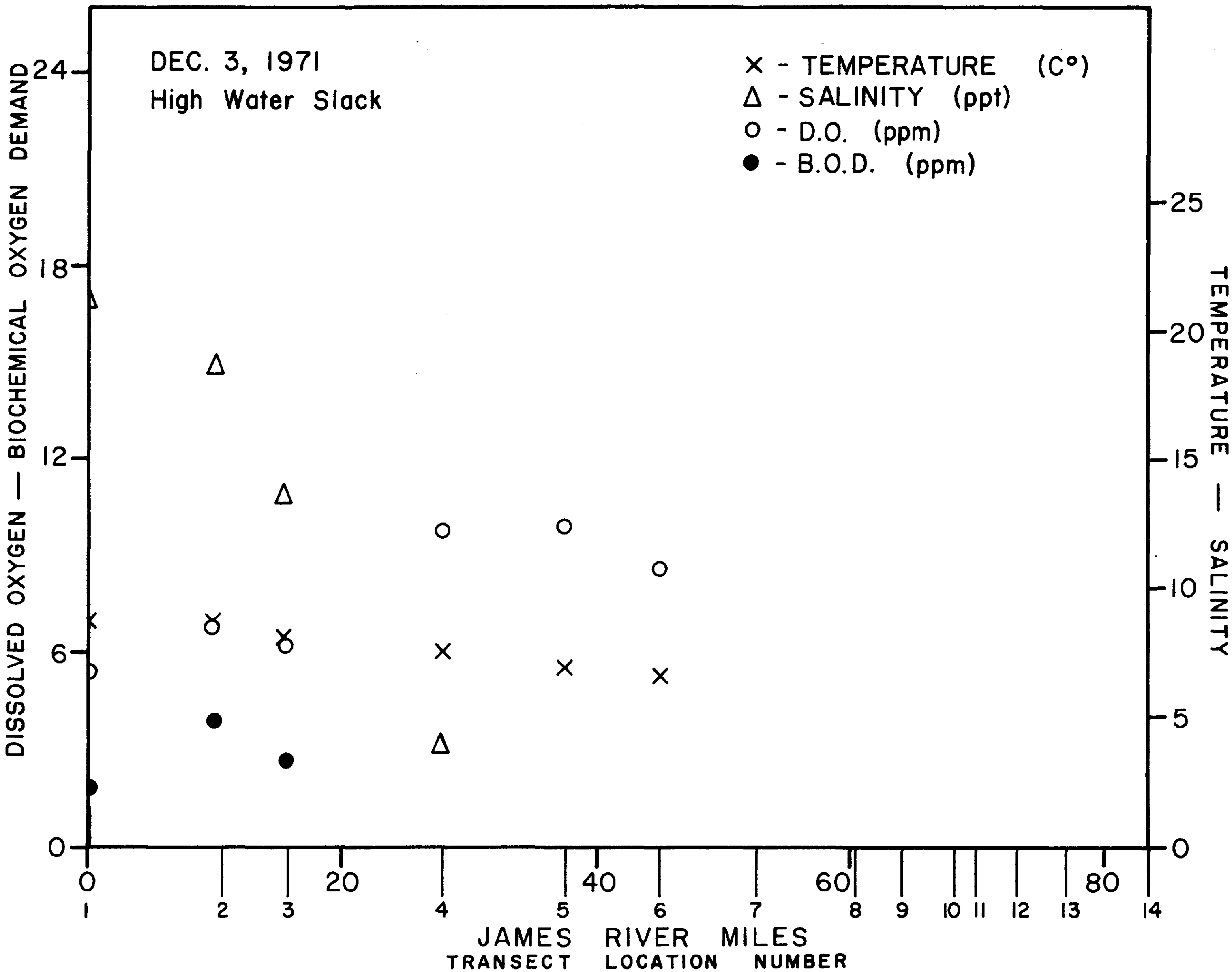
X

APPENDIX A

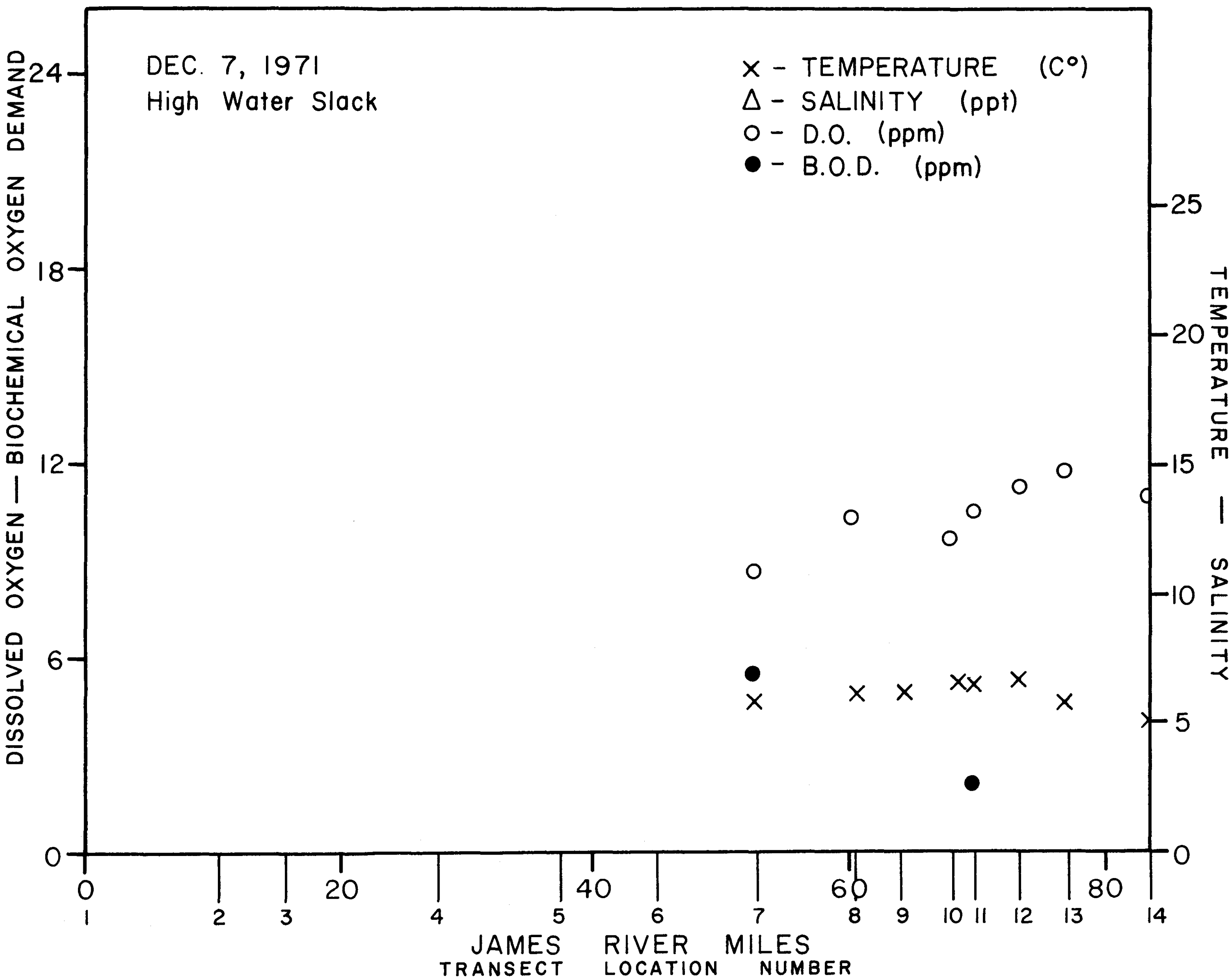
Results of Slack Water Runs

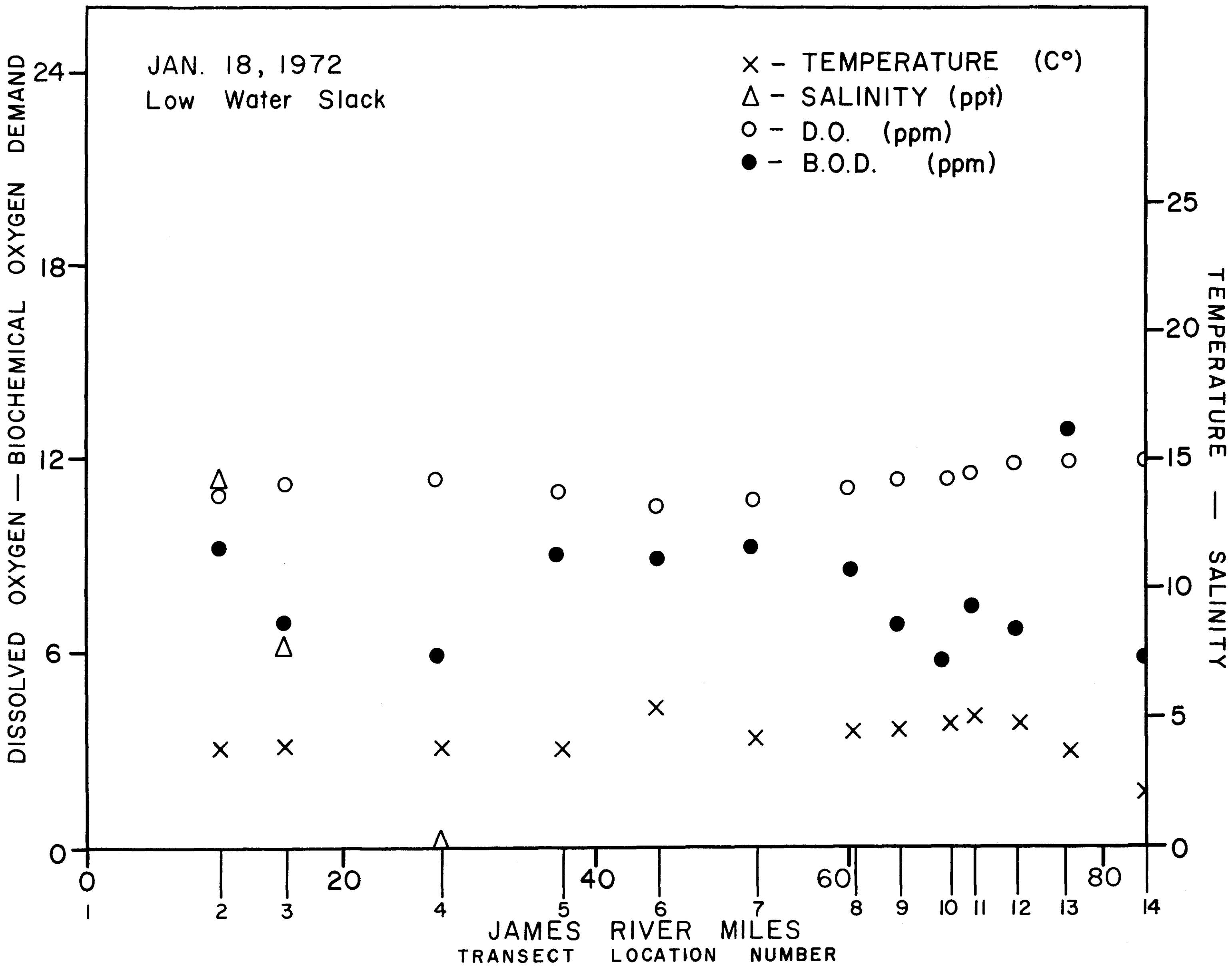
(1971 and 1972)

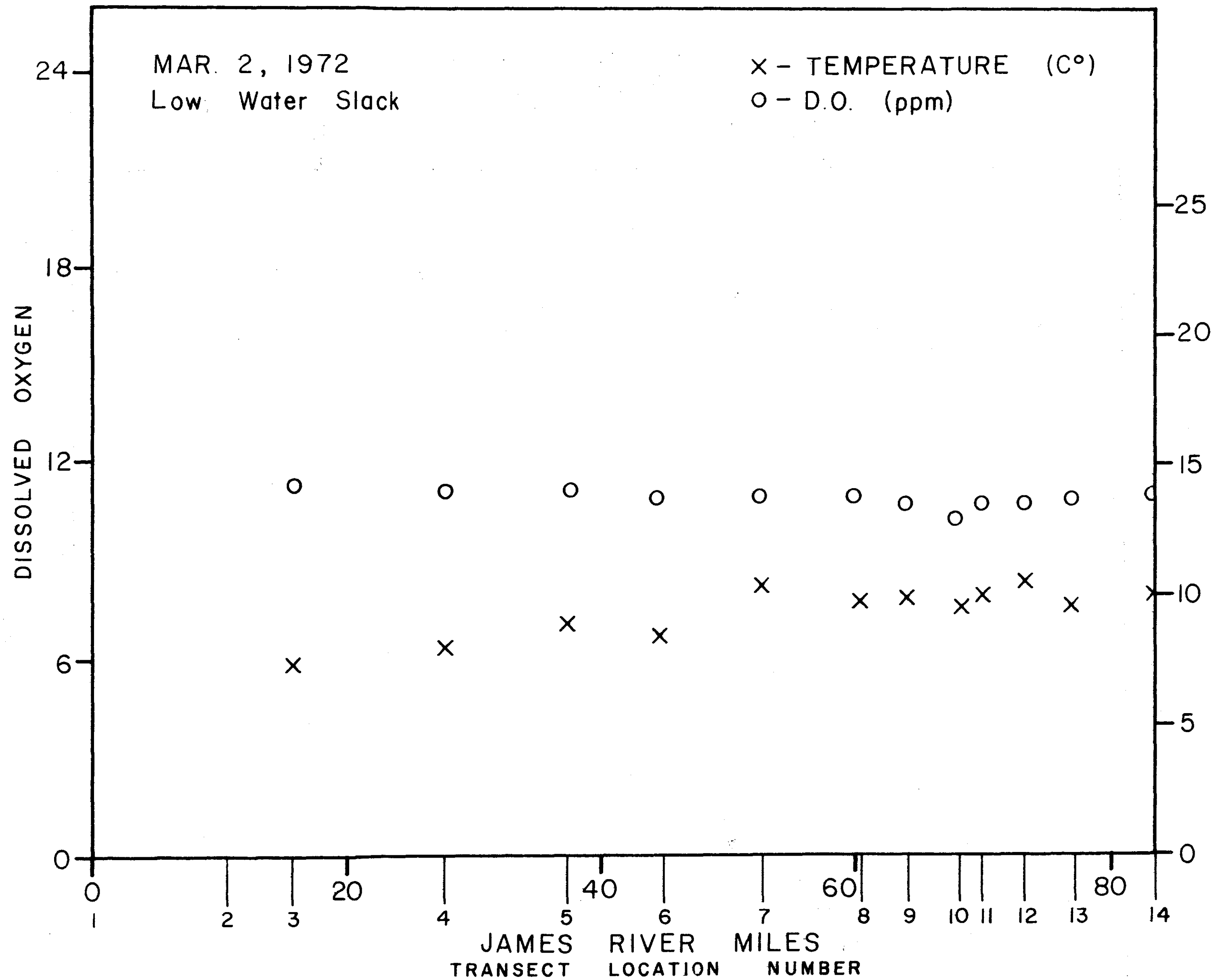

OCT. 28, 1971
High Water Slack
X – TEMPERATURE (C°)
Δ – SALINITY (ppt)
○ – D.O. (ppm)
● – B.O.D. (ppm)
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE — SALINITY
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

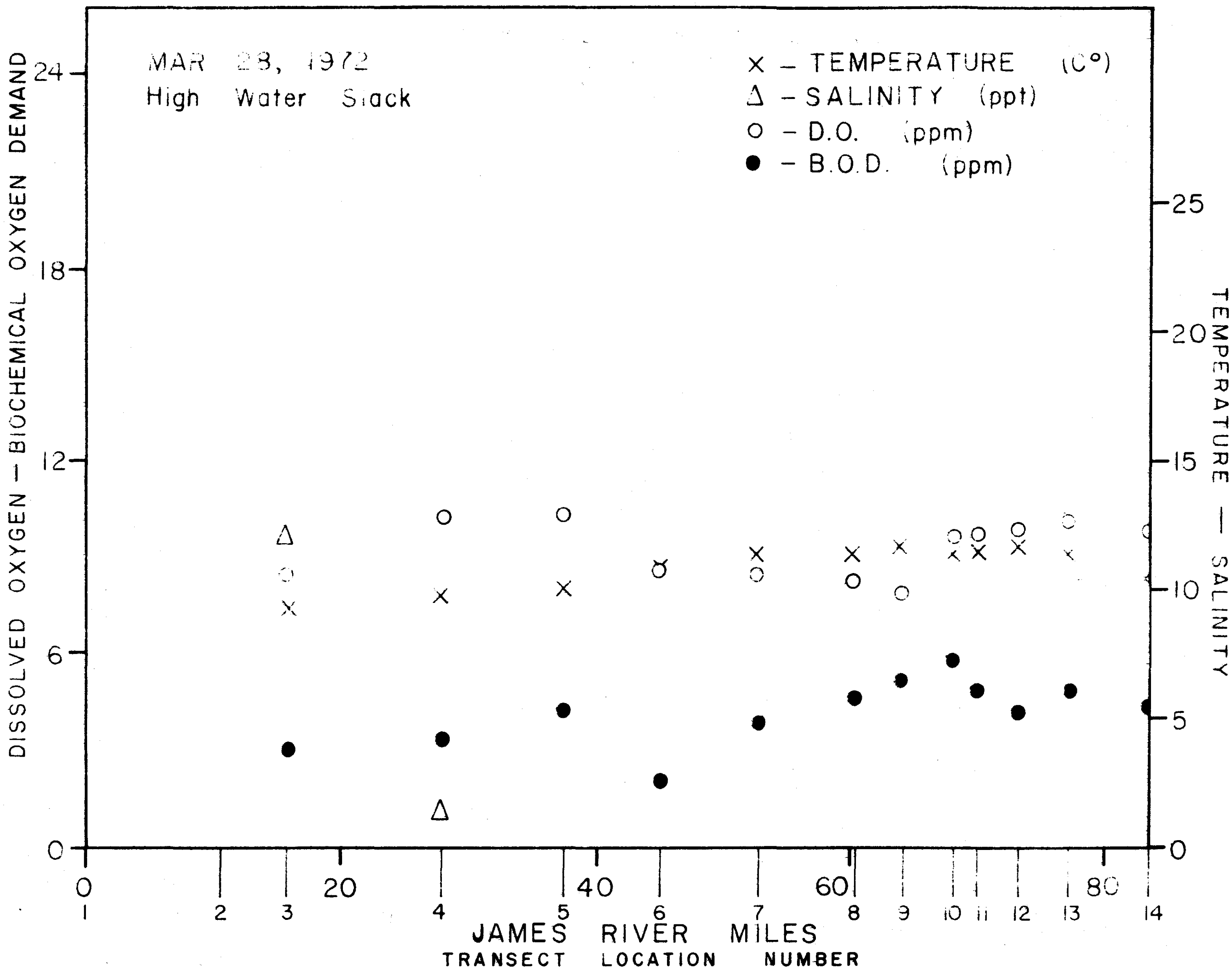


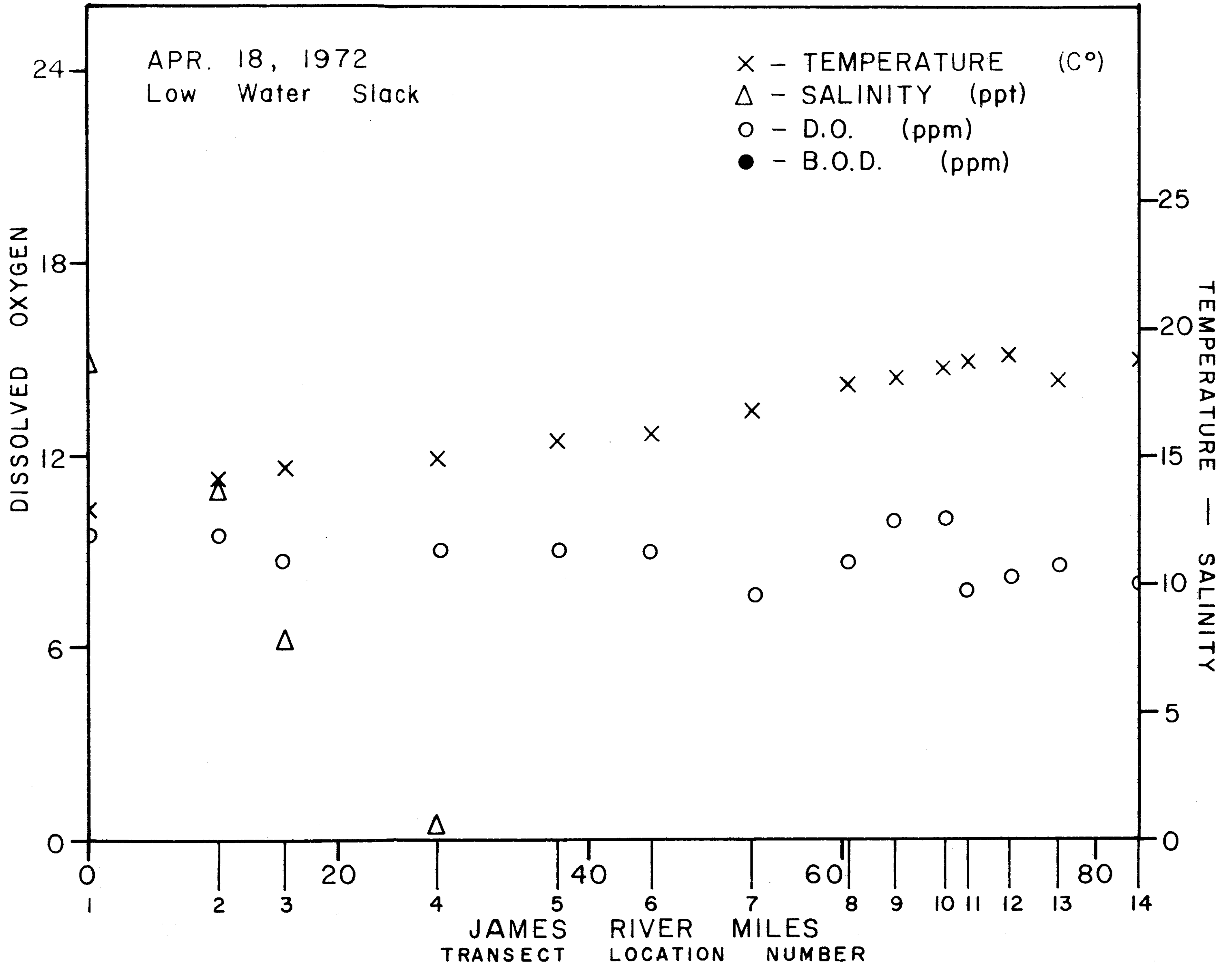
DEC. 3, 1971
High Water Slack
× - TEMPERATURE (C°)
Δ - SALINITY (ppt)
○ - D.O. (ppm)
● - B.O.D. (ppm)
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE — SALINITY
0
6
12
18
24
0
5
10
15
20
25
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

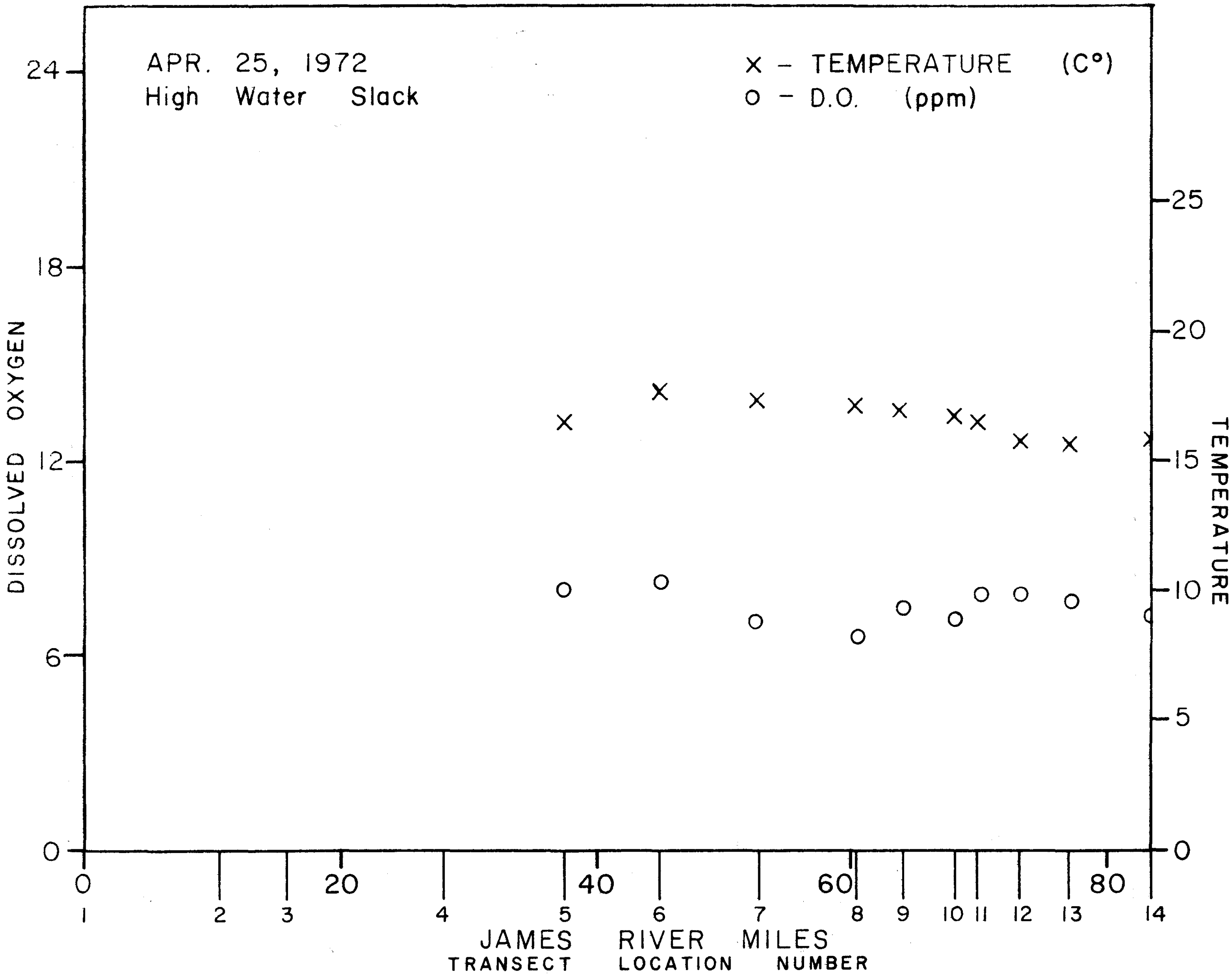

DEC. 7, 1971
High Water Slack
X - TEMPERATURE (C°)
Δ - SALINITY (ppt)
○ - D.O. (ppm)
● - B.O.D. (ppm)
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE — SALINITY
0
6
12
18
24
5
10
15
20
25
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

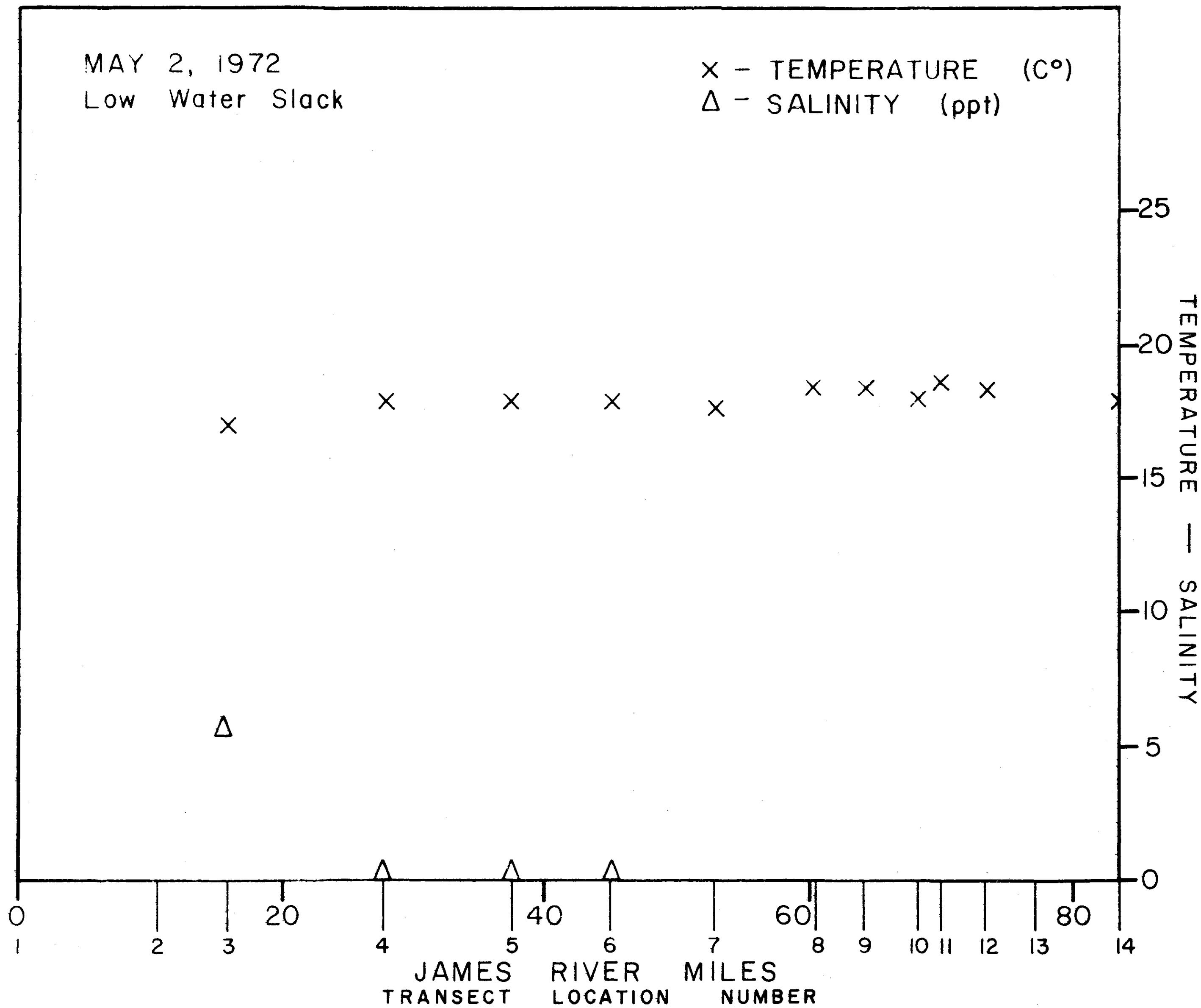

JAN. 18, 1972
Low Water Slack
× – TEMPERATURE (C°)
Δ – SALINITY (ppt)
○ – D.O. (ppm)
● – B.O.D. (ppm)
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE — SALINITY
JAMES RIVER MILES
TRANSECT LOCATION NUMBER
0
6
12
18
24
5
10
15
20
25
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14

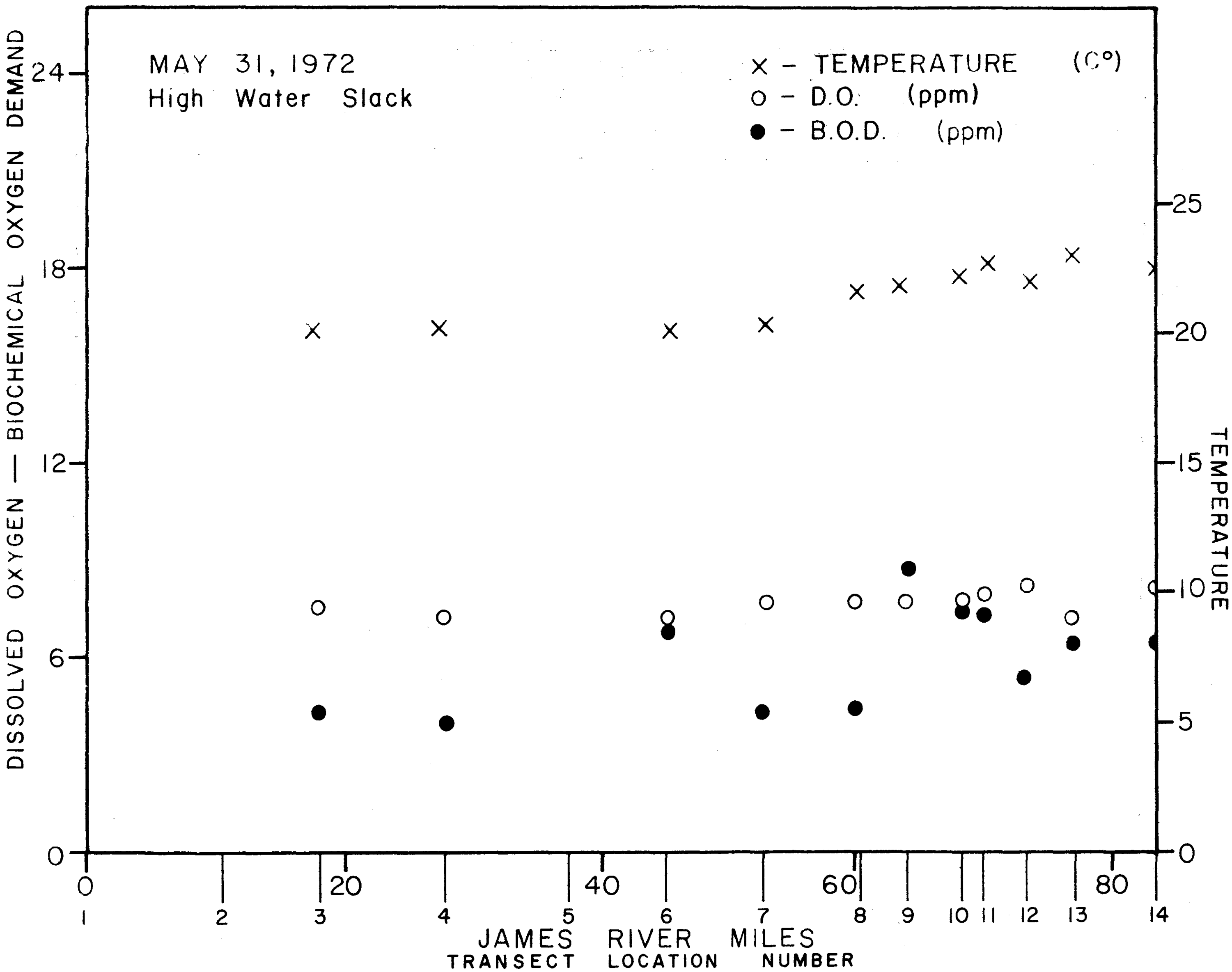

MAR. 2, 1972
Low Water Slack
X – TEMPERATURE (C°)
O – D.O. (ppm)
DISSOLVED OXYGEN
TEMPERATURE
24
18
12
6
0
25
20
15
10
5
0
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

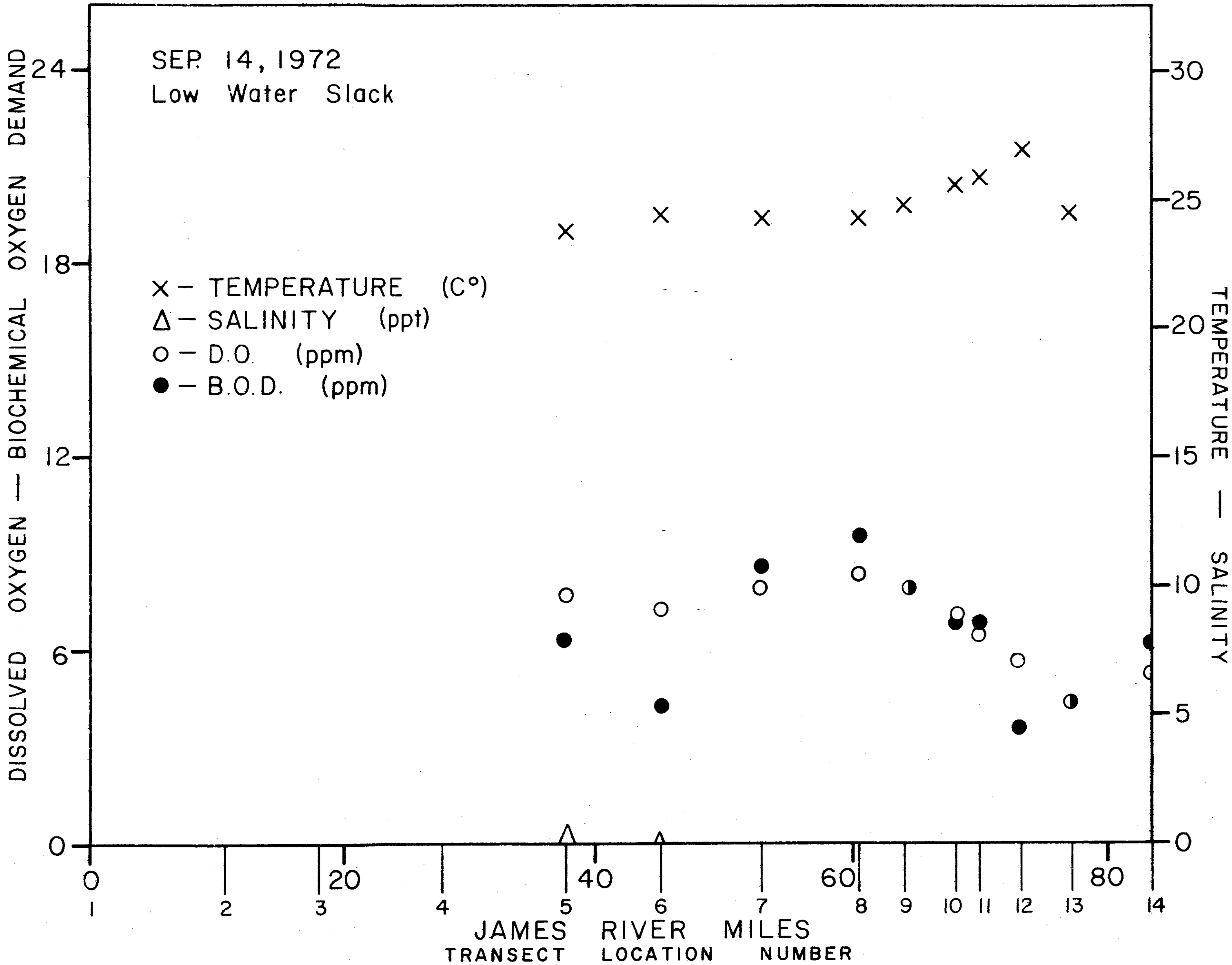

MAR 28, 1972
High Water Slack
X – TEMPERATURE (C°)
Δ – SALINITY (ppt)
o – D.O. (ppm)
● – B.O.D. (ppm)
DISSOLVED OXYGEN – BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE — SALINITY
0
6
12
18
24
0
5
10
15
20
25
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER


APR. 18, 1972
Low Water Slack
× – TEMPERATURE (C°)
Δ – SALINITY (ppt)
○ – D.O. (ppm)
● – B.O.D. (ppm)
DISSOLVED OXYGEN
TEMPERATURE — SALINITY
JAMES RIVER MILES
TRANSECT LOCATION NUMBER
0
6
12
18
24
5
10
15
20
25
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14

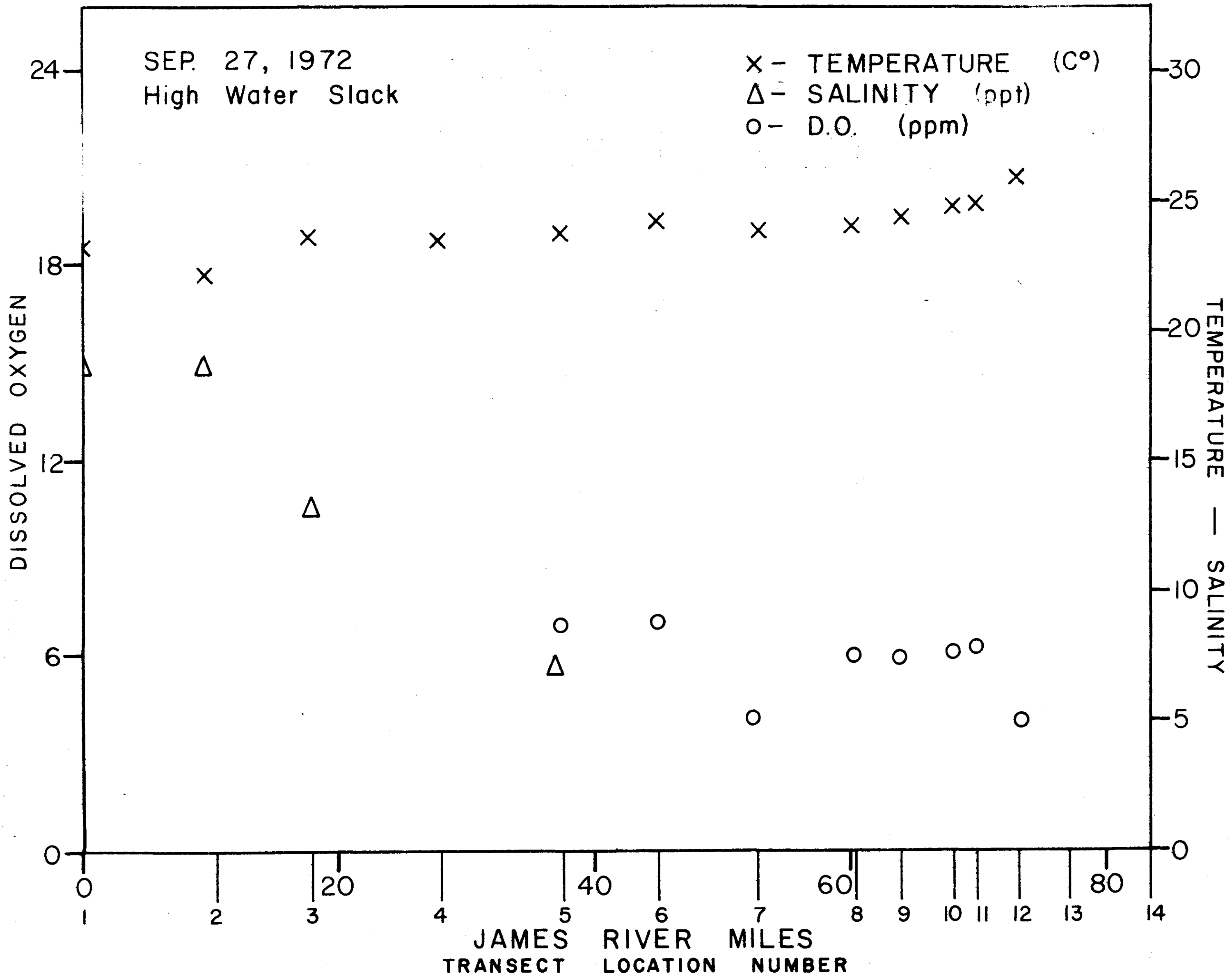

APR. 25, 1972
High Water Slack
X - TEMPERATURE (C°)
o - D.O. (ppm)
DISSOLVED OXYGEN
TEMPERATURE
24
18
12
6
0
25
20
15
10
5
0
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

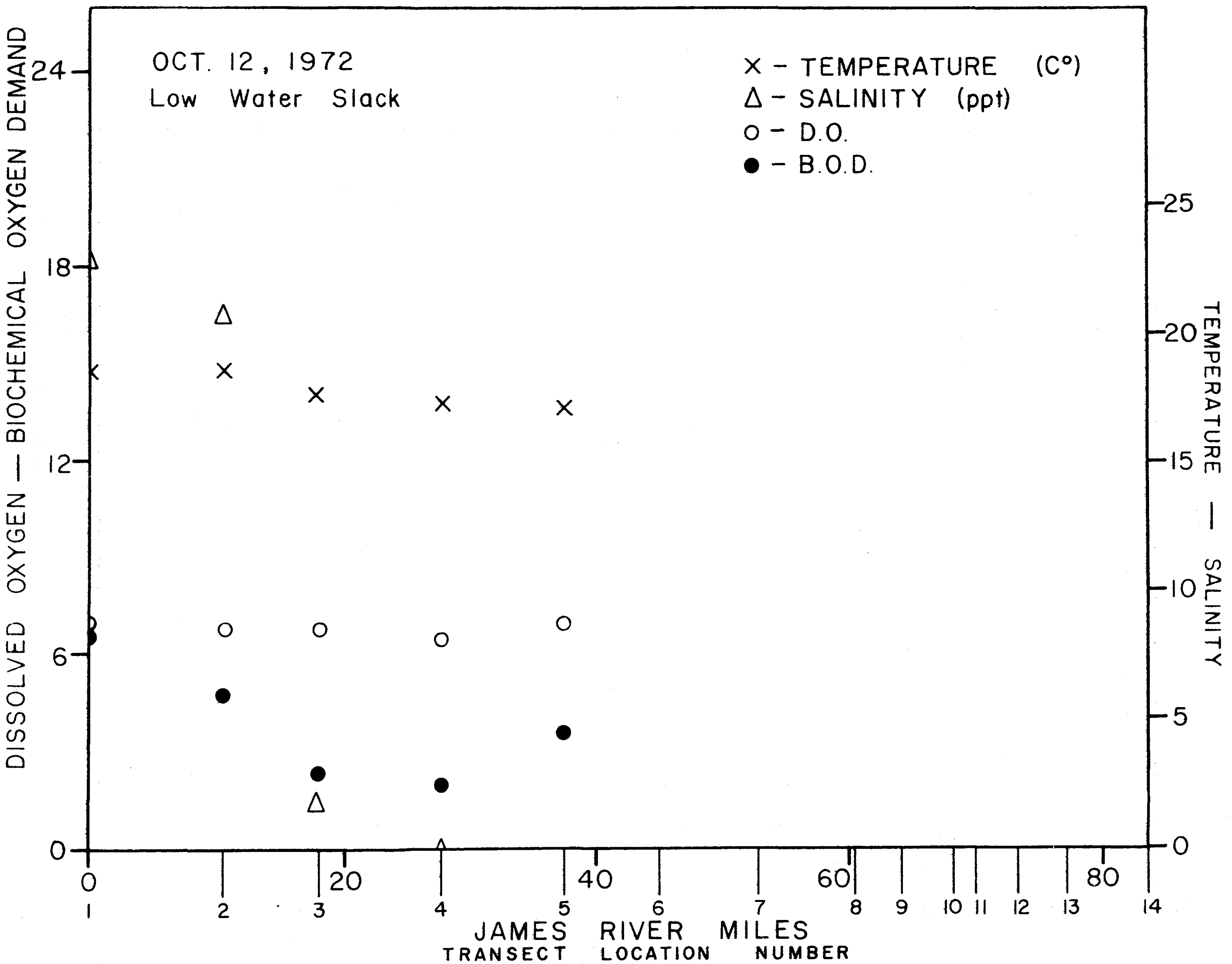

MAY 2, 1972
Low Water Slack
× – TEMPERATURE (C°)
Δ – SALINITY (ppt)
TEMPERATURE — SALINITY
0
5
10
15
20
25
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

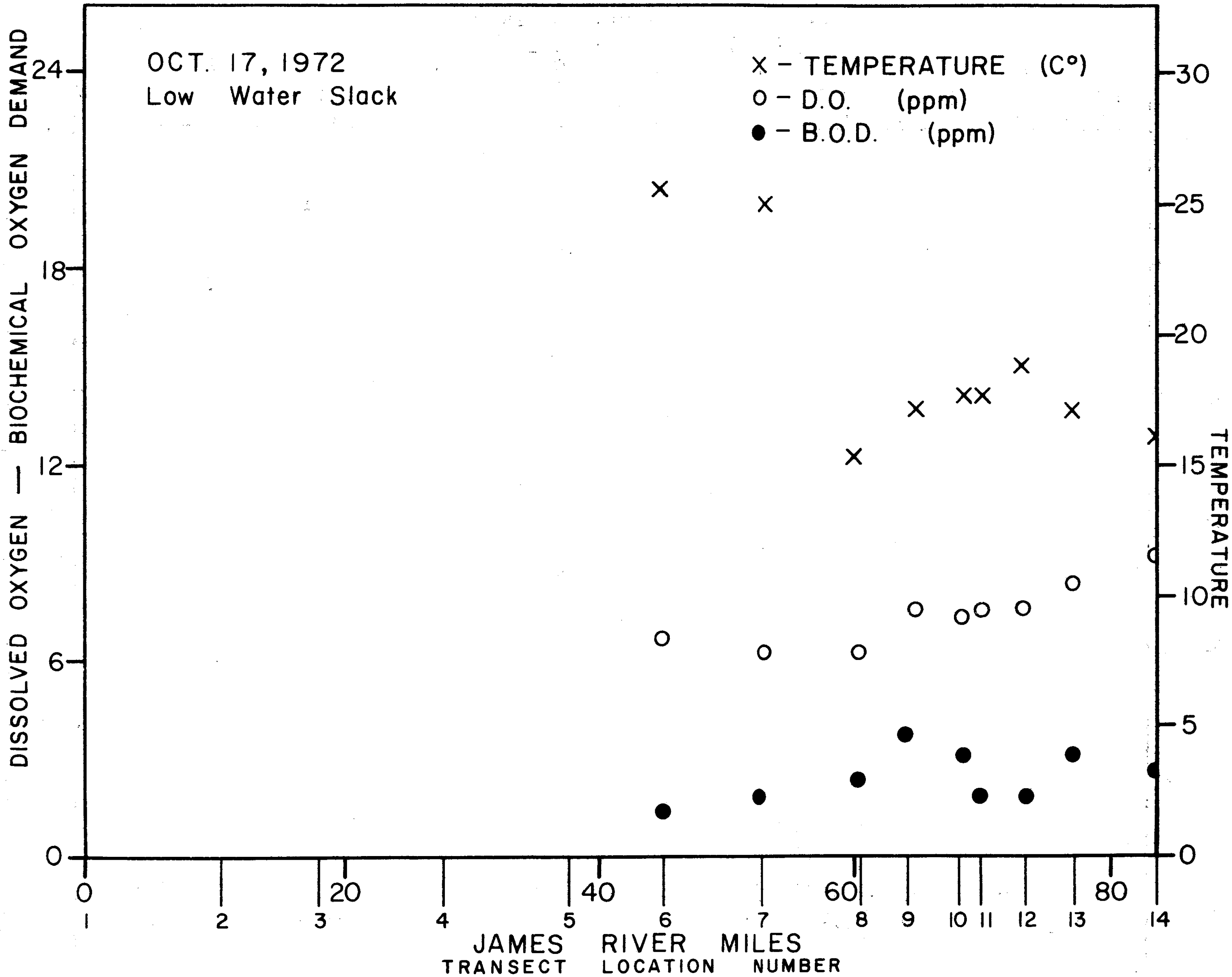

MAY 31, 1972
High Water Slack
× – TEMPERATURE (C°)
○ – D.O. (ppm)
● – B.O.D. (ppm)
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE
0
6
12
18
24
0
5
10
15
20
25
0
20
40
60
80
1 2 3 4 5 6 7 8 9 10 11 12 13 14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

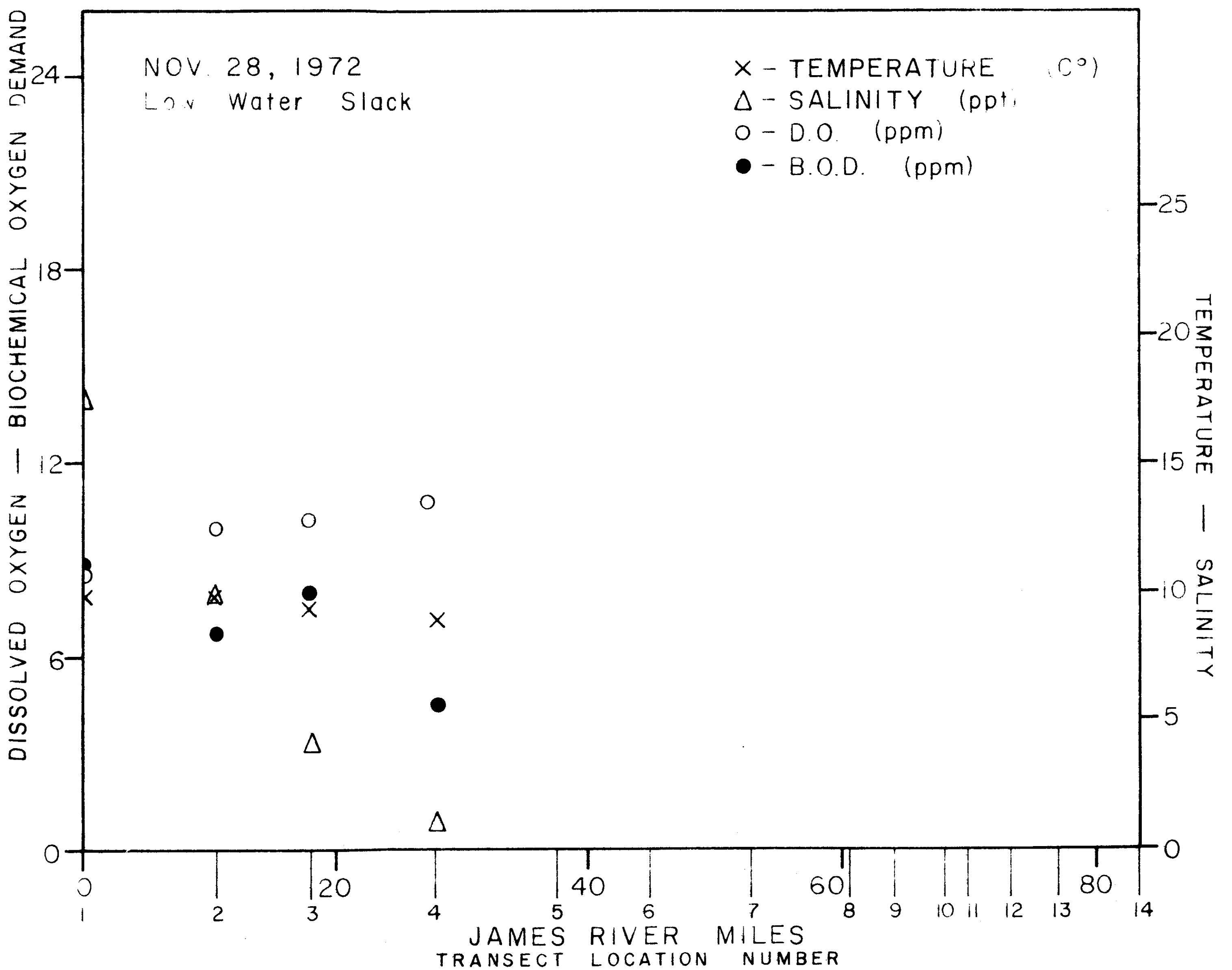


SEP. 14, 1972
Low Water Slack
X – TEMPERATURE (C°)
Δ – SALINITY (ppt)
○ – D.O. (ppm)
● – B.O.D. (ppm)
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE — SALINITY
0
6
12
18
24
0
5
10
15
20
25
30
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

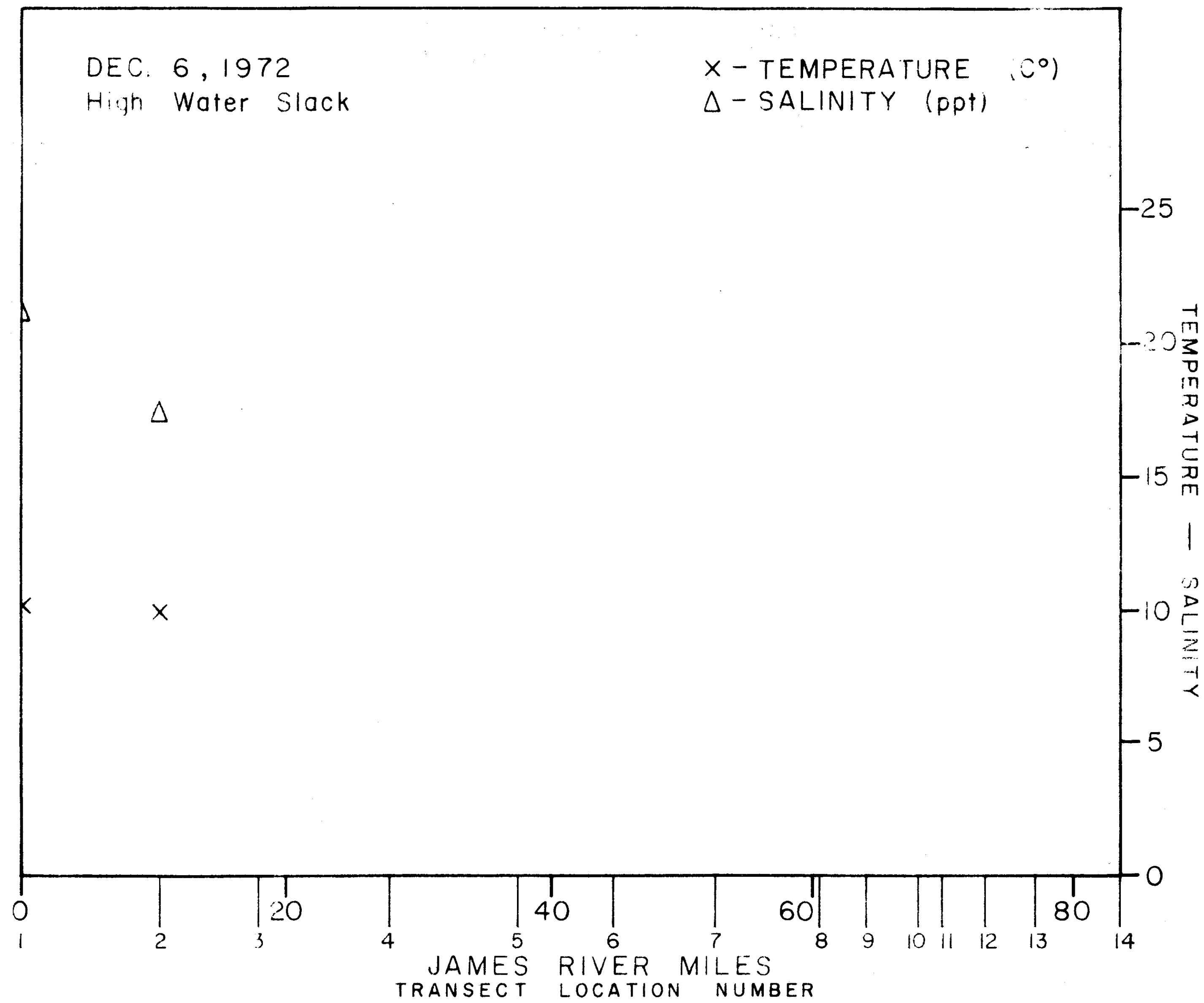

SEP. 27, 1972
High Water Slack
X – TEMPERATURE (C°)
Δ – SALINITY (ppt)
o – D.O. (ppm)
DISSOLVED OXYGEN
TEMPERATURE — SALINITY
JAMES RIVER MILES
TRANSECT LOCATION NUMBER
0
6
12
18
24
5
10
15
20
25
30
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14

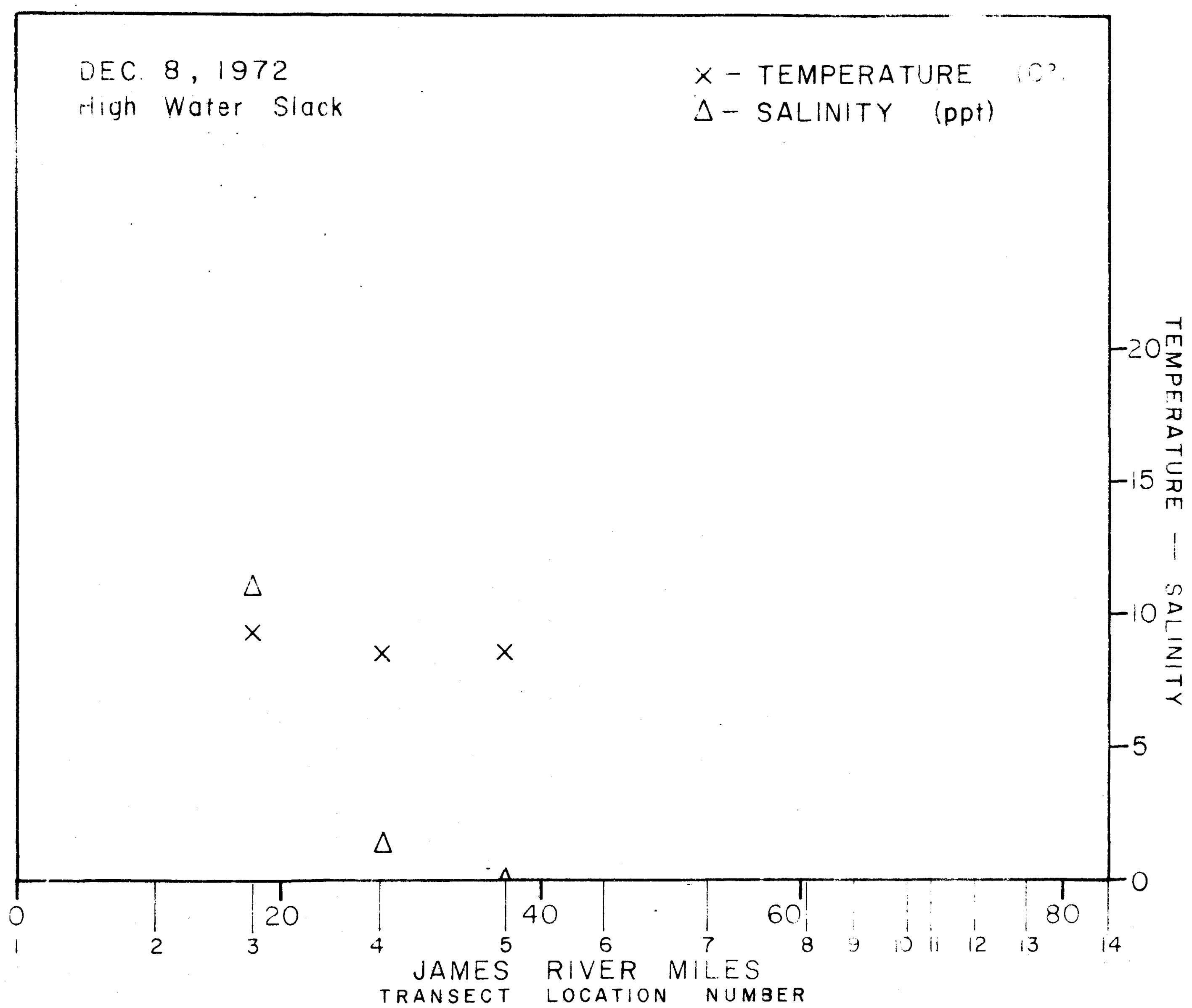

OCT. 12, 1972
Low Water Slack
X - TEMPERATURE (C°)
Δ - SALINITY (ppt)
o - D.O.
● - B.O.D.
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE — SALINITY
0
6
12
18
24
0
5
10
15
20
25
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER


OCT. 17, 1972
Low Water Slack
X – TEMPERATURE (C°)
o – D.O. (ppm)
● – B.O.D. (ppm)
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
TEMPERATURE
0
6
12
18
24
0
5
10
15
20
25
30
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER



NOV. 28, 1972
Low Water Slack
× - TEMPERATURE (C°)
Δ - SALINITY (ppt
○ - D.O. (ppm)
● - B.O.D. (ppm)
DISSOLVED OXYGEN — BIOCHEMICAL OXYGEN DEMAND
0
6
12
18
24
TEMPERATURE — SALINITY
0
5
10
15
20
25
0
20
40
60
80
1 2 3 4 5 6 7 8 9 10 11 12 13 14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER


DEC. 6, 1972
High Water Slack
X - TEMPERATURE (C°)
Δ - SALINITY (ppt)
TEMPERATURE — SALINITY
0
5
10
15
20
25
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER


DEC. 8, 1972
High Water Slack
X - TEMPERATURE (C°)
Δ - SALINITY (ppt)
TEMPERATURE — SALINITY
0
5
10
15
20
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
JAMES RIVER MILES
TRANSECT LOCATION NUMBER

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE HSW

DATE 28 October '71

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(0.0)	20	0	1050	19.8	12.01	7.81	5.06
		2		19.8	13.52		
		4		19.7	16.88		
		6		19.7	18.37		
		8		19.6	20.53		
		10		19.6	21.71	7.53	
		12		19.6	22.17		
		14		19.6	22.95		
		16		19.6	23.30		
		18		19.6	23.57		
		20		19.6	25.17	6.79	6.53
J(10.3)	12	0	1130	19.8	6.13	11.37	7.52
		2		19.7	7.92		
		4		19.7	9.50		
		6		19.6	15.34	7.16	
		8		19.6	15.08		
		10		19.6	17.02		
		12		19.6	17.06	7.38	6.79
J(17.9)	8	0	1158	19.6	1.43	7.22	2.17
		2		19.5	1.98		
		4		19.5	3.09	7.40	
		6		19.5	8.06		
		8		19.6	15.16	6.17	4.03
J(28.2)	10	0	1242	19.5	.14	6.29	2.0
		2		19.5	.14		
		4		19.4	.15		
		6		19.4	.14	5.55	
		8		19.5	.14		
		10		19.5	.14	1.30	-
J(37.4)	10	0	1325	19.0	.04	5.47	1.35
		2		18.8	.04		
		4		18.8	.03		
		6		18.8	.03	5.37	
		8		18.8	.03		
		10		19.0	.03	3.97	-

SLACK WATER DATA SUMMARY

RIVER JAMES

TIDE HSW

DATE 28 October '71

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (^{o}C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(45.0)	10	0	1403	18.6	.02	5.33	1.65
		2		18.5	.02		
		4		18.6	.02		
		6		18.6	.02	5.65	
		8		18.7	.02		
		10		18.7	.02	1.48	
J(52.8)	12	0	1433	18.7	.02	5.96	2.42
		2		18.7	.02		
		4		18.7	.02		
		6		18.7	.02	6.21	
		8		18.8	.02		
		10		18.8	.02		
		12		18.8	.02	5.98	1.92
J(60.3)	8	0	1507	18.7		7.34	3.25
		2		18.7			
		4		18.7		7.11	
		6		18.7			
		8		18.8		4.42	-
J(64.0)	8	0	1530	18.9		7.55	3.22
		2		18.9			
		4		18.9		7.09	
		6		18.9			
		8		18.9		6.68	.82

SLACK WATER DATA SUMMARY

RIVER James TIDE HSW

DATE 3 December 1971

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(0.0)	12	0	1120	8.38	20.90	lost	
		2		8.81	21.22		
		4		8.97	21.31		
		6		8.92	21.43	broken	
		8		8.93	21.46		
		10		8.88	21.51		
		12		8.91	21.50	5.24	1.76
J(10.3)	12	0	1155	8.57	18.22	6.55	3.46
		2		8.83	18.47		
		4		8.92	18.62		
		6		8.91	18.68	7.53	
		8		8.88	18.90		
		10		8.79	19.21		
		12		8.73	19.25	6.75	4.76
J(17.9)	10	0	1225	7.79	11.92	7.35	2.71
		2		7.99	13.03		
		4		8.26	13.78		
		6		8.25	14.02	7.37	
		8		8.34	14.31		
		10		8.33	14.36	4.33	0.32
J(28.2)	8	0	1252	7.21	3.80	10.37	6.16
		2		7.36	4.07		
		4		7.38	4.17	9.47	
		6		7.40	4.18		
		8		7.38	4.26	10.57	6.75
J(37.4)	6	0	1325	7.27	0.25	9.99	5.24
		2		7.28	0.30	broken	
		4		7.05	0.36		
		6		7.00	0.38	10.47	
J(45.0)	8	0	1355	7.06	0.19	9.08	4.48
		2		7.13	0.22		
		4		7.11	0.23	8.84	
		6		7.09	0.23		
		8		7.05	0.23	8.04	

SLACK WATER DATA SUMMARY

RIVER James

TIDE HSW

DATE December 7, 1971

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(52.8)	10	0	1205	6.20	.05	8.78	5.56
		2		6.14	.04		
		4		6.05	.04		
		6		5.98	.05	7.75	
		8		5.94	.05		
		10		5.91	.03	9.57	4.75
J(60.3)	8	0	1240	6.47	.06	10.45	5.6
		2		6.34	.06		
		4		6.37	.06	10.69	
		6		6.36	.05		
		8		6.35	.04	10.05	8.17
J(64.0)	8	0	1308	6.47		8.56	
		2		6.43			
		4		6.47		11.08	
		6		6.49			
		8		6.50		9.65	1.4
J(68.3)	6	0	1329	6.50		10.07	2.48
		2		6.46			
		4		6.49		11.44	
		6		6.44		10.47	3.46
J(69.9)	6	0	1342	6.52		9.08	2.22
		2		6.45			
		4		6.45		7.85	
		6		6.45		9.28	
J(73.2)	8	0	1355	7.53		11.44	4.36
		2		7.26			
		4		7.18		10.92	
		6		7.02			
		8		7.05		11.62	3.90
J(77.3)	8	0	1412	5.66		11.30	8.46
		2		5.70			
		4		5.69		12.00	
		6		5.70			
		8		5.68		11.90	11.14

SLACK WATER DATA SUMMARY

RIVER James

TIDE HSW

DATE December 7, 1971

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(83.4)	6	0	1435	5.37		11.54	3.02
		2		5.36		11.18	
		4		5.37			
		6		5.39		10.37	

SLACK WATER DATA SUMMARY

RIVER James

TIDE ISW

DATE 18 January 72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(10.3)	14	0	0734	3.87	12.71	10.99	8.71
		2		3.75	13.20		
		4		3.79	13.82		
		6		3.84	13.89	10.91	
		8		4.09	14.27		
		10		4.60	15.04		
		12		4.77	15.49		
		14		4.72	15.54	10.83	9.88
J(17.9)	8	0	0810	4.09	6.58	11.49	6.52
		2		4.14	7.05		
		4		4.10	7.89	11.55	
		6		4.23	8.28		
		8		4.30	9.96	11.41	7.62
J(28.2)	6	0	0840	4.13	0.69	11.33	5.75
		2		4.15	0.82	11.59	
		4		4.09	0.94		
		6		3.96	1.06	11.47	6.43
J(37.4)	10	0	0905	4.33	0.06	11.51	8.59
		2		4.34	0.07		
		4		4.33	0.08		
		6		4.26	0.08	10.85	
		8		4.16	0.08		
		10		4.15	0.08	10.82	9.9
J(45.0)	6	0	0935	5.83	0.12	10.54	10.84
		2		5.83	0.12	10.42	
		4		5.83	0.13		
		6		5.82	0.13	10.63	7.19
J(52.8)	8	0	1000	4.23		10.36	6.27
		2		4.21			
		4		4.20		10.75	
		6		4.21			
		8		4.19		11.03	12.29

SLACK WATER DATA SUMMARY

RIVER James TIDE LSW

DATE 18 January 72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(60.3)	7	0	1040	4.63		11.11	9.61
		2		4.56			
		4		4.59		11.33	
		6		4.58			
		7		4.59		10.71	7.48
J(64.0)	8	0	1055	4.48		11.23	7.8
		2		4.45			
		4		4.46		11.35	
		6		4.46			
		8		4.46		11.43	6.03
J(68.3)	6	0	1110	4.92		11.29	5.62
		2		4.86			
		4		4.80		11.51	
		6		4.80		11.57	6.06
J(69.9)	6	0	1120	4.99		11.88	7.46
		2		4.99		11.49	
		4		4.99			
		6		5.04		11.55	
J(73.2)	7	0	1135	4.88		12.00	7.20
		2		4.83			
		4		4.76		12.04	
		6		4.71			
		7		4.67		11.90	6.65
J(77.3)	6	0	1155	3.22		12.14	7.93
		2		3.21		11.96	
		4		3.17			
		6		3.18		12.24	18.14
J(83.4)	5	0	1210	1.81		12.00	6.11
		2.5		1.86		12.02	
		5		1.88		11.90	5.43

SLACK WATER DATA SUMMARY

RIVER James TIDE LSW

DATE March 2, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (^{o}C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
	SKIPPED FIRST TWO STATIONS						
J(17.9)	6	0	0745	7.33	0.15	11.15	8.07
		2		7.33	0.22		
		3				11.09	
		4		7.33	0.34		
		6		7.33	0.43	11.23	9.00
J(28.2)	6	0	0835	8.32	0.09	11.19	8.74
		2		8.29	0.11		
		3				11.07	
		4		8.26	0.09		
		6		7.79	0.07	10.97	4.93
J(37.4)	6	0	0920	8.93	0.02	11.11	4.49
		2		8.91	0.02		
		3				11.09	
		4		8.79	0.04		
		6		8.91	0.04	11.23	6.60
J(45.0)	7	0	0955	8.72		11.01	6.89
		2		8.64			
		3.5				10.91	
		4		8.57			
		6		8.49			
		7		8.36		11.03	7.47
J(52.8)	4	0	1050	10.20		Broken	
		2		10.03		10.93	
		4		9.87		11.03	8.20
J(60.3)	6	0	1105	9.92		11.09	6.25
		2		9.78		10.99	
		3					
		4		9.75			
		6		9.71		10.91	7.29

SLACK WATER DATA SUMMARY

RIVER James

TIDE LSW

DATE March 2, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(64.0)	7	0	1125	10.27		10.97	6.20
		2		10.03			
		3.5				10.89	
		4		9.95			
		6		9.87			
		7		9.87		10.83	3.73
J(68.3)	4	0	1145	9.82		10.34	5.03
		2		9.78		10.44	
		4		9.72		10.46	5.55
J(69.9)	5	0	1200	10.07		10.81	4.30
		2		10.04			
		2.5				10.73	
		4		9.99			
		5		9.99		10.83	5.80
J(73.2)	7	0	1210	11.44		10.83	4.52
		2		11.15			
		3.5				10.97	
		4		10.74			
		6		10.49			
		7		10.44		10.95	8.04
J(77.3)	7	0	1230	9.74		10.93	5.97
		2		9.74			
		3.5				11.05	
		4		9.72			
		6		9.72			
		7		9.69		10.99	8.07
J(83.4)	5	0	1255	10.21		11.19	4.61
		2		10.18			
		2.5				Broken	
		4		10.20			
		5		10.18		10.31	4.80

SLACK WATER DATA SUMMARY

RIVER JAMES

TIDE HSW

DATE 28 III 72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(17.9)	5.8	0	0930	9.37	11.2	8.86	5.11
		2		9.32	11.5	8.65	
		4		9.26	13.2	8.14	1.25
J(28.2)	8	0	1030	10.00	2.61	10.50	3.39
		2		9.88	2.55		
		4		9.71	2.63	10.11	
		6		9.70	2.66		
		8		9.79	2.55	10.23	3.00
J(37.2)	9	0	1220	10.38		10.23	4.22
		2		10.30			
		4		10.08			
		6		10.00		10.46	
		8		10.00			
		9		10.01		10.62	4.52
J(45.0)	9.5	0	1245	11.75			
		2		11.50		8.89	1.90
		4		11.00			
		6		10.70		8.55	
		8		10.64			
		9.5		10.64		Broken	
J(52.8)	8	0	1320	11.53		8.44	2.36
		2		11.46			
		4		11.31		8.57	
		6		11.30			
		8		11.29		8.67	5.60
J(60.3)	8	0	1345	11.75		8.26	3.11
		2		11.66			
		4		11.42		8.34	
		6		11.40			
		8		11.40		8.40	6.14

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE HSW

DATE 28 III 72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(64.0)	8.7	0	1400	11.78		8.32	4.57
		2.6		11.73			
		4.8		11.71		7.84	
		6.8		11.70			
		8.7		11.70		7.64	6.01
J(68.3)	7	0	1430	12.20			
		2		11.70			
		4		11.56			
		6		11.55			
		7		11.55		9.62	5.93
J(69.9)	9	0	1440	11.82		9.85	6.14
		2		11.75			
		4		11.73			
		6		11.72		9.68	
		8		11.68			
		9		11.68		9.80	3.76
J(73.7)	9	0	1500	11.59		9.72	3.44
		2		11.53			
		4		11.49			
		6		11.42		9.89	
		8		11.40			
		9		11.39		10.17	5.30
J(77.3)	9.4	0	1515	10.61		10.07	4.85
		2		10.62			
		4		10.54			
		6		10.29		10.13	
		8		10.29			
		9.4		10.28		10.21	5.11
J(83.4)	8	0	1540	10.38		10.05	4.38
		2		10.37			
		4		10.36		9.83	
		6		10.34			
		8		10.32		9.74	4.43

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE LSW

DATE 18/IV/72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(0.0)	22	0	0758	13.54	17.15	9.61	
		2		13.19	17.54		
		4		13.05	17.48		
		6		12.76	17.80		
		8		12.88	18.41		
		10		12.84	18.41		
		12		12.83	18.41	9.45	
		14		12.96	18.38		
		16		12.94	18.47		
		18		12.66	19.20		
		20		12.00	20.74		
		22		11.92	21.07	9.39	
J(10.3)	10	0	0832	14.45	11.64	9.65	
		2		14.46	12.39		
		4		14.09	14.13	9.49	
		6		13.95	14.72		
		8		13.88	15.00		
		10		13.79	15.42	9.57	
J(17.9)	10	0	0905	15.00	6.16	8.58	
		2		14.75	6.48		
		4		14.64	6.89		
		6		14.56	7.83	9.29	
		8		14.50	8.23		
		10		14.22	11.01	8.46	
J(28.2)	6	0	0938	15.20	0.53	9.37	
		2		14.97	0.58		
		4		14.91	0.62	9.13	
		6		14.91	0.60	8.56	
J(37.2)	10	0	1010	15.74	0.16	9.29	
		2		15.65	0.117		
		4		15.61	0.17		
		6		15.54	0.17	9.11	
		8		15.47	0.17		
		10		15.44	0.37	8.64	

SLACK WATER DATA SUMMARY

RIVER JAMES

TIDE ISW

DATE 18/IV/72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (^oC)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(45.0)	10	0	1131	15.94		9.27	
		2		15.84			
		4		15.69			
		6		15.65		9.11	
		8		15.63			
		10		15.62		9.52	
J(52.8)	8	0	1158	17.07		9.29	
		2		16.88			
		4		16.82			
		6		16.79			
		8		16.77		6.21	
J(60.3)	6	0	1225	18.03		8.86	
		2		17.99			
		4		17.94		9.11	
		6		17.91		8.19	
J(64.0)	10	0	1238	18.32		9.39	
		2		18.34			
		4		18.29		9.21	
		6		18.24			
		8		18.22			
		10		18.22		8.38	
J(68.3)	6	0	1300	18.62		9.21	
		2		18.57			
		4		18.53		9.09	
		6		18.52		8.76	
J(69.9)	6	0	1309	18.67		8.09	
		2		18.63			
		4		18.62		7.87	
		6		18.62		7.50	
J(73.2)	8	0	1322	19.28		8.23	
		2		19.11			
		4		18.89		8.38	
		6		18.79			
		8		18.75		8.15	

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE LSW

DATE 18/IV/72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(77.3)	10	0	1345	18.44		8.64	
		2		18.06			
		4		17.83			
		6		17.77		8.62	
		8		17.75			
		10		17.74		8.50	
J(83.4)	6	0	1400	19.14		7.87	
		2		18.87			
		4		18.79		7.95	
		6		18.75		8.27	

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE HWS

DATE 25/IV/72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(37.2)	6	0	0945	16.56		8.06	
		2		16.56			
		4		16.57		8.10	
		6		16.56		8.32	
J(45.0)	10	0	1013	17.78		8.22	
		2		17.72			
		4		17.72			
		6		17.72		8.16	
		8		17.74			
		10		17.75		8.34	
J(52.8)	8	0	1038	17.48		8.28	
		2		17.48			
		4		17.48		6.38	
		6		17.46			
		8		17.45		6.60	
J(60.3)	8	0	1106	17.45		6.66	
		2		17.44			
		4		17.38		6.60	
		6		17.33			
		8		17.30		6.48	
J(64.0)	10	0	1119	17.05		7.38	
		2		17.07			
		4		17.03			
		6		17.00		7.52	
		8		16.95			
		10		16.93		7.58	
J(68.3)	6	0	1136	16.93		6.92	
		2		16.74			
		4		16.70		7.20	
		6		16.69		7.02	
J(69.9)	8	0	1150	16.40		7.58	
		2		16.45			
		4		16.45		8.20	
		6		16.46			
		8		16.47		7.80	

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE HWS

DATE 25/IV/72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(72.2)	8	0	1200	15.33		7.72	
		2		15.90			
		4		15.96		7.80	
		6		15.95			
		8		15.96		7.58	
J(77.3)	9.3	0	1225	15.44		7.64	
		2		15.55			
		4		15.61		7.74	
		6		15.62			
		8		15.62			
		9.3		15.63		7.58	
J(83.4)	6	0	1240	15.91		6.98	
		2		15.97			
		4		16.00		7.50	
		6		16.01		7.28	

SLACK WATER DATA SUMMARY

RIVER James

TIDE LSW

DATE May 2, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(15.9)	8	0	0550	17.01	3.86		
		2		16.81	5.14		
		4		16.59	6.43		
		6		16.53	6.47		
		8		16.49	6.69		
J(28.2)	8	0	0626	17.93	.11		
		2		17.85	.11		
		4		17.77	.11		
		6		17.69	.11		
		8		17.66	.11		
J(37.4)	16	0	0650	17.86	.09		
		2		17.88	.09		
		4		17.89	.09		
		6		17.90	.09		
		8		17.90	.09		
		10		17.91	.09		
		12		17.93	.09		
		14		17.93	.09		
		16		17.94	.09		
J(45.0)	8	0	0750	17.94	.09		
		2		17.92	.08		
		4		17.87	.08		
		6		17.83	.08		
		8		17.83	.13		
J(52.8)	8	0	0812	17.76			
		2		17.75			
		4		17.73			
		6		17.72			
		8		17.72			
J(60.3)	6	0	0836	18.54			
		2		18.52			
		4		18.43			
		6		18.43			

SLACK WATER DATA SUMMARY

RIVER James

TIDE LSW

DATE May 2, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(64.0)	8	0	0852	18.59			
		2		18.55			
		4		18.52			
		6		18.51			
		8		18.48			
J(68.3	6	0	0908	18.15			
		2		18.16			
		4		18.15			
		6		18.15			
J(69.9)	8	0	0919	18.63			
		2		18.62			
		4		18.60			
		6		18.60			
		8		18.59			
J(73.2)	8	0	0931	18.89			
		2		19.23			
		4		19.16			
		6		19.15			
J(77.2)	6	0	0950	19.46			
		2		19.23			
		4		19.16			
		6		19.15			
J(83.4)	6	0	1006	18.06			
		2		17.90			
		4		17.86			
		6		17.81			

SLACK WATER DATA SUMMARY

RIVER James River TIDE HSW

DATE May 31, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(17.9)	6	0	0938	20.33	1.86	7.70	5.40
		2		20.14	2.44		
		4		20.12	2.96	7.58	
		6		20.09	3.04	7.80	3.17
J(28.2)	6	0	1023	20.25		Broken	
		2		20.25			
		4		20.25		7.76	
		6		20.20		6.82	4.00
J(45.0)	9	0	1204	20.4		7.58	6.86
		2		21.5			
		4		20.5		7.46	
		6		20.5			
		8		20.5			
		9		20.5		5.62	
J(52.8)	6	0	1232	20.5		7.68	
		2		20.4			
		4		20.35		7.76	
		6		20.35		7.38	4.38
J(60.3)	8	0	1316	21.9		7.77	8.97
		2		21.7			
		4		21.7		7.58	
		6		21.65			
		8		21.65		7.42	10.82
J(64.0)	8	0	1334	22.0		7.88	7.27
		2		21.9			
		4		21.7		8.00	
		6		21.7			
		8		21.7		7.60	7.93
J(68.3)	7	0	1351	22.2		7.96	9.17
		2		22.1			
		4		22.1		7.90	
		6		22.5			
		7		22.0		7.96	5.49

SLACK WATER DATA SUMMARY

RIVER James River

TIDE HSW

DATE May 31, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(69.9)	6	0	1402	22.70		7.98	6.19
		2		22.3			
		4		22.3		8.04	
		6		22.3		7.82	4.63
J(73.7)	8	0	1416	16.9		8.14	
		2		22.6			
		4		21.9		8.26	
		6		21.5			
		8		21.5		8.20	6.51
J(77.3)	7	0	1435	22.8		7.36	8.95
		2		22.75			
		4		22.75		7.46	
		6		22.60			
		7		22.55		6.98	4.57
J(83.4)	6	0	1455	22.5		8.06	5.93
		2		22.5			
		4		22.0		8.20	
		6		22.0		8.14	6.70

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE LSW

DATE September 14, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (^{o}C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(37.4)	18	0	1100	23.55	.51	7.99	6.12
		2		23.57	.51		
		4		23.50	.51		
		6		23.50	.57		
		8		23.49	.57	7.89	
		10		23.49	.60		
		12		23.48	.61		
		16		23.47	.65		
		18		23.45	.79	7.54	6.80
J(45.0)	8	0	1135	24.37	.17	6.95	1.69
		2		24.28	.17		
		4		24.29	.17	7.94	
		6		24.32	.25		
		8		24.44	.33	7.14	6.88
J(52.8)	6	0	1203	24.06		7.82	6.52
		2		24.06			
		4		24.08		7.24	
		6		24.13		8.74	10.70
J(60.3)	6	0	1233	24.22		8.44	8.69
		2		24.19			
		4		24.20		8.44	
		6		24.20		8.32	10.28
J(64.0)	8	0	1250	24.69		7.94	8.16
		2		24.62			
		4		24.61		8.16	
		6		24.60			
		8		24.66		7.84	8.02
J(68.3)	6	0	1312	25.45		7.66	5.38
		2		25.47			
		4		25.52		7.29	
		6		25.63		7.14	8.22

SLACK WATER DATA SUMMARY

RIVER JAMES   TIDE LSW

DATE September 14, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(69.9)	8	0	1321	25.80		7.54	6.28
		2		25.80			
		4		25.81		5.43	
		6		25.83			
		8		25.86		6.33	7.33
J(73.2)	8	0	1343	27.55		5.87	3.65
		4		26.58		5.61	
		8		26.24		5.75	
J(77.3)	8	0	1400	24.68		4.84	4.26
		4		24.07		4.22	
		8		24.10		3.90	4.52
J(83.4)	6	0	1421	25.55		4.66	5.53
		3		24.35		5.33	
		6		24.41		5.63	6.82

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE HSW

DATE September 27, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (^oC)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(0.0)	16	0	1400	23.2	18.17		
		2		23.0	18.38		
		4		22.9	18.59		
		6		22.9	18.72		
		8		22.9	18.76		
		10		22.9	18.87		
		12		22.8	18.86		
		14		22.8	18.99		
		16		22.8	19.80		
J(10.3)	16	0	1510	22.6	17.19		
		2		22.6	17.63		
		4		22.6	17.99		
		6		22.4	18.18		
		8		22.0	17.81		
		10		22.0	18.13		
		12		22.0	18.12		
		14		22.0	18.17		
		16		22.0	18.15		
J(17.9)	10	0	1555	23.6	13.46		
		2		23.5	13.85		
		4		23.2	13.73		
		6		23.2	13.94		
		8		23.0	13.81		
		10		23.0	13.91		
J(28.2)	8	0	1635	23.6	7.09		
		2		23.4	7.12		
		4		23.6	7.14		
		6		23.8	7.24		
		8		23.8	7.25		
J(37.4)	12	0	1540	23.7		6.72	
		2		23.5			
		4		23.5			
		6		23.6		6.90	
		8		23.7			
		10		23.8			
		12		23.8		7.12	

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE HSW

DATE September 27, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)	
J(45.0)	12	0	1600	25.4		7.30		
		2		23.9				
		4		23.7				
		6		23.7		7.50		
		8		23.7				
		10		23.8				
		12		23.7		6.30		
J(52.8)	10	0	1630	23.7		4.20		
		2		23.7				
		4		23.8		5.00		
		6		23.8				
		8		23.8				
		10		23.8		5.02		
J(60.3)	8	0	1700	23.9		6.14		
		2		24.0				
		4		24.0		5.94		
		6		24.0				
		8		24.0		5.90		
J(64.0)	8	0	1715	25.1		5.94		
		4		24.3		5.92		
		8		24.2		5.70		
J(68.3)	6	0	1735	24.7		5.70		
		3		24.7		5.90		
		6		24.7		5.90		
J(69.9)	6	0	1745	24.9		6.00		
		3		24.9		6.10		
		6		24.9		5.80		
J(73.2)	8	0	1800	25.9		4.00		
		4		25.8		3.70		
		8		25.6		4.10		

SLACK WATER DATA SUMMARY

RIVER James

TIDE LSW

DATE Oct. 12, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(00.0)	12	0	0730	18.69	22.00	7.76	7.70
		2		18.71	22.19		
		4		18.73	22.65		
		6		18.74	22.67	6.86	
		8		18.75	22.87		
		10		18.73	23.74		
		12		18.80	23.29	6.63	5.79
J(10.3)	18	0	0815	17.40	13.80	7.02	2.54
		2		17.60	14.00		
		4		17.90	14.20		
		6		18.25	14.60		
		8		18.20	15.09		
		10		18.50	17.50	7.41	
		12		18.70	18.60		
		14		18.68	18.75		
		16		18.70	18.74		
		18		18.72	18.79	6.71	7.14
J(17.9)	12	0	0856	16.50		7.02	
		2		16.36			
		4		16.60			
		6		16.80		6.75	
		8		17.05	.24		
		10		17.71	4.30		
		12		18.60	8.74	6.67	2.30
J(28.2)	14	0	0915	17.30		6.63	2.85
		2		17.04			
		4		16.99			
		6		17.01		6.59	
		8		17.00			
		10		17.00			
		12		16.94			
		14		16.93		6.34	1.00

SLACK WATER DATA SUMMARY

RIVER James

TIDE LSW

DATE Oct. 12, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(37.2)	18	0	1030	16.90		6.92	4.45
		2		16.88			
		4		16.98			
		6		16.90			
		8		16.88			
		10		16.87		7.10	
		12		16.90			
		14		16.91			
		16		16.80			
		18		16.96		7.02	2.54

SLACK WATER DATA SUMMARY

RIVER JAMES TIDE LSW

DATE 10/17/72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (^{o}C)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J(45.0)	10	0	1330	25.70		7.0	2.38
		2		25.70			
		4		25.50			
		6		25.55		6.8	
		8		25.60			
		10		25.80		6.7	.63
J(52.8)	12	0	1407	25.10		6.4	2.22
		2		25.10			
		4		25.20			
		6		25.20		6.4	
		8		25.30			
		10		25.35			
		12		25.50		6.3	1.58
J(60.3)	8	0	1440	16.80		6.4	3.14
		2		16.80			
		4		16.80		6.4	
		6		16.90			
		8		17.10		6.3	1.58
J(64.0)	10	0	1500	17.30		8.1	3.80
		2		17.25			
		4		17.25			
		6		17.30		7.1	
		8		17.30			
		10		17.40		7.5	3.89
J(68.3)	6	0	1525	17.60		7.6	2.85
		3		17.60		7.6	
		6		17.80		7.3	3.49
J(69.9)	8	0	1535	17.90		7.6	1.74
		4		17.90		7.7	
		8		18.00		7.6	2.06
J(73.2)	8	0	1556	19.10		7.6	1.90
		4		18.30		7.9	
		8		18.20		7.7	

SLACK WATER DATA SUMMARY

RIVER JAMES

TIDE LSW

DATE 10/17/72

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)	
J(77.3)	8	0	1620	17.10		7.7	1.77	
		4		16.80		8.6		
		8		17.00		8.9	4.63	
J(83.4)	6	0	1645	16.40		9.0	4.28	
		3		16.40		9.2		
		6		16.40		9.0	1.42	

SLACK WATER DATA SUMMARY

RIVER James

TIDE LSW

DATE Nov. 28, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (°C)	Salinity (ppt)	DO (ppm)	BOD (ppm)	
J00.0	20	0	1050	9.37	8.66	10.0	9.85	
		2		9.34	8.66			
		4		9.36	11.36			
		6		9.41	14.41			
		8		9.86	18.88			
		10		9.93	20.95	8.1		
		12		9.95	21.31			
		14		9.96	21.69			
		16		9.95	21.77			
		18		9.98	21.74			
		20		9.98	21.76	7.5	7.85	
J10.3	16	0	1125	9.73	3.00	10.9	4.86	
		2		9.28	3.30			
		4		9.50	3.30			
		6		8.95	4.87			
		8		9.98	9.58	9.9		
		10		10.33	14.98			
		12		10.36	16.36			
		14		10.21	16.60			
		16		10.33	16.67	9.3	8.68	
J17.9	10	0	1155	9.00	0.66	11.0	6.71	
		2		9.77	1.08			
		4		8.82	0.84			
		6		9.03	1.02	10.2		
		8		9.44	8.35			
		10		9.61	11.84	9.8	9.28	
J28.2	14	0	1238	8.57	0.31	10.5	4.57	
		2		7.88	1.03			
		4		9.24	1.04			
		6		8.82	0.71			
		8		8.44	1.59	11.1		
		10		8.78	0.97			
		12		9.05	1.07			
		14		10.80	1.32	10.9		

SLACK WATER DATA SUMMARY

RIVER James

TIDE HSW

DATE Dec. 6, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (^oC)	Salinity (ppt)	DO (ppm)	BOD (ppm)
J00.0	12	0	1050	10.12	19.48		
		2		10.90	19.50		
		4		10.10	19.54		
		6		10.10	17.52		
		8		9.96	19.97		
		10		9.98	28.80		
		12		9.99	21.04		
J10.3	16	0	1114	9.99	13.64		
		2		9.88	13.69		
		4		9.77	16.30		
		6		9.75	16.94		
		8		9.76	17.48		
		10		9.81	17.53		
		12		9.96	18.61		
		14		9.78	20.57		
		16		9.86	20.86		

SLACK WATER DATA SUMMARY

RIVER James

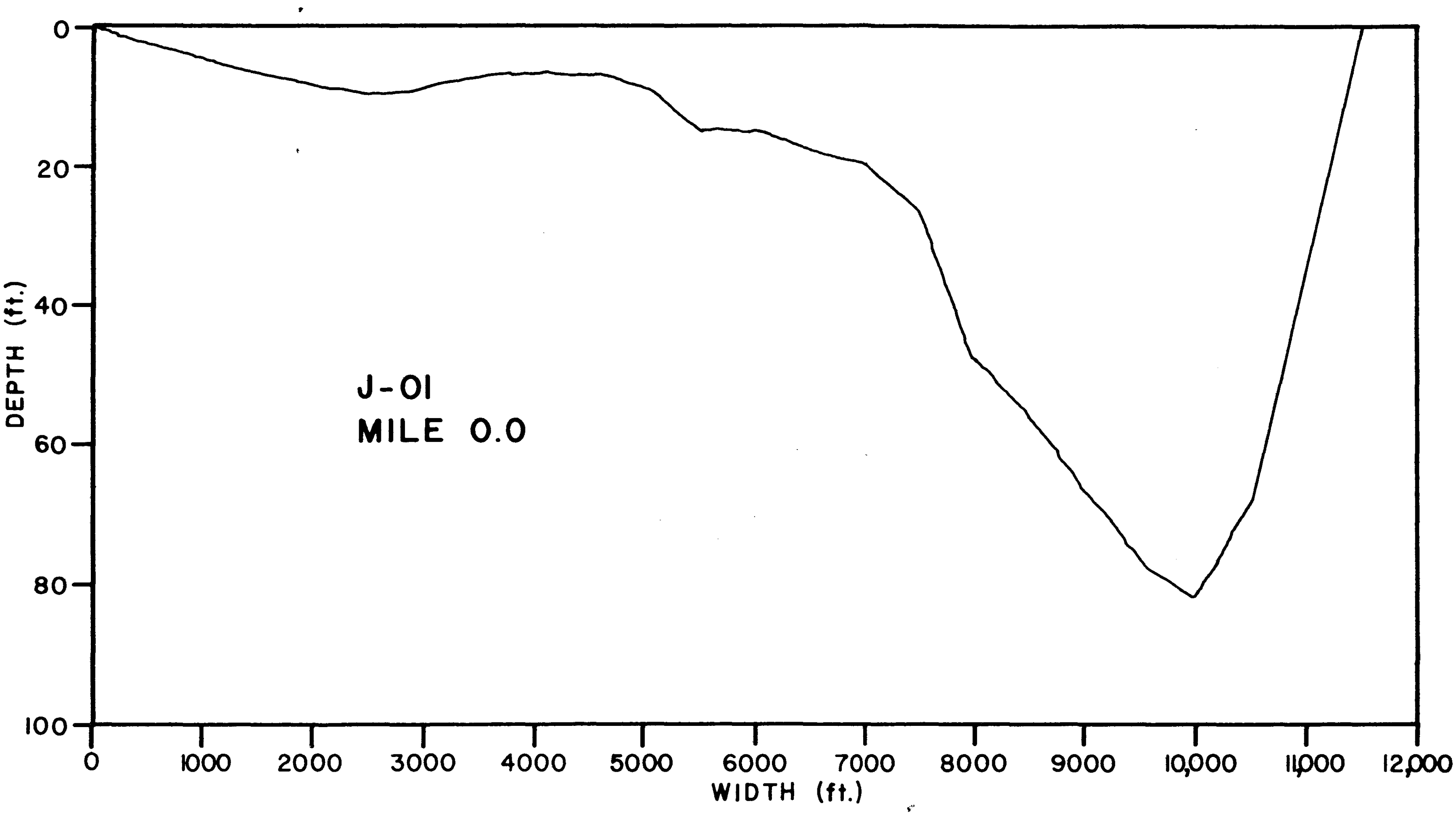
TIDE HSW

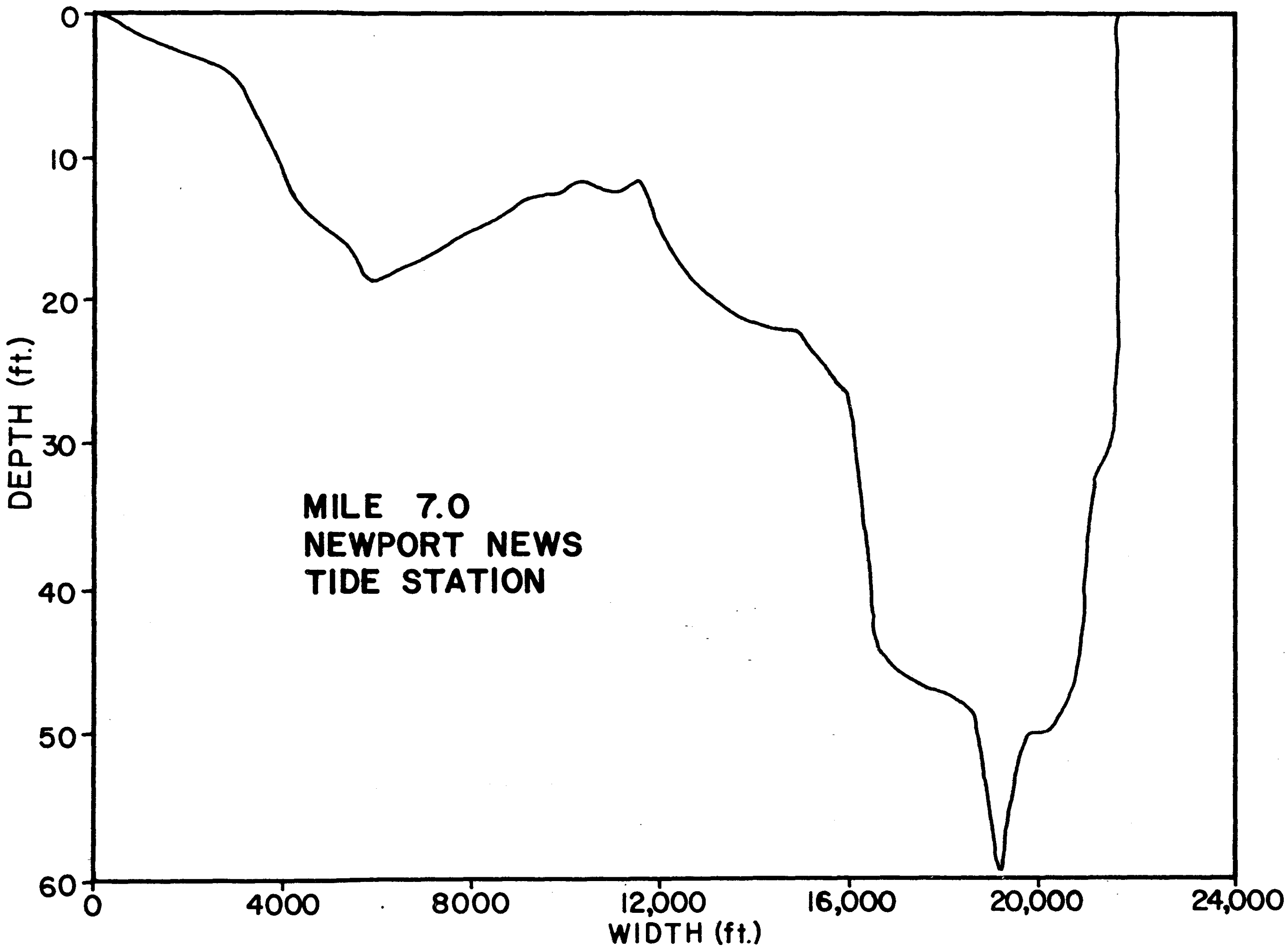
DATE Dec. 8, 1972

Transect Designation	Total Water Depth (m)	Sample Depth (m)	Time of Sampling (EST)	Temp. (^{o}C) GF	Salinity (ppt) NF	DO (ppm)	BOD (ppm)
J17.9	12	0	1210	8.78	7.48		
		2		8.77	7.70		
		4		9.20	10.59		
		6		9.60	12.03		
		8		9.89	13.07		
		10		9.91	13.13		
		12		9.89	13.13		
J28.2	10	0	1240	8.71	0.90		
		2		8.64	0.91		
		4		8.62	1.00		
		6		8.67	1.19		
		8		8.75	1.79		
		10		8.88	1.83		
J37.4	10	0	1305	8.75	0.14		
		2		8.75	0.14		
		4		8.72	0.15		
		6		8.72	0.16		
		8		8.71	0.16		
		10		8.77	0.16		

APPENDIX B

Profiles of Cross-Sections


J-01
MILE 0.0
DEPTH (ft.)
WIDTH (ft.)
0
20
40
60
80
100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
11,000
12,000


MILE 7.0
NEWPORT NEWS
TIDE STATION
DEPTH (ft.)
0
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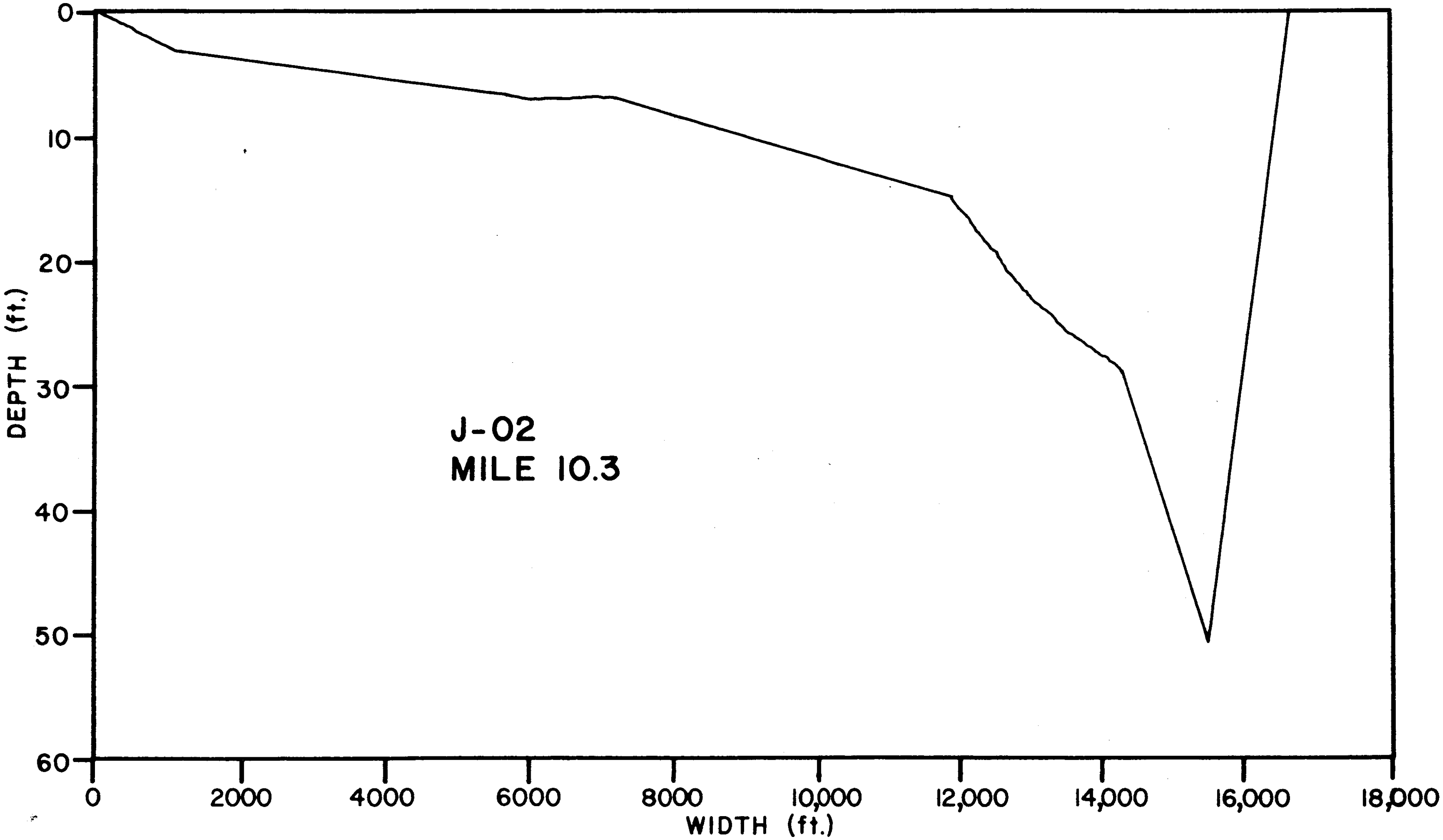
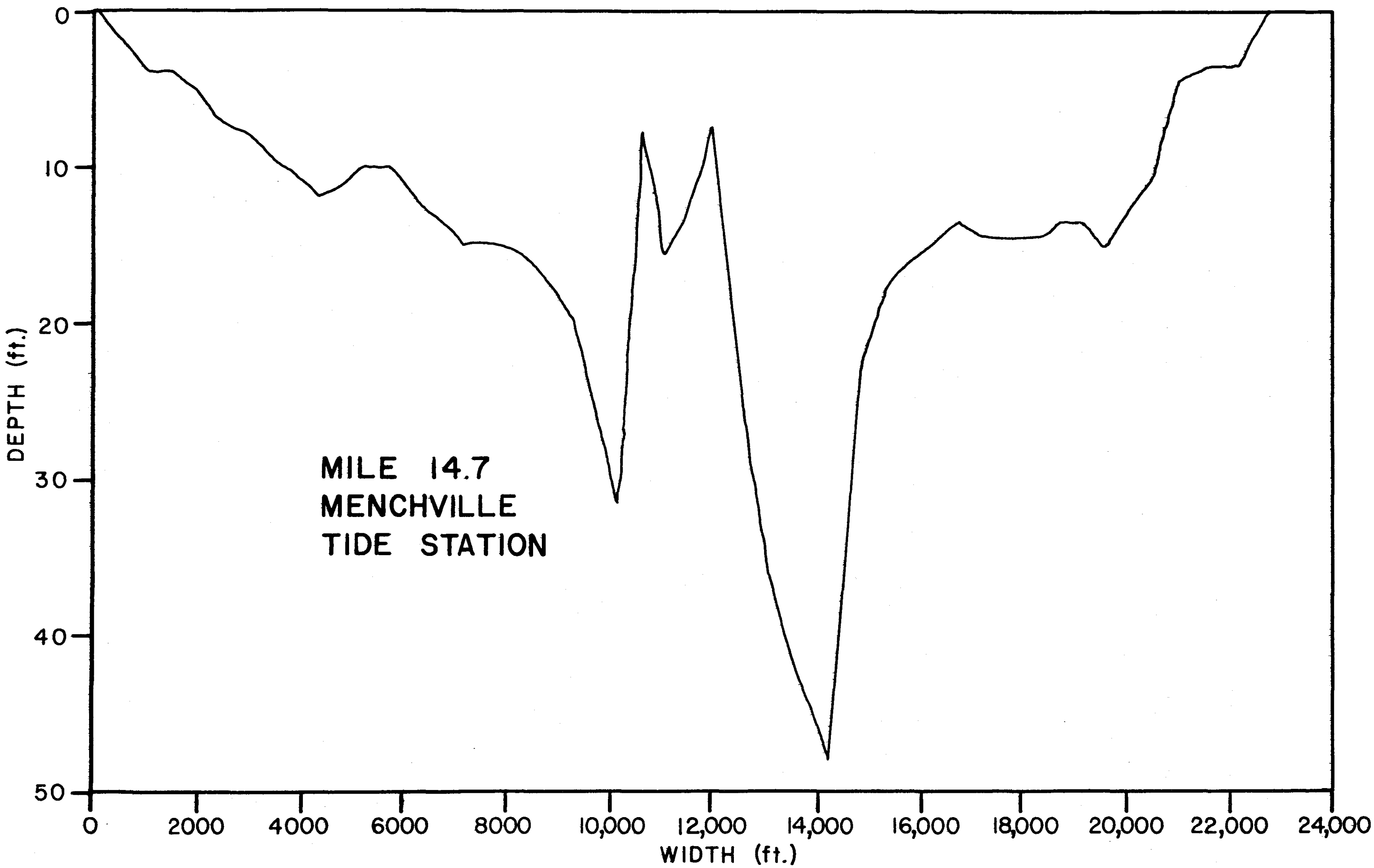
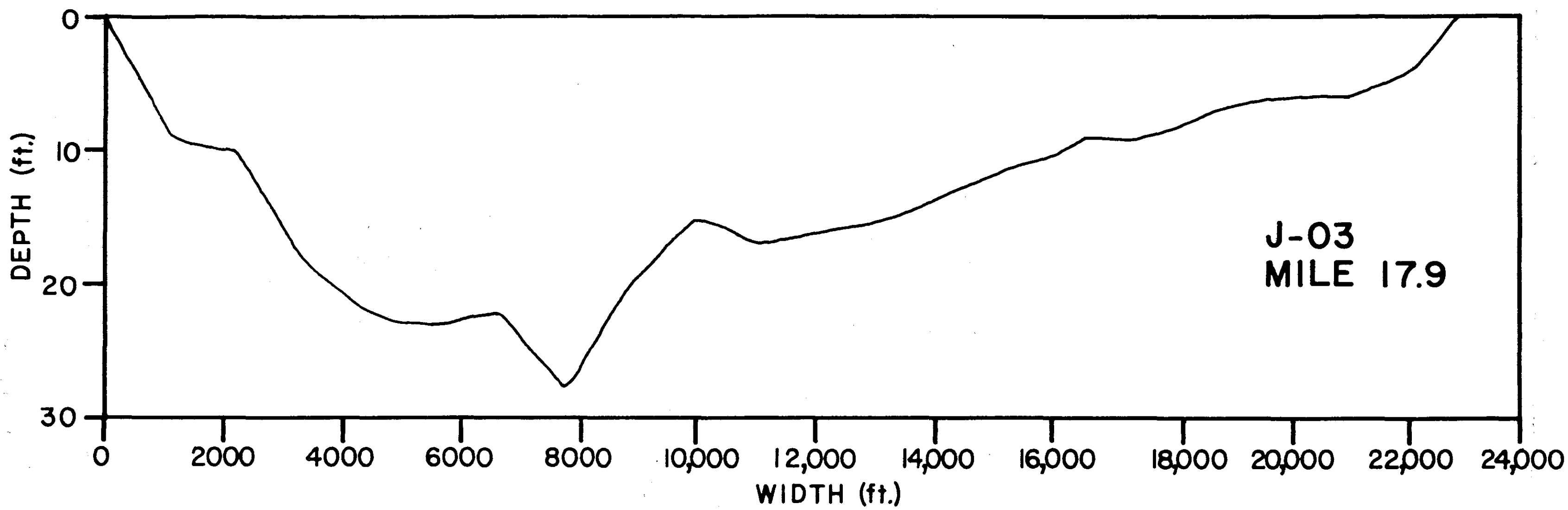
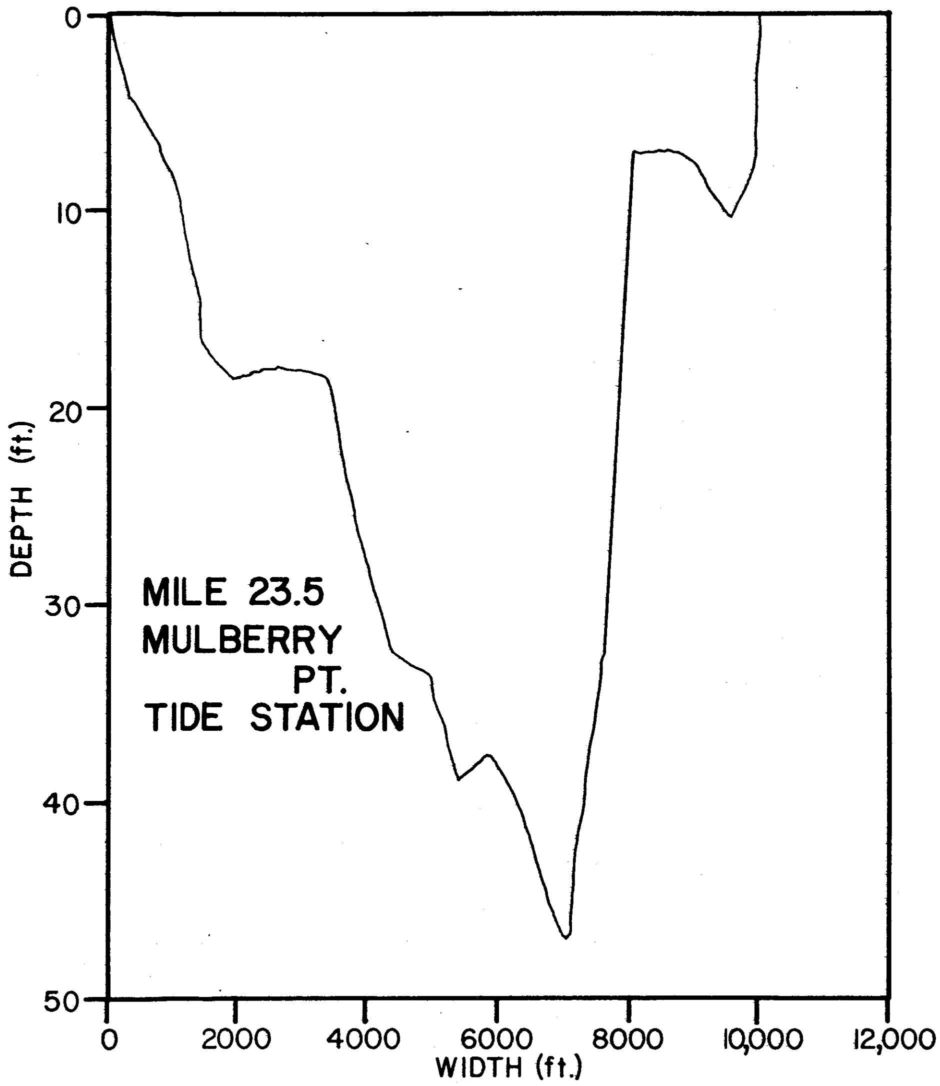
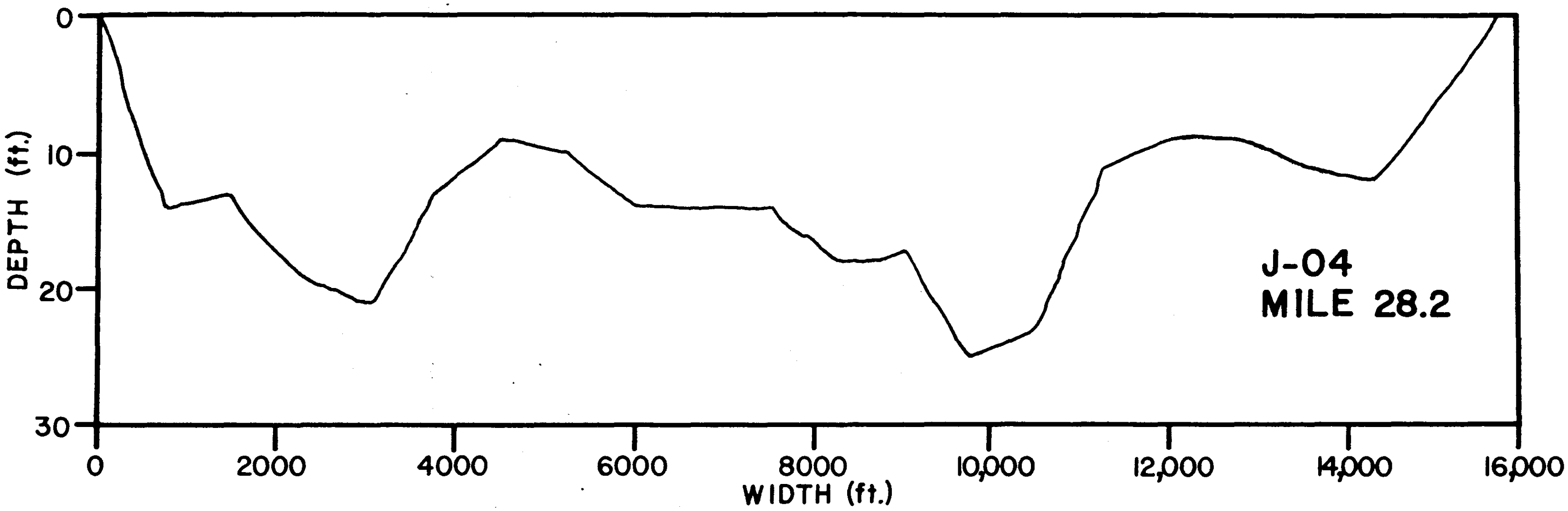
20
30
40
50
60
WIDTH (ft.)
0
4000
8000
12,000
16,000
20,000
24,000

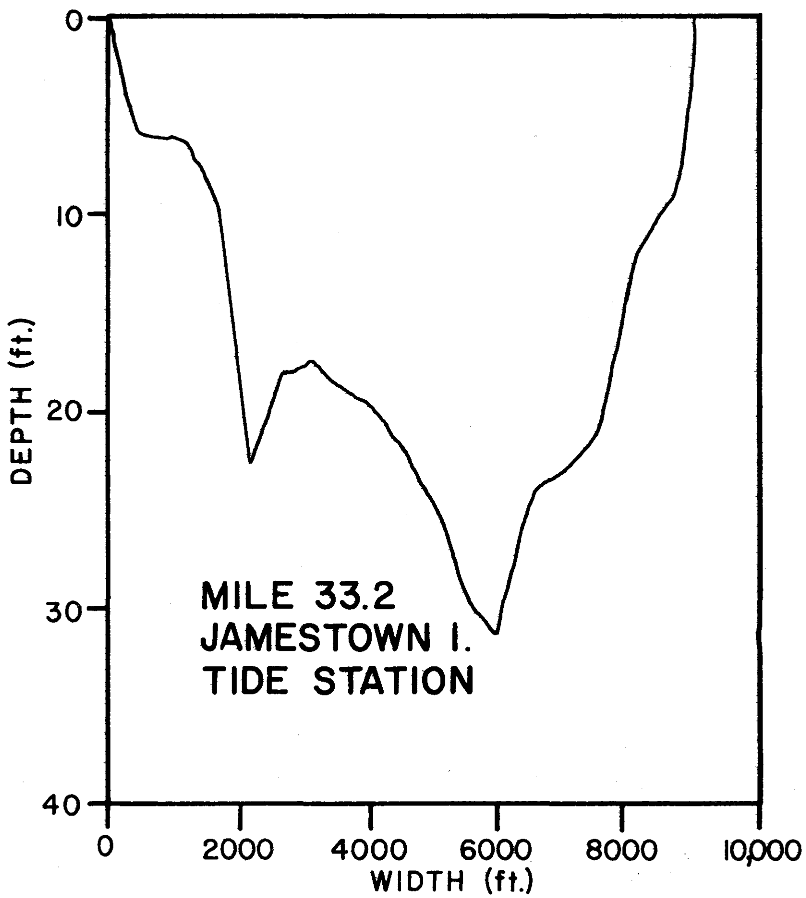

J-02
MILE 10.3
DEPTH (ft.)
WIDTH (ft.)
0
10
20
30
40
50
60
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000
18,000

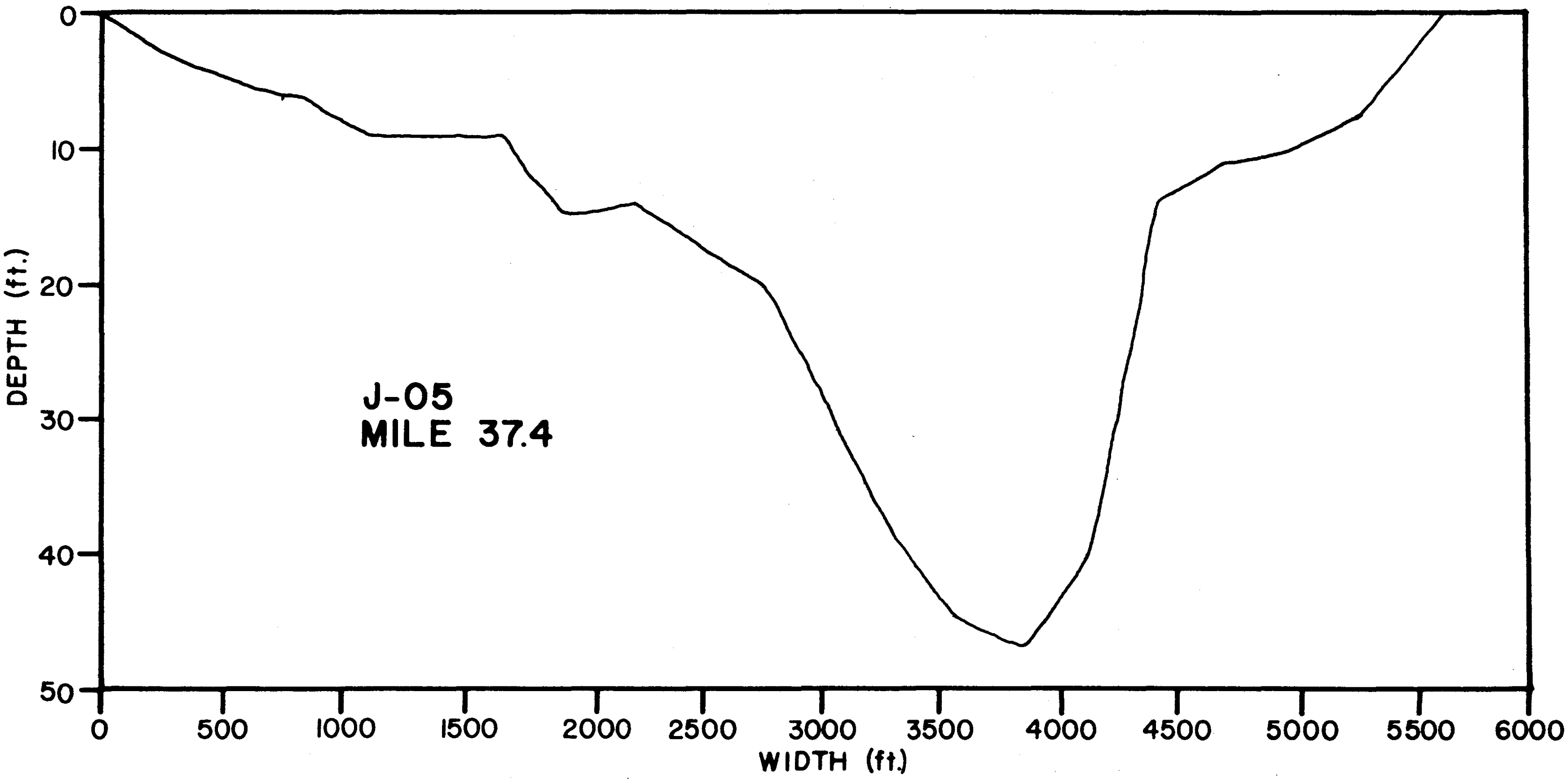

MILE 14.7
MENCHVILLE
TIDE STATION
DEPTH (ft.)
0
10
20
30
40
50
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000
18,000
20,000
22,000
24,000
WIDTH (ft.)

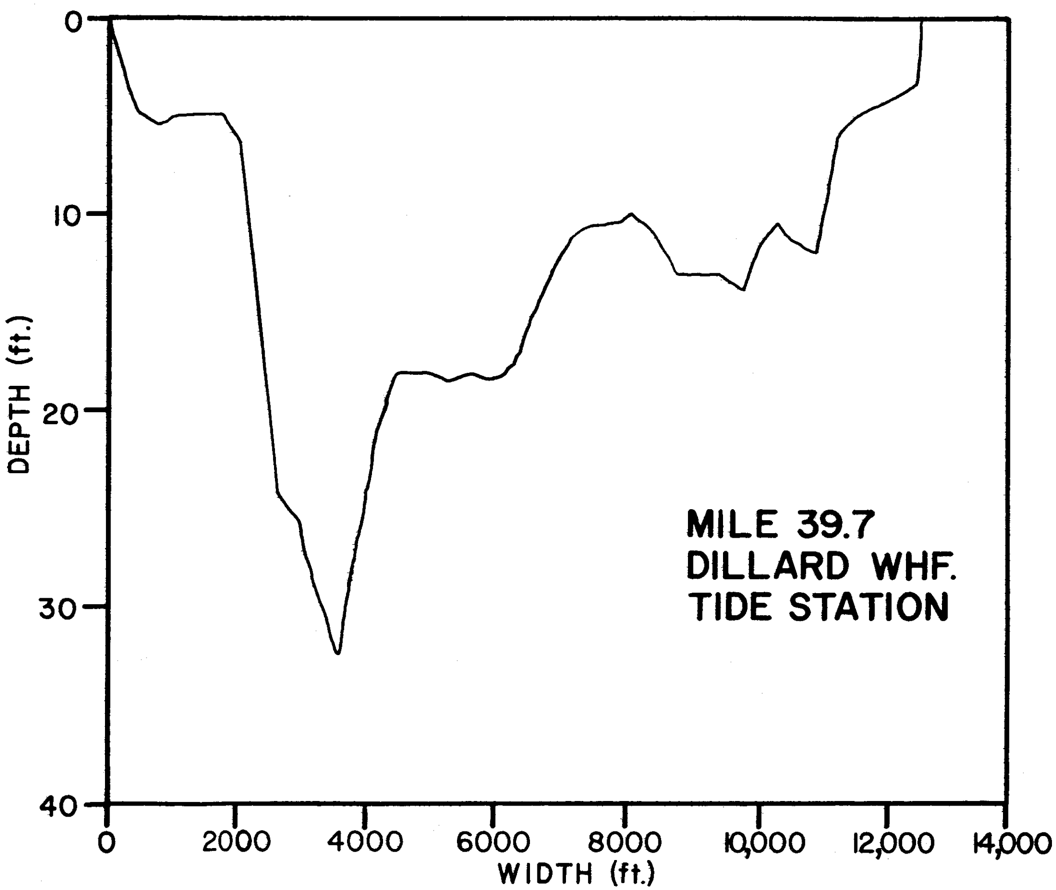

DEPTH (ft.)
0
10
20
30
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000
18,000
20,000
22,000
24,000
WIDTH (ft.)
J-03
MILE 17.9


MILE 23.5
MULBERRY
PT.
TIDE STATION
DEPTH (ft.)
0
10
20
30
40
50
0
2000
4000
6000
8000
10,000
12,000
WIDTH (ft.)

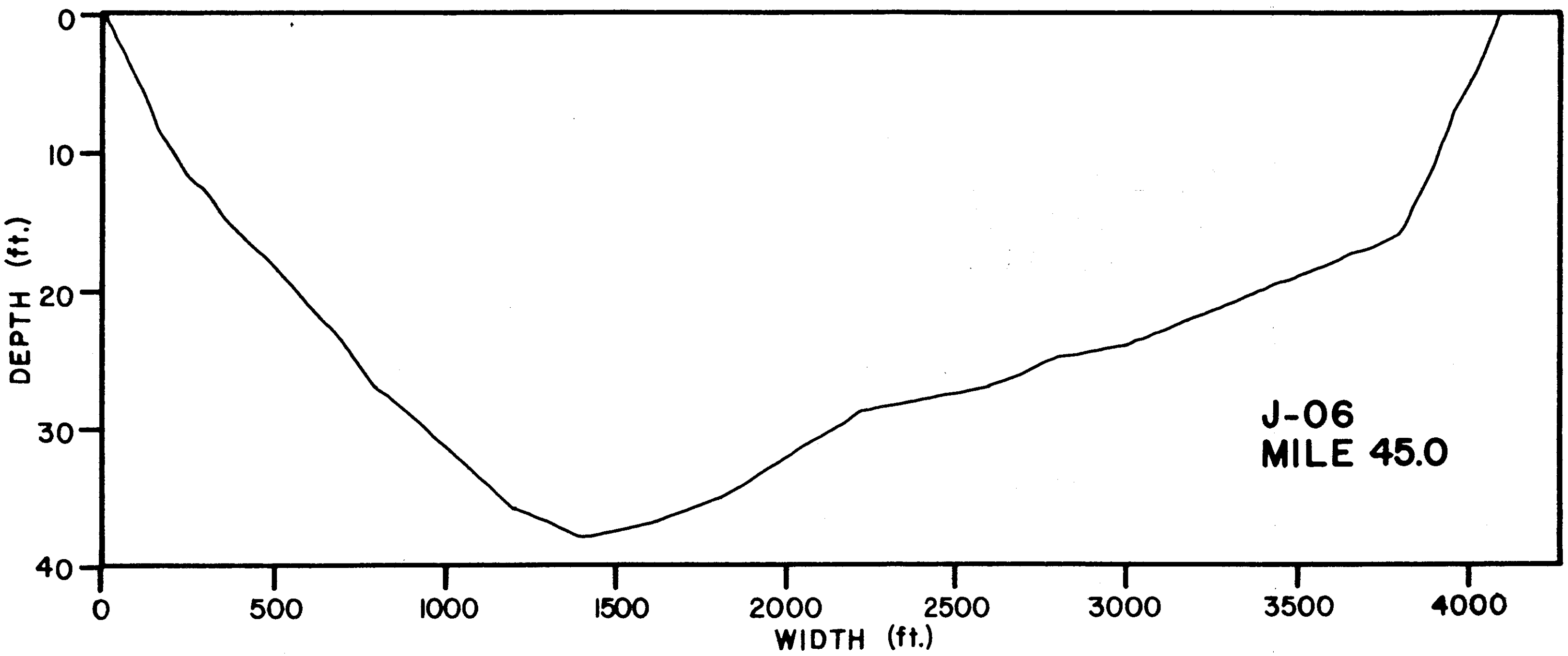

J-04
MILE 28.2
DEPTH (ft.)
0
10
20
30
WIDTH (ft.)
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000


0
10
20
30
40
DEPTH (ft.)
0
2000
4000
6000
8000
10,000
WIDTH (ft.)
MILE 33.2
JAMESTOWN I.
TIDE STATION

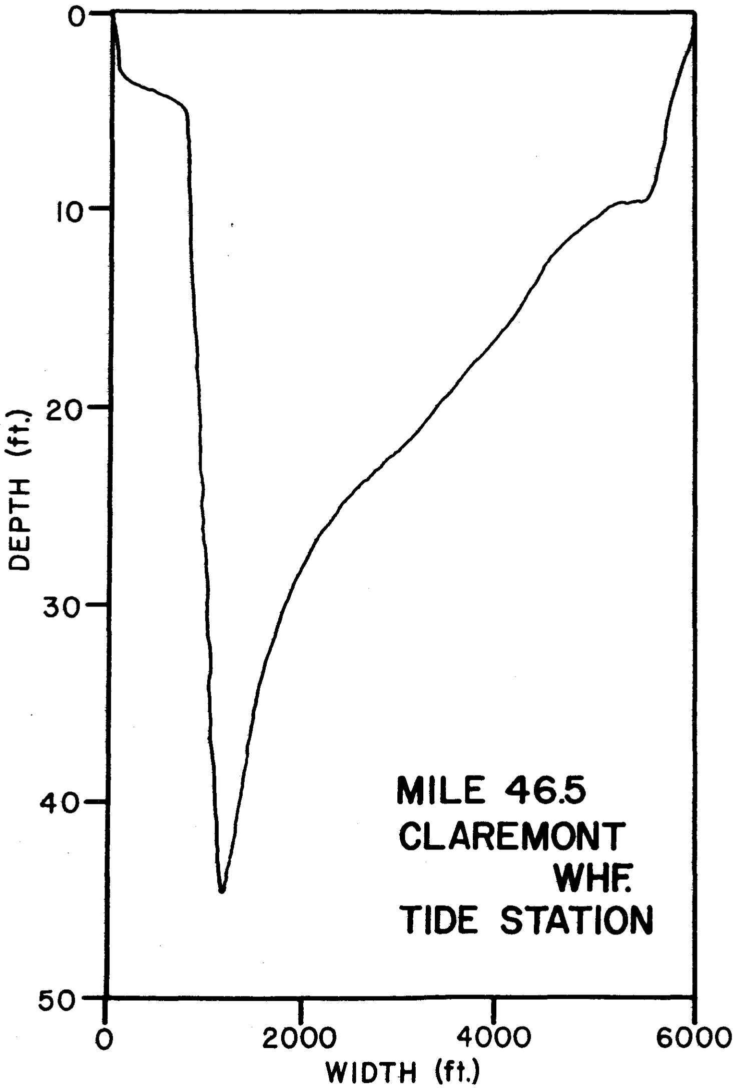

J-05
MILE 37.4
DEPTH (ft.)
0
10
20
30
40
50
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
WIDTH (ft.)

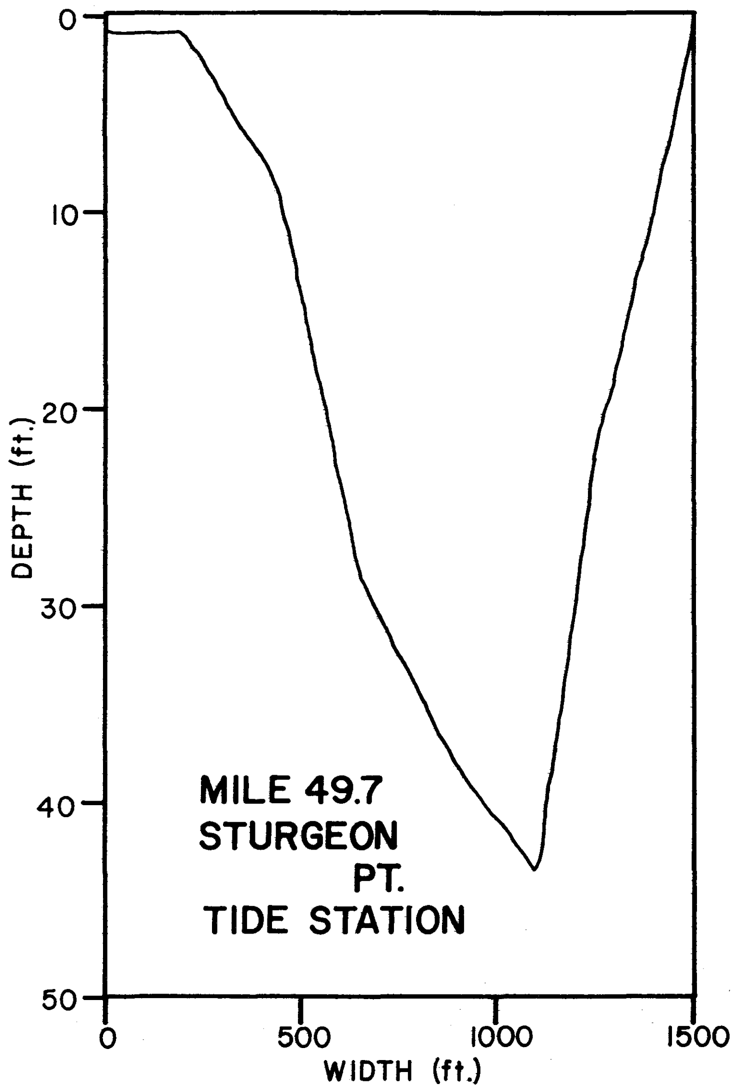


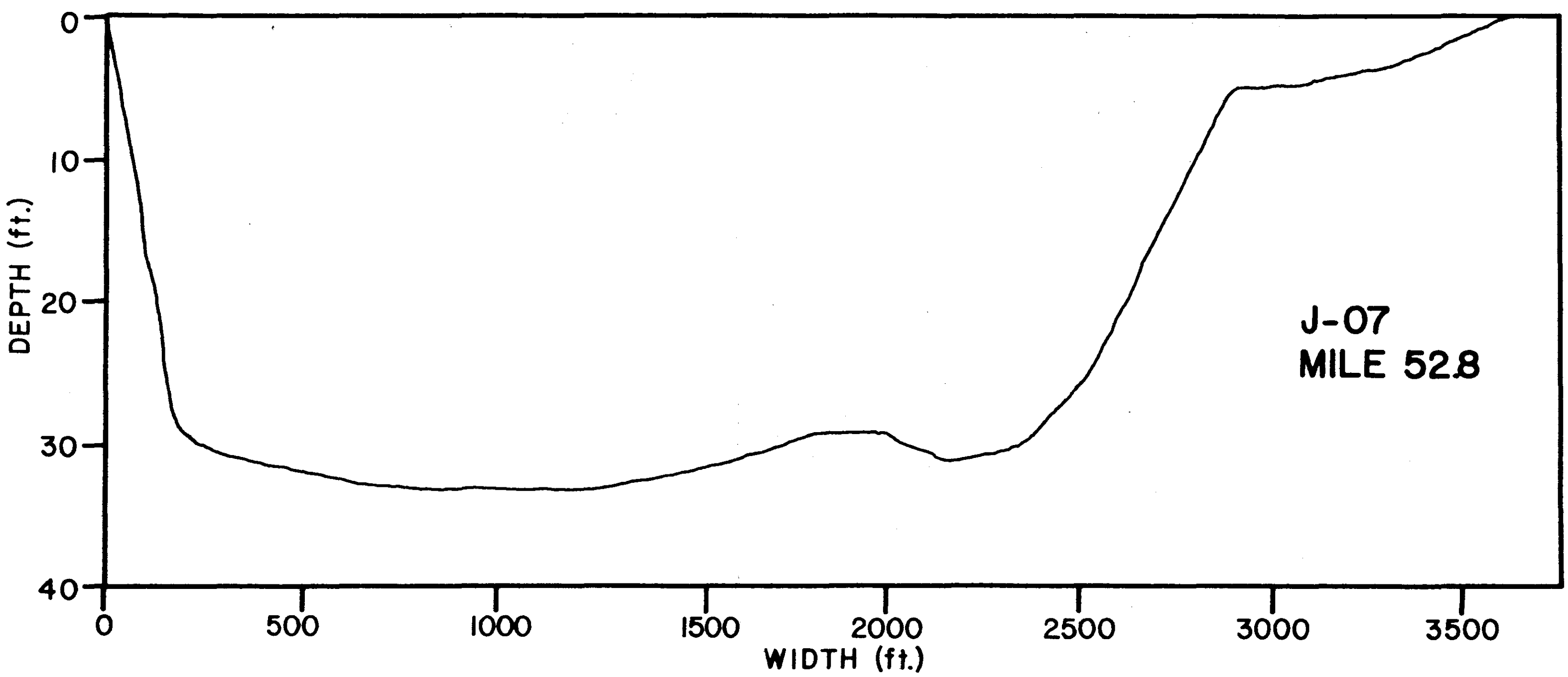
0
10
20
30
40
DEPTH (ft.)
0
2000
4000
6000
8000
10,000
12,000
14,000
WIDTH (ft.)
MILE 39.7
DILLARD WHF.
TIDE STATION

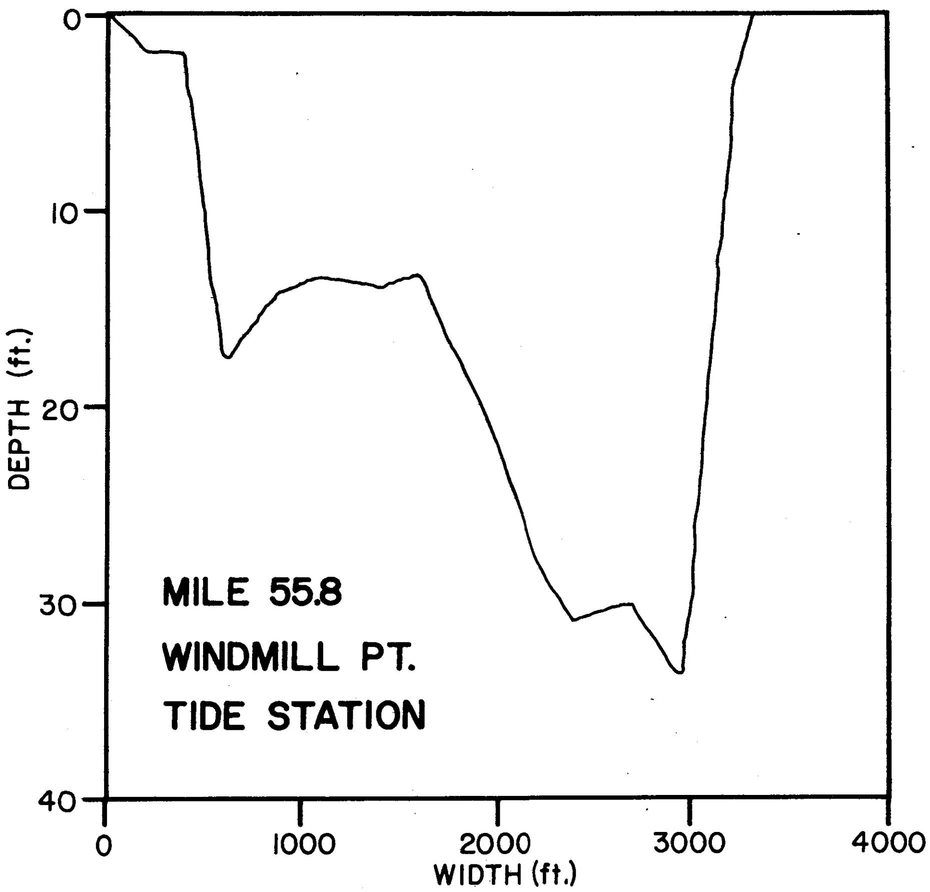


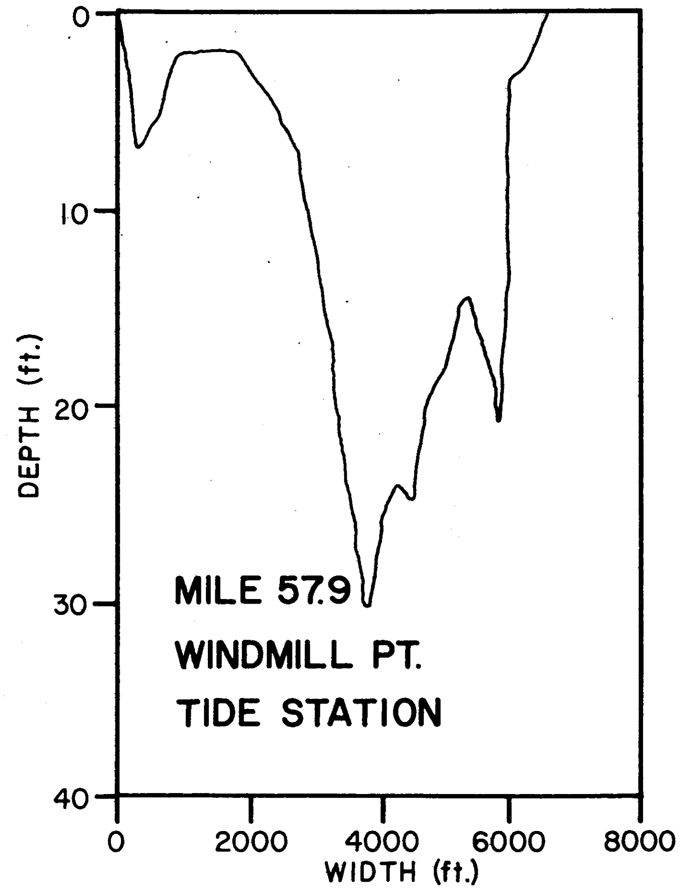
0
10
20
30
40
DEPTH (ft.)
0
500
1000
1500
2000
2500
3000
3500
4000
WIDTH (ft.)
J-06
MILE 45.0

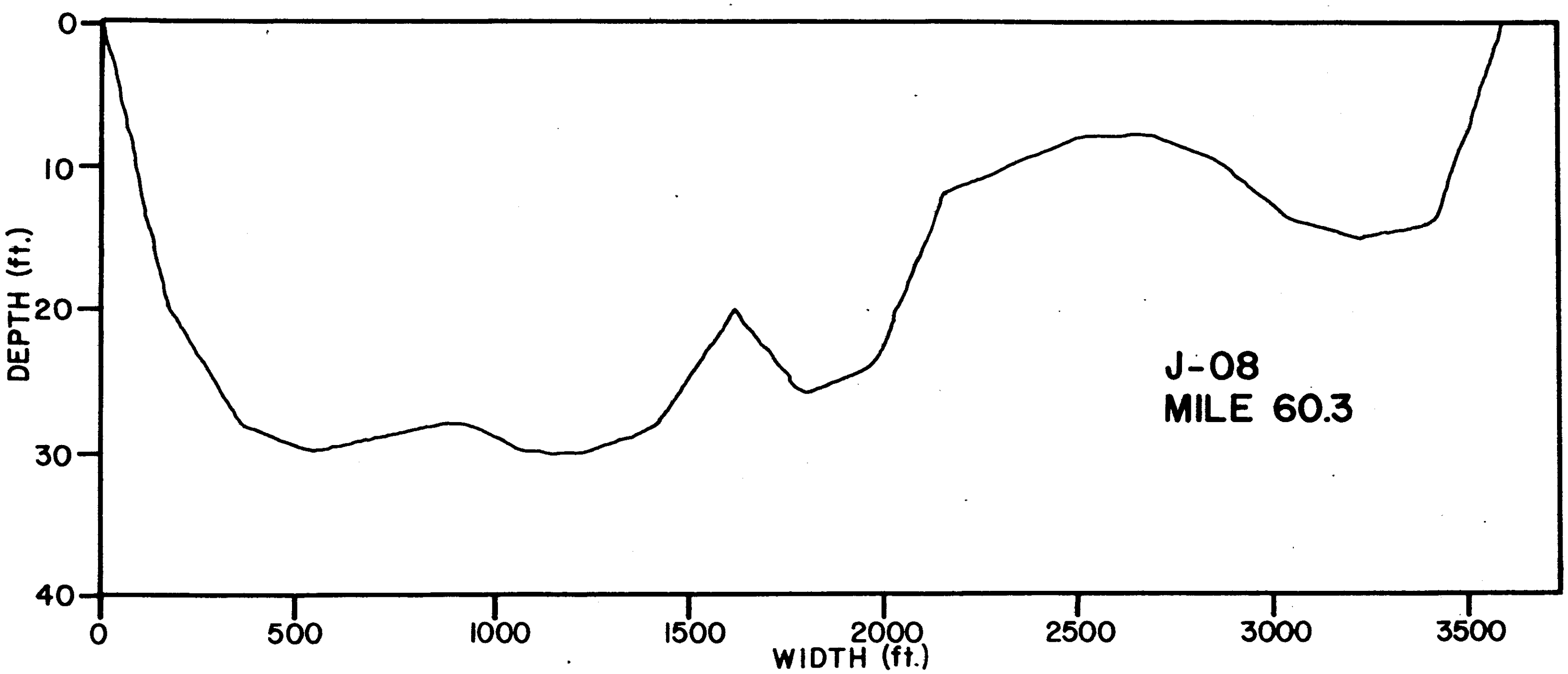

MILE 46.5
CLAREMONT WHF.
TIDE STATION
DEPTH (ft.)
WIDTH (ft.)
0
10
20
30
40
50
0
2000
4000
6000

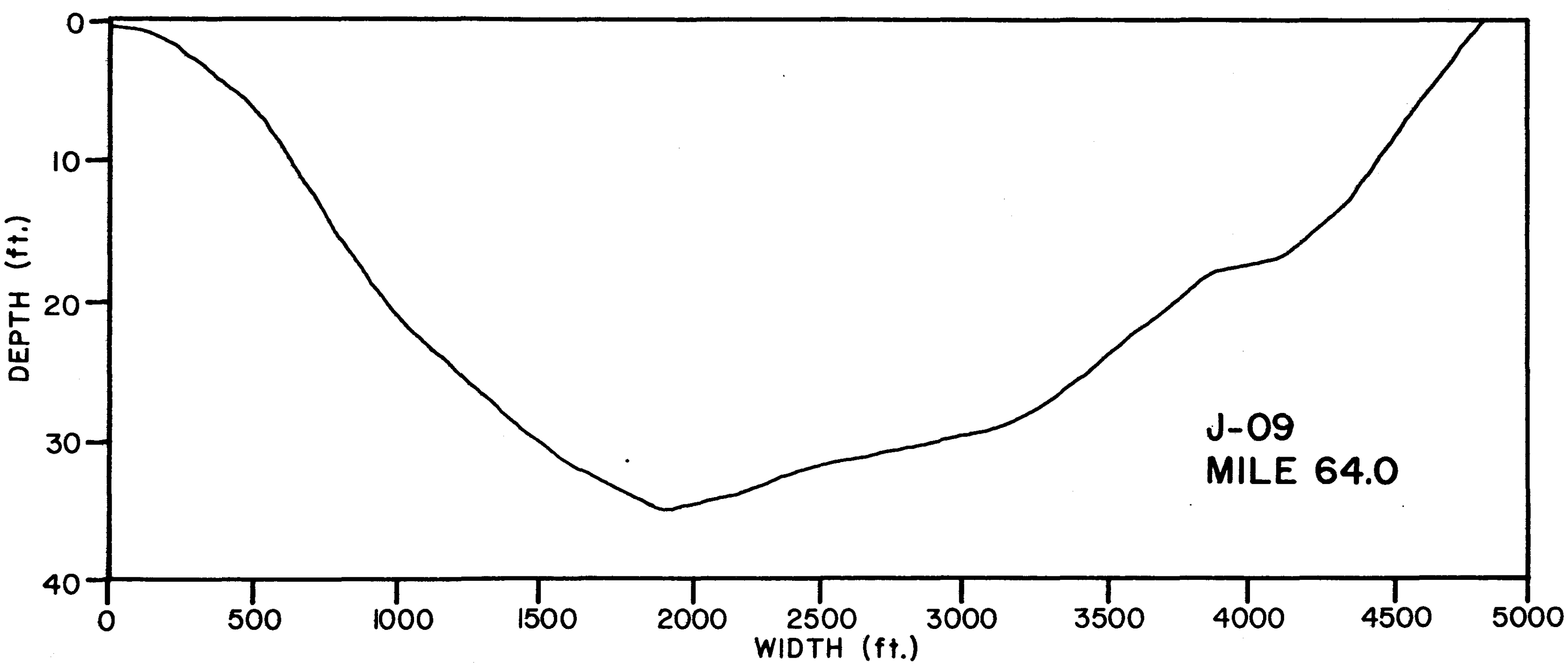

MILE 49.7
STURGEON PT.
TIDE STATION
DEPTH (ft.)
WIDTH (ft.)
0
10
20
30
40
50
0
500
1000
1500


J-07
MILE 52.8
DEPTH (ft.)
0
10
20
30
40
WIDTH (ft.)
0
500
1000
1500
2000
2500
3000
3500

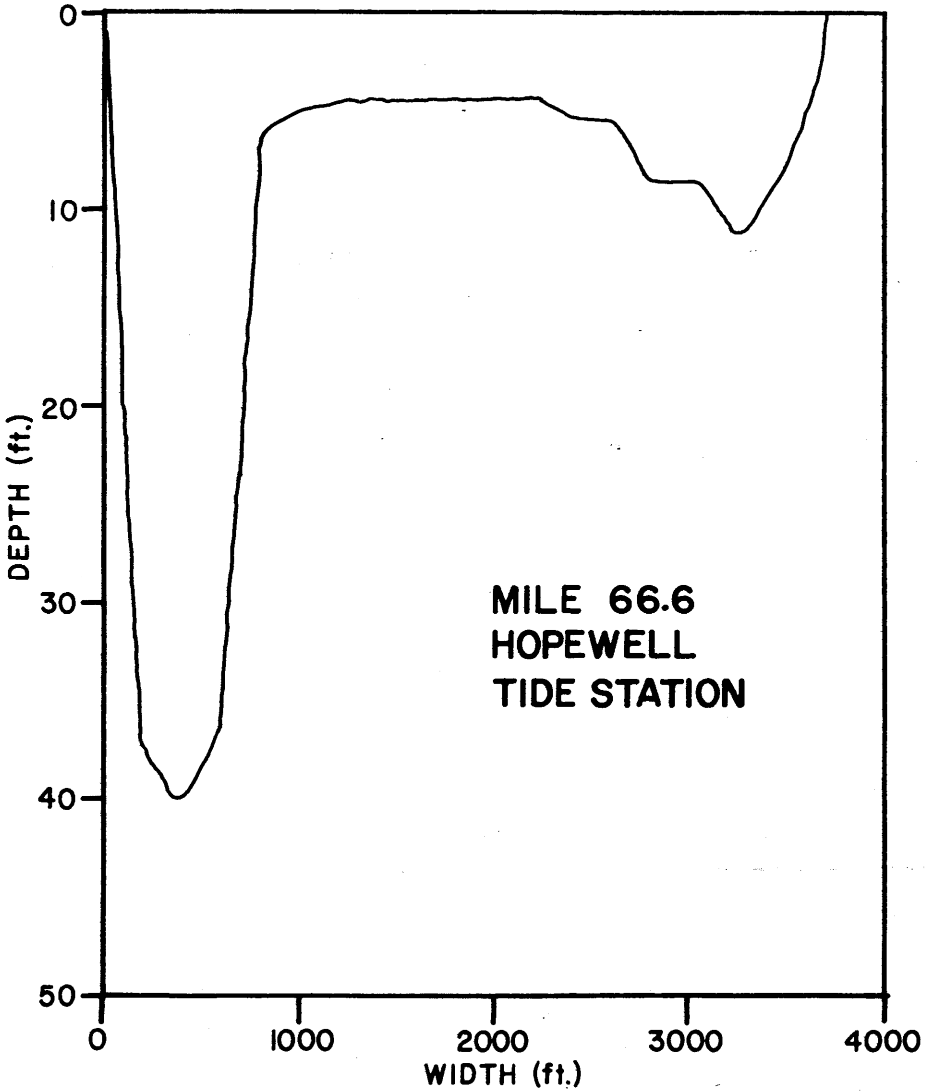

MILE 55.8
WINDMILL PT.
TIDE STATION
DEPTH (ft.)
WIDTH (ft.)
0
10
20
30
40
0
1000
2000
3000
4000

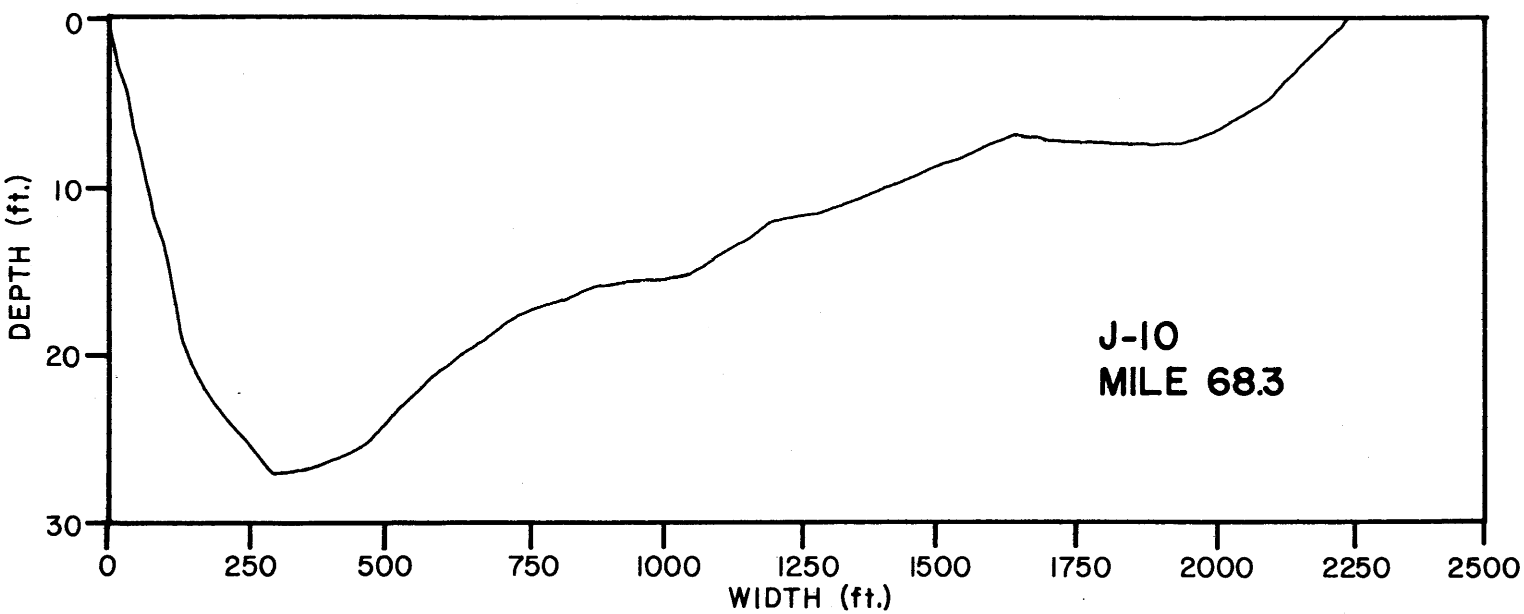

MILE 57.9
WINDMILL PT.
TIDE STATION
DEPTH (ft.)
WIDTH (ft.)
0
10
20
30
40
0
2000
4000
6000
8000

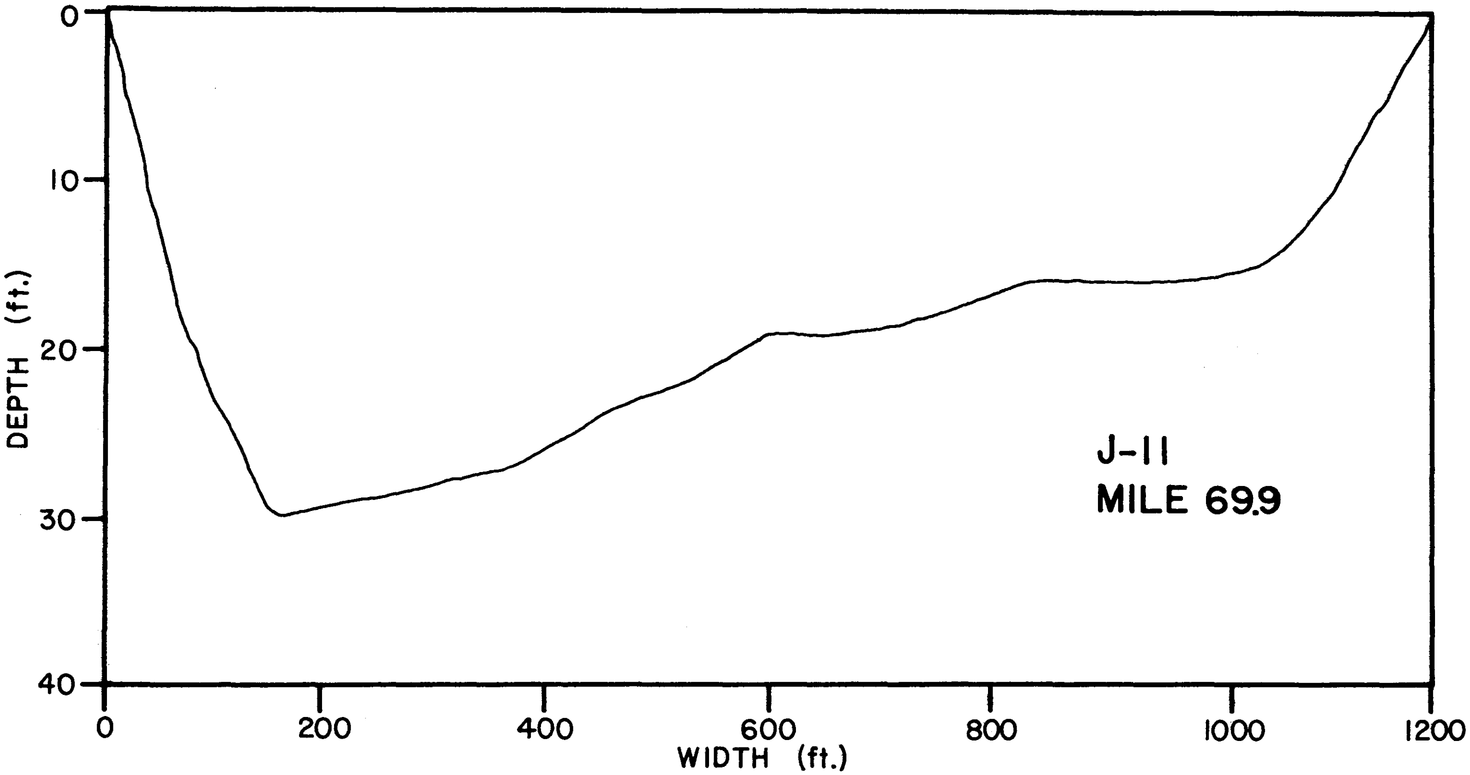

DEPTH (ft.)
0
10
20
30
40
WIDTH (ft.)
0
500
1000
1500
2000
2500
3000
3500
J-08
MILE 60.3

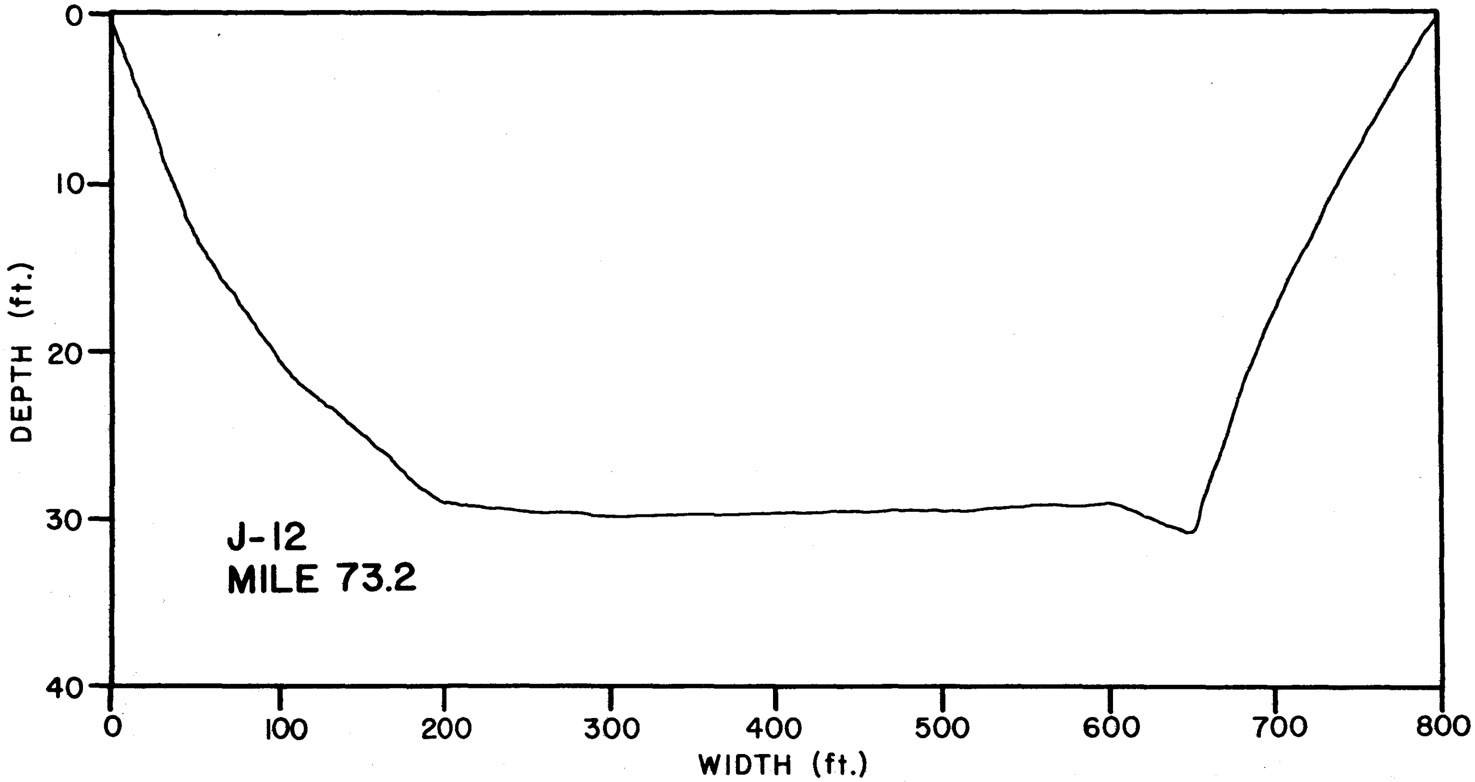


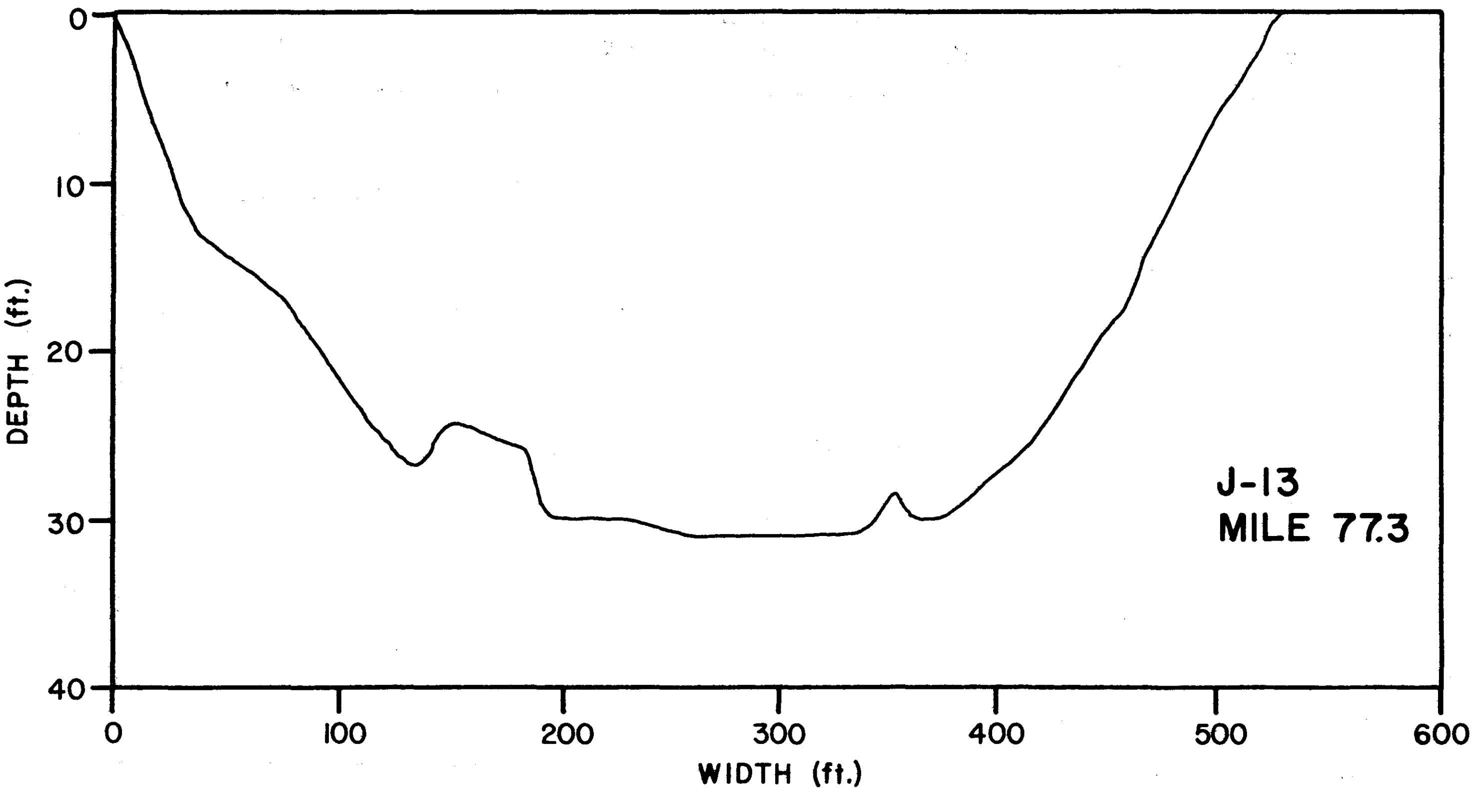
DEPTH (ft.)
0
10
20
30
40
WIDTH (ft.)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
J-09
MILE 64.0

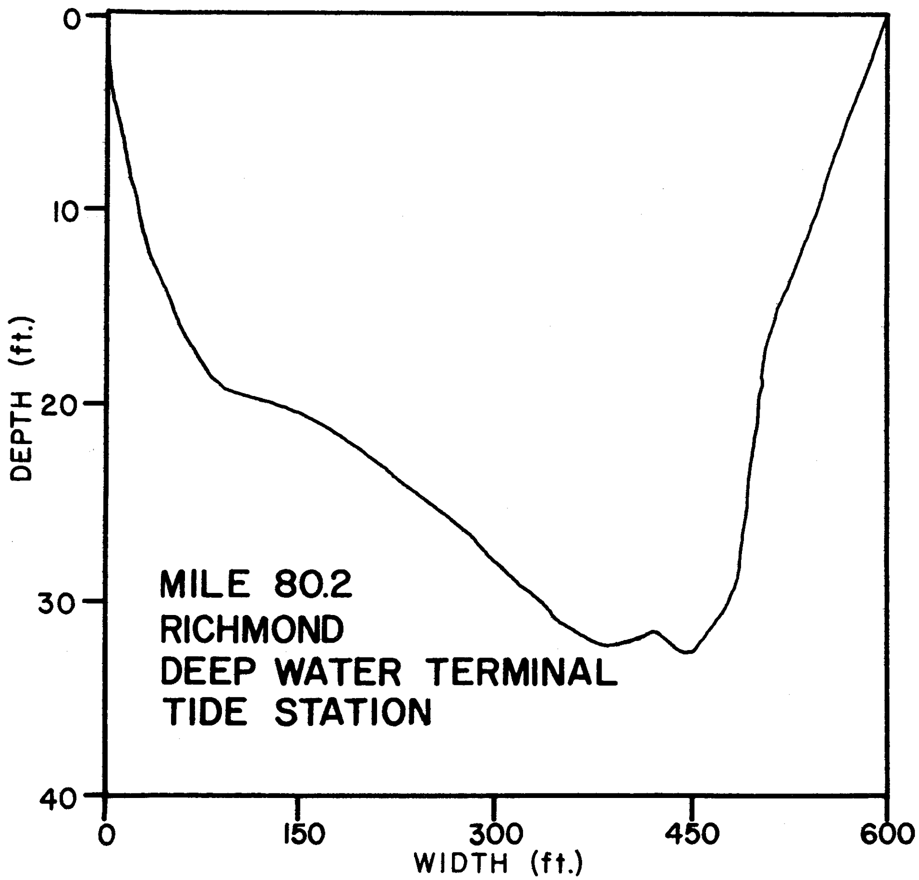

MILE 66.6
HOPEWELL
TIDE STATION
DEPTH (ft.)
WIDTH (ft.)
0
10
20
30
40
50
0
1000
2000
3000
4000

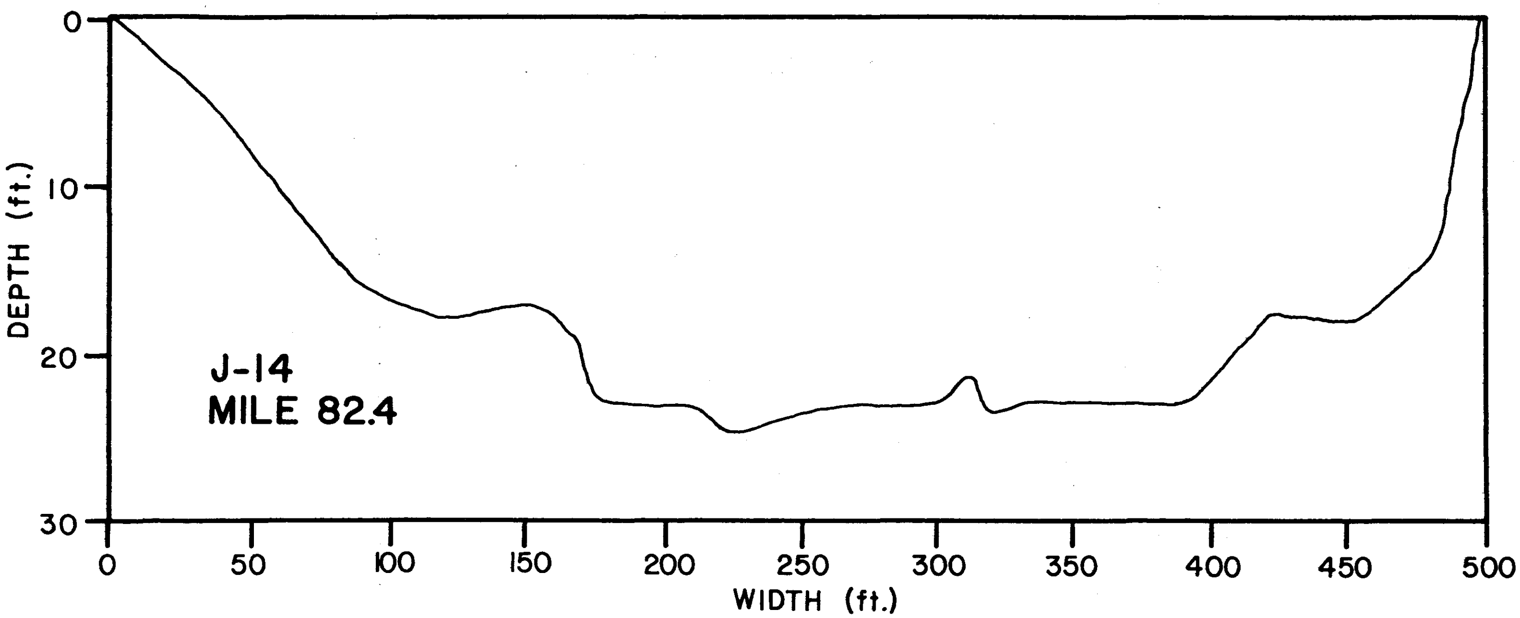

J-10
MILE 68.3
DEPTH (ft.)
0
10
20
30
WIDTH (ft.)
0
250
500
750
1000
1250
1500
1750
2000
2250
2500


J-11
MILE 69.9
DEPTH (ft.)
WIDTH (ft.)
0
10
20
30
40
0
200
400
600
800
1000
1200


J-12
MILE 73.2
DEPTH (ft.)
0
10
20
30
40
WIDTH (ft.)
0
100
200
300
400
500
600
700
800

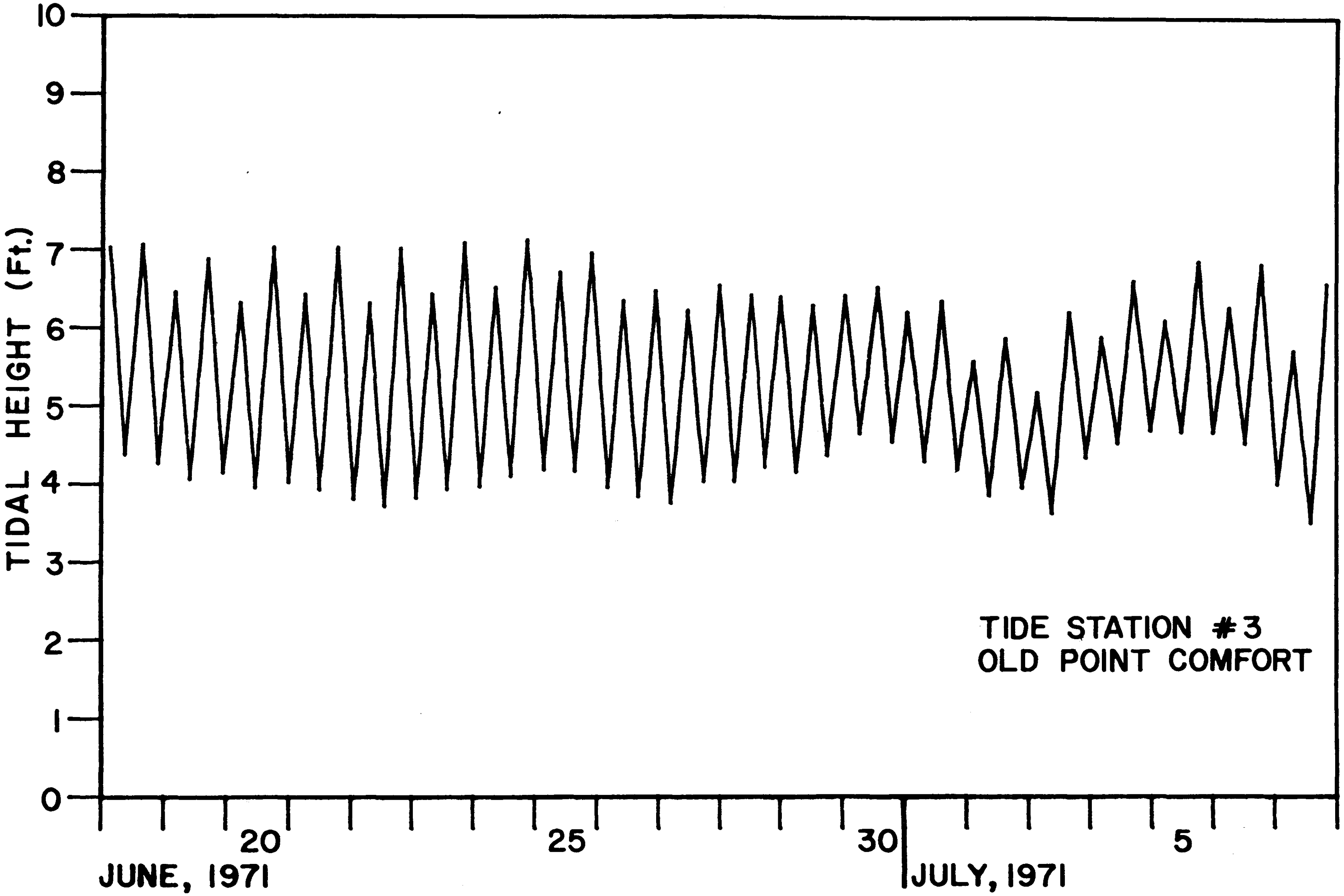

DEPTH (ft.)
0
10
20
30
40
WIDTH (ft.)
0
100
200
300
400
500
600
J-13
MILE 77.3

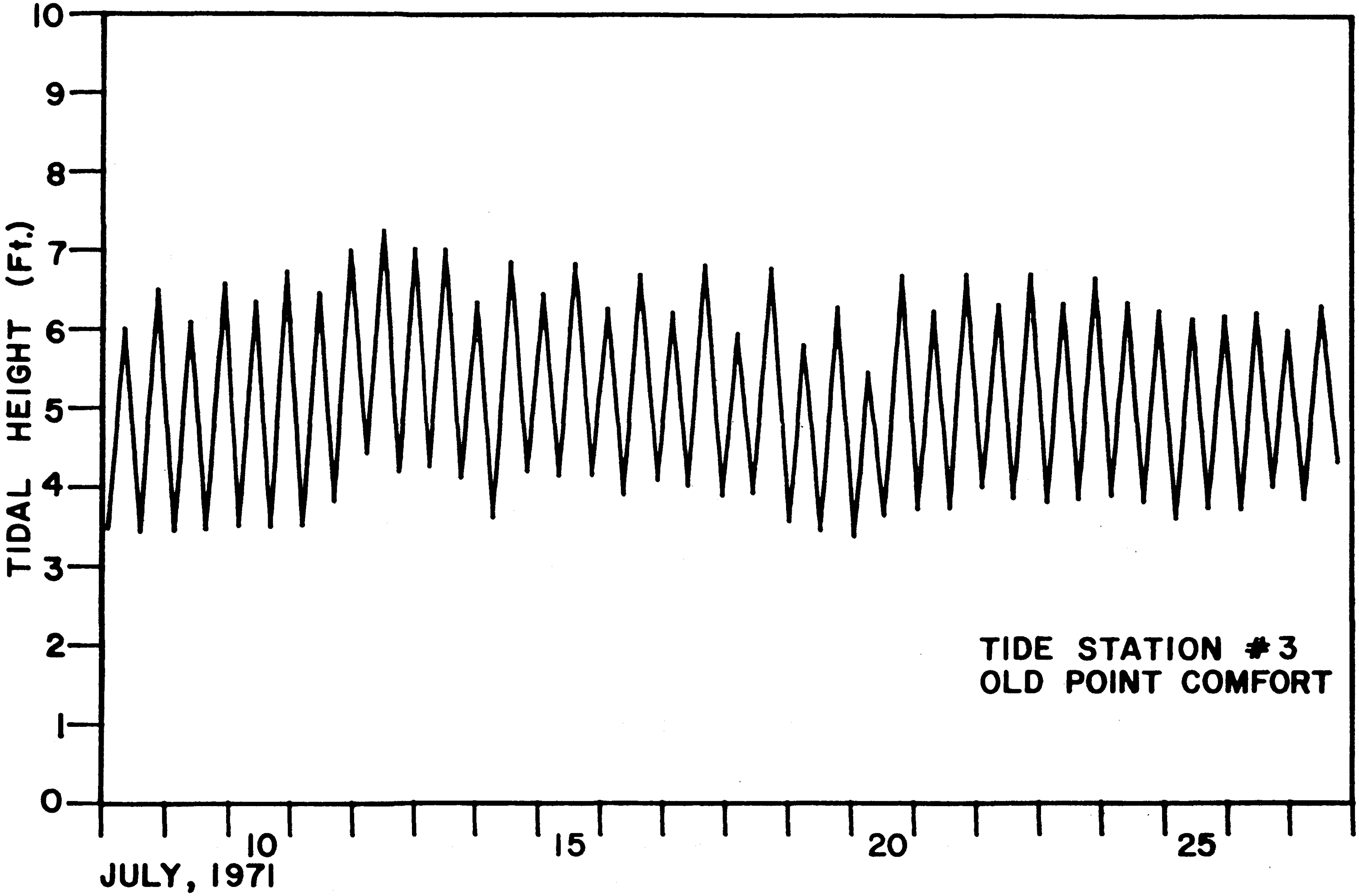

MILE 80.2
RICHMOND
DEEP WATER TERMINAL
TIDE STATION
DEPTH (ft.)
WIDTH (ft.)
0
10
20
30
40
0
150
300
450
600


J-14
MILE 82.4
DEPTH (ft.)
0
10
20
30
WIDTH (ft.)
0
50
100
150
200
250
300
350
400
450
500

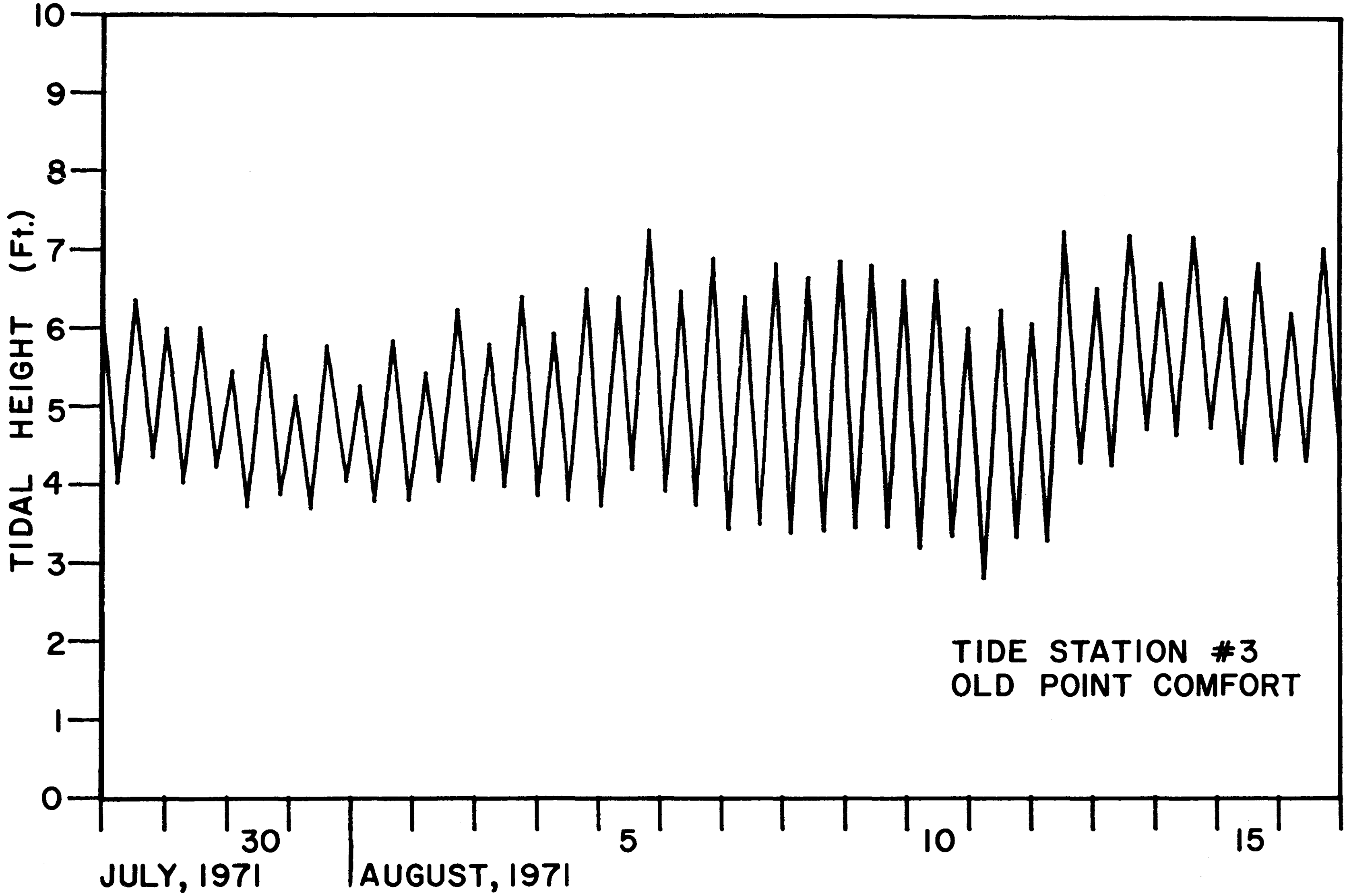
APPENDIX C

Tidal Observations

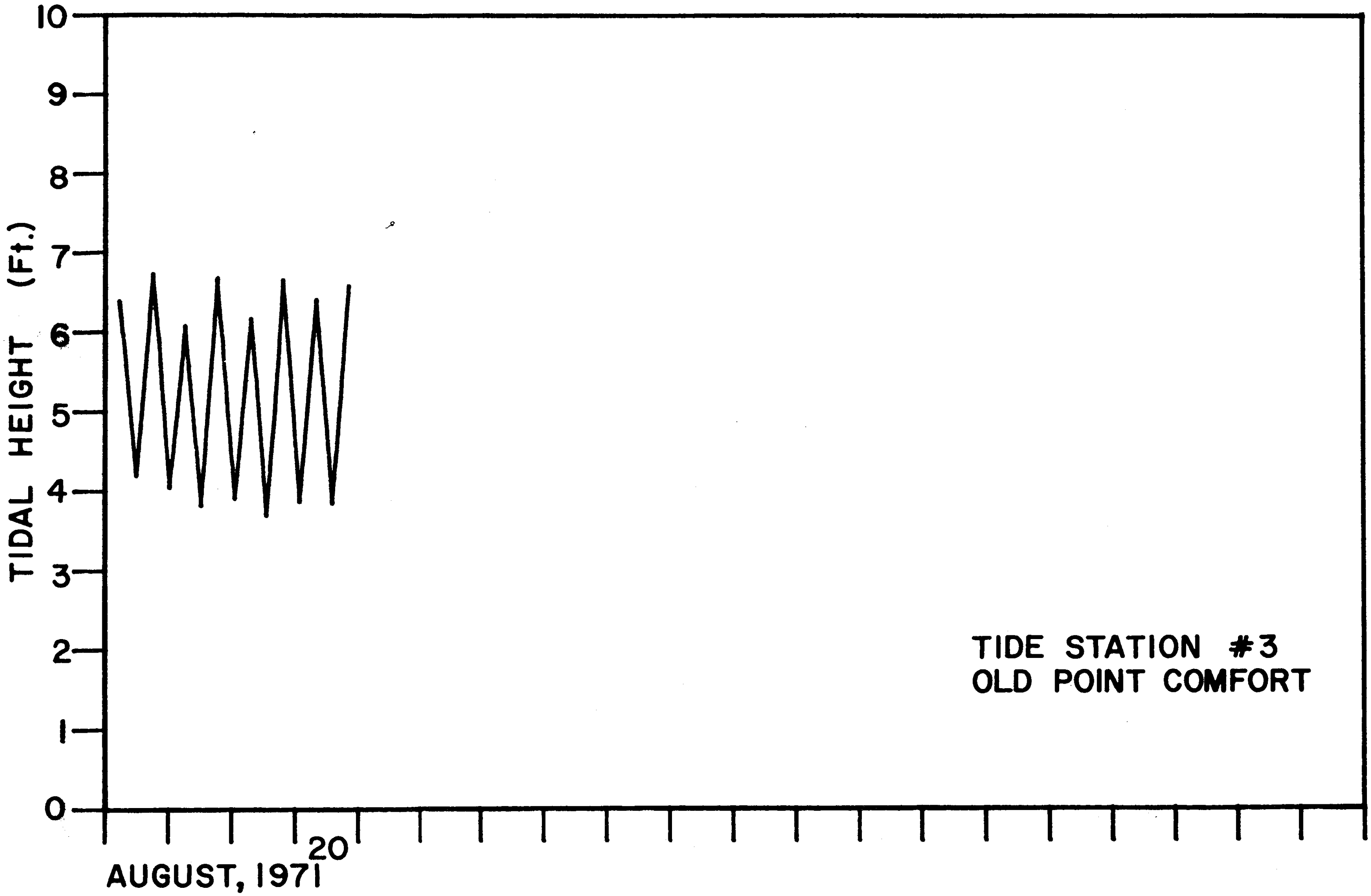

TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
20
25
30
5
JUNE, 1971
JULY, 1971
TIDE STATION #3
OLD POINT COMFORT

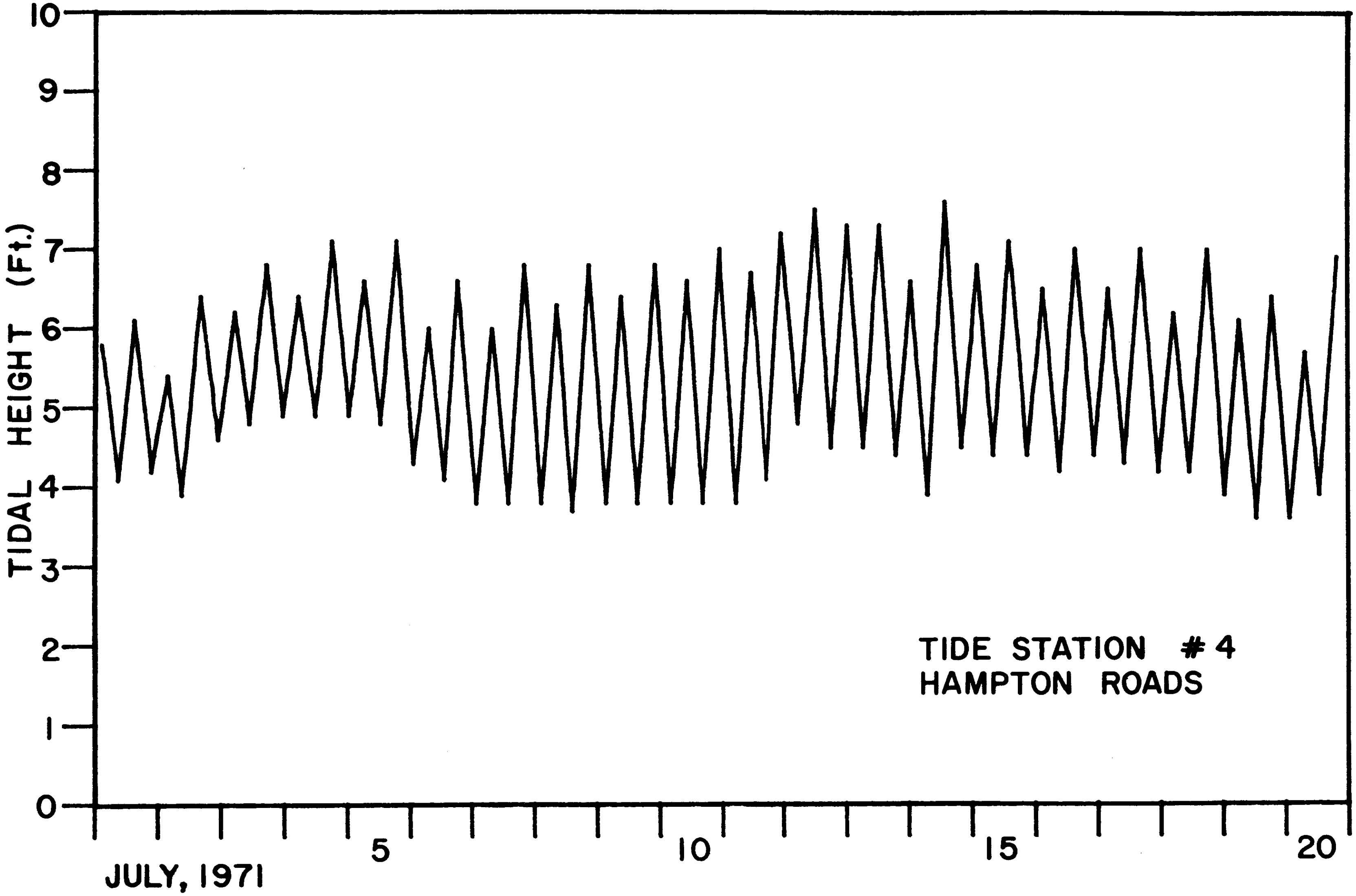


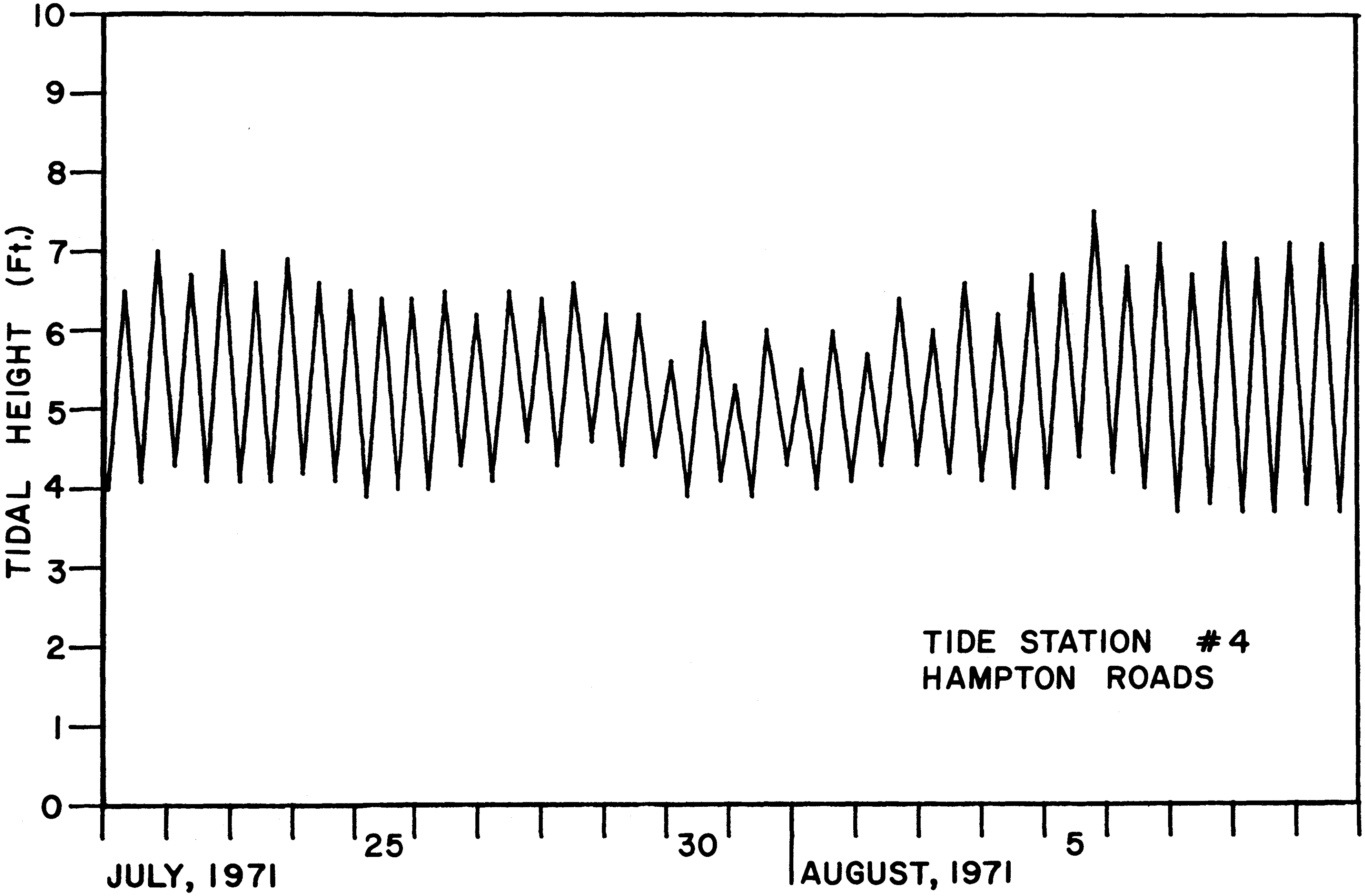
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
25
JULY, 1971
TIDE STATION #3
OLD POINT COMFORT

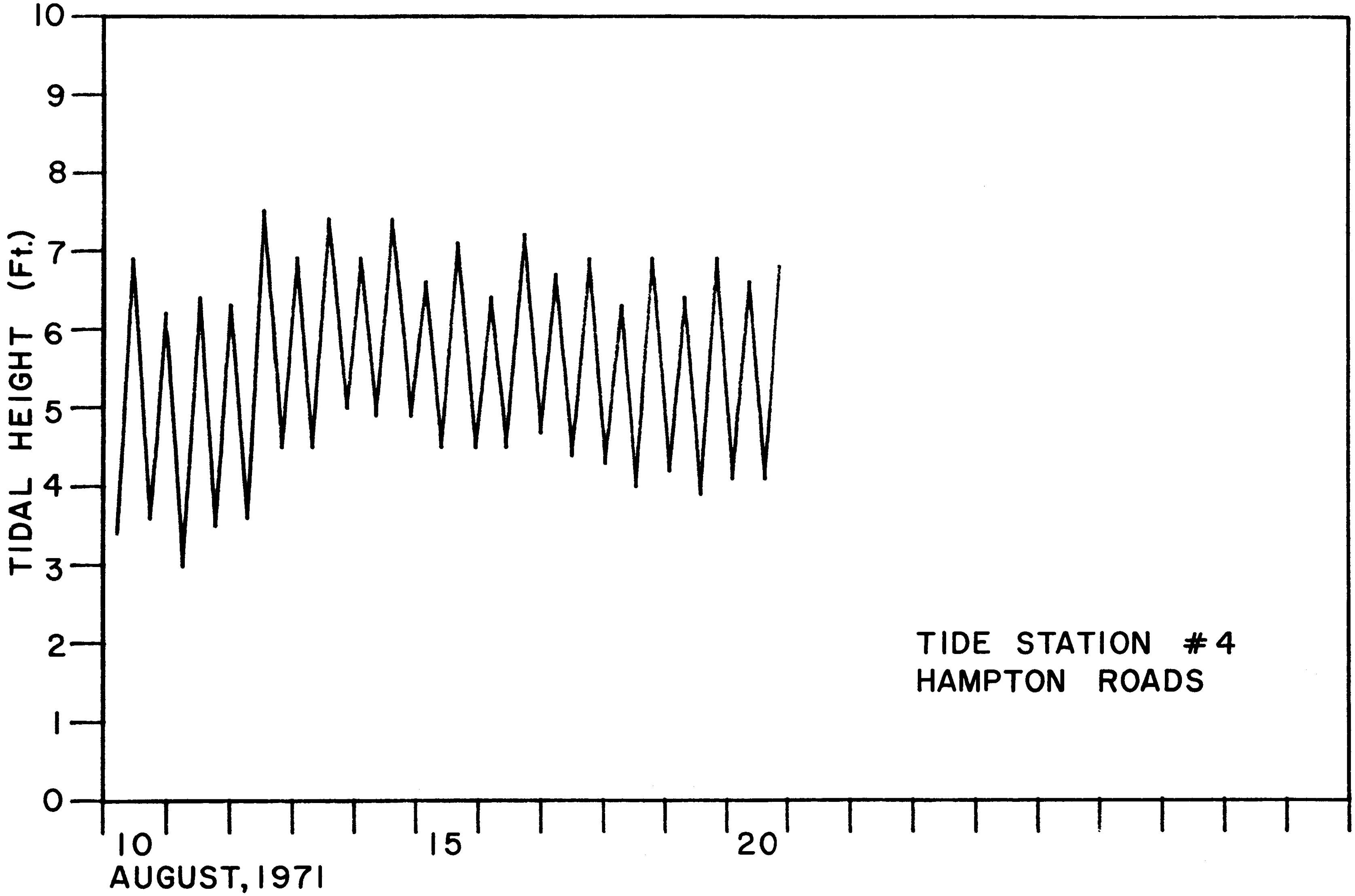


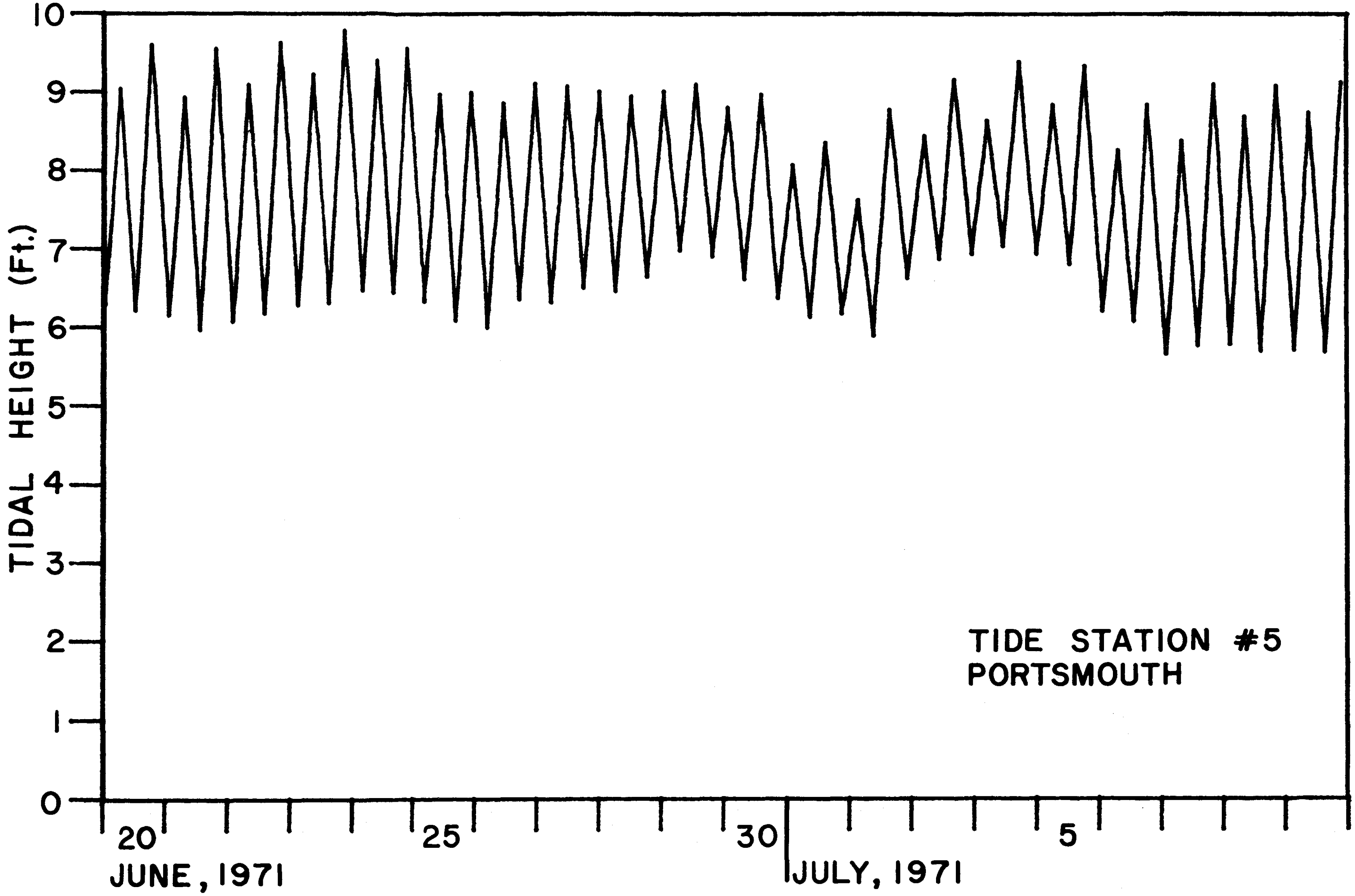
10
9
8
7
6
5
4
3
2
1
0
TIDAL HEIGHT (Ft.)
TIDE STATION #3
OLD POINT COMFORT
30
5
10
15
JULY, 1971
AUGUST, 1971

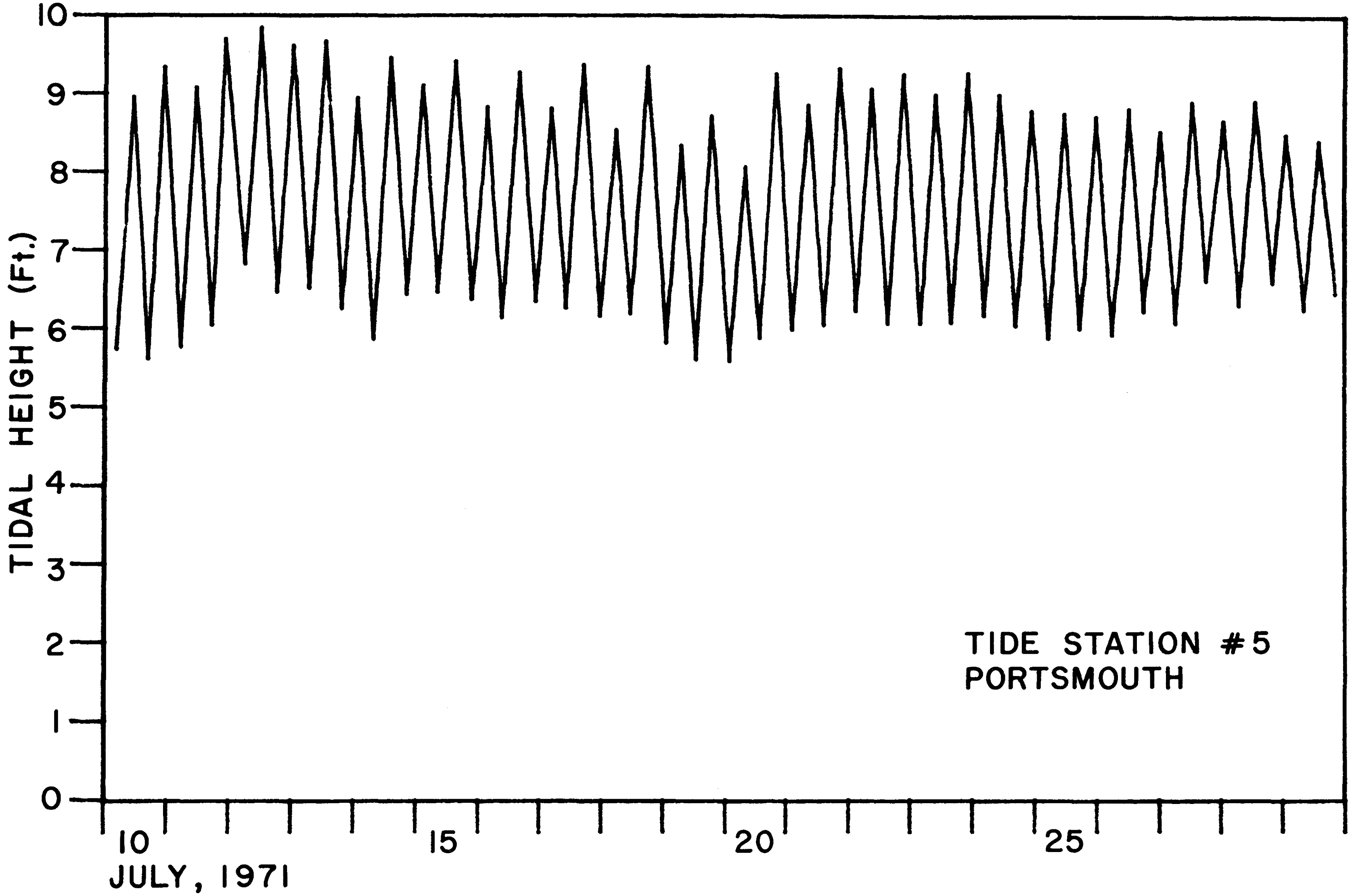

10
9
8
7
6
5
4
3
2
1
0
TIDAL HEIGHT (Ft.)
20
AUGUST, 1971
TIDE STATION #3
OLD POINT COMFORT

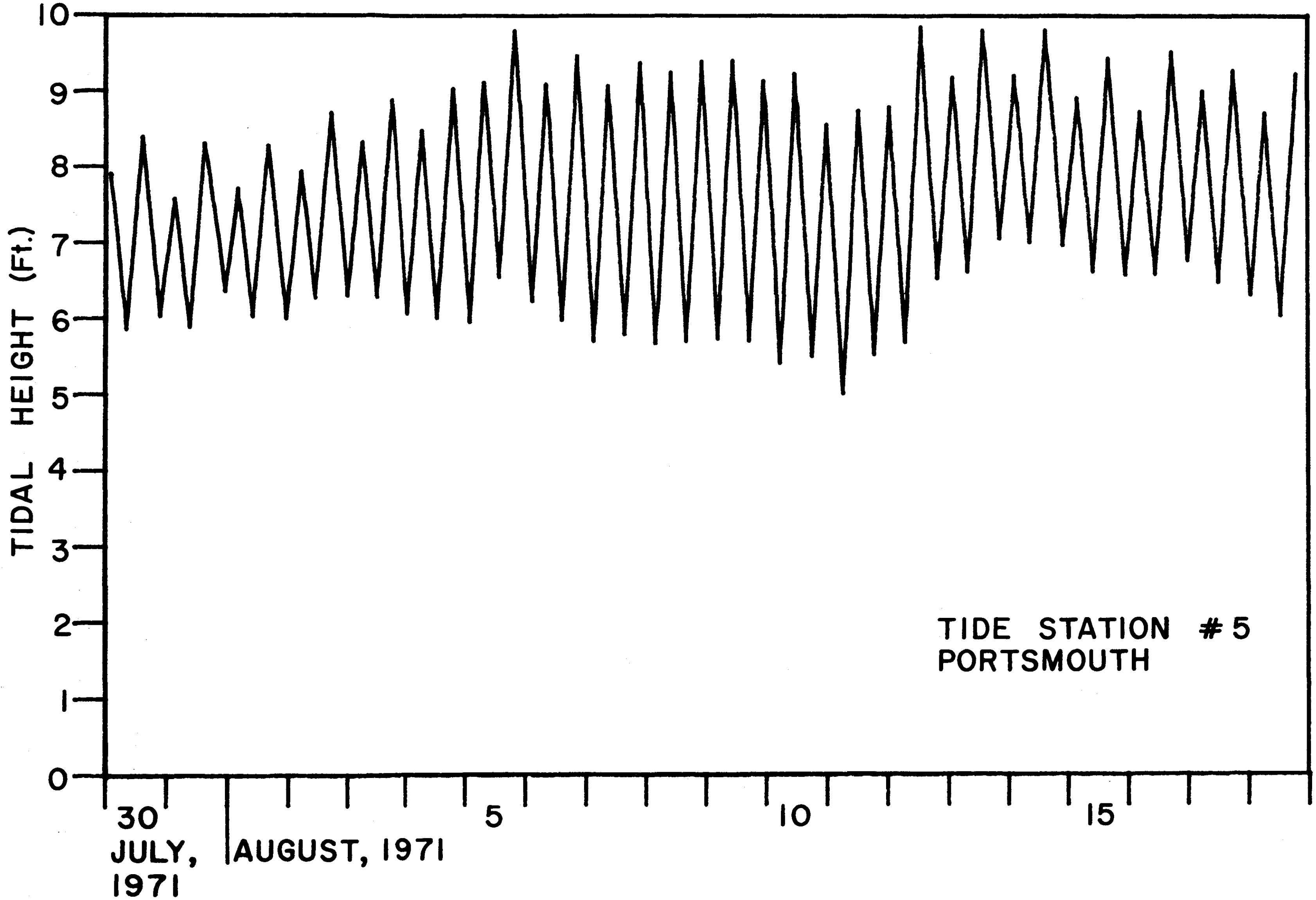

TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
5
10
15
20
JULY, 1971
TIDE STATION # 4
HAMPTON ROADS


TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
25
30
5
JULY, 1971
AUGUST, 1971
TIDE STATION #4
HAMPTON ROADS

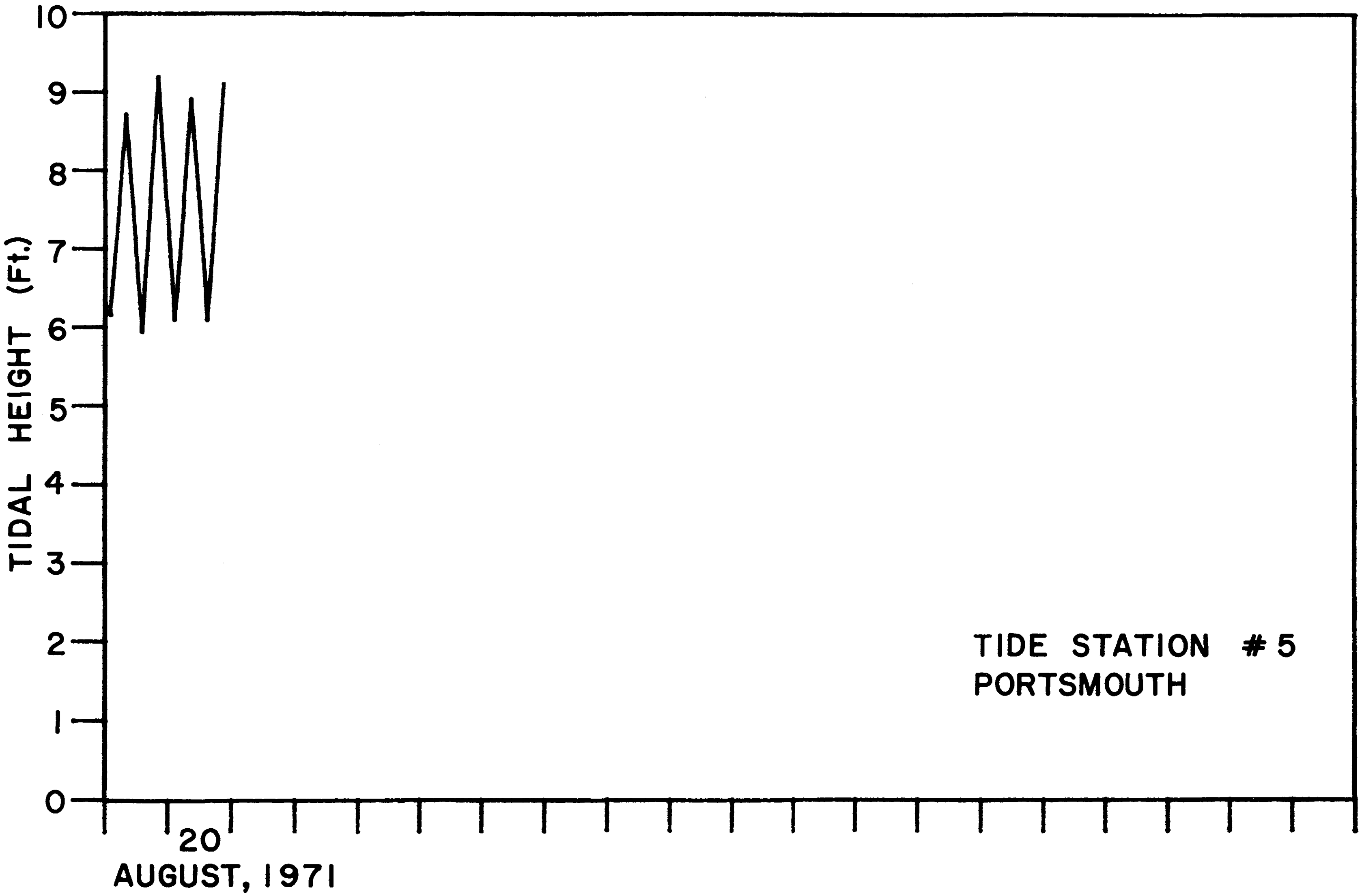

TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
AUGUST, 1971
TIDE STATION #4
HAMPTON ROADS

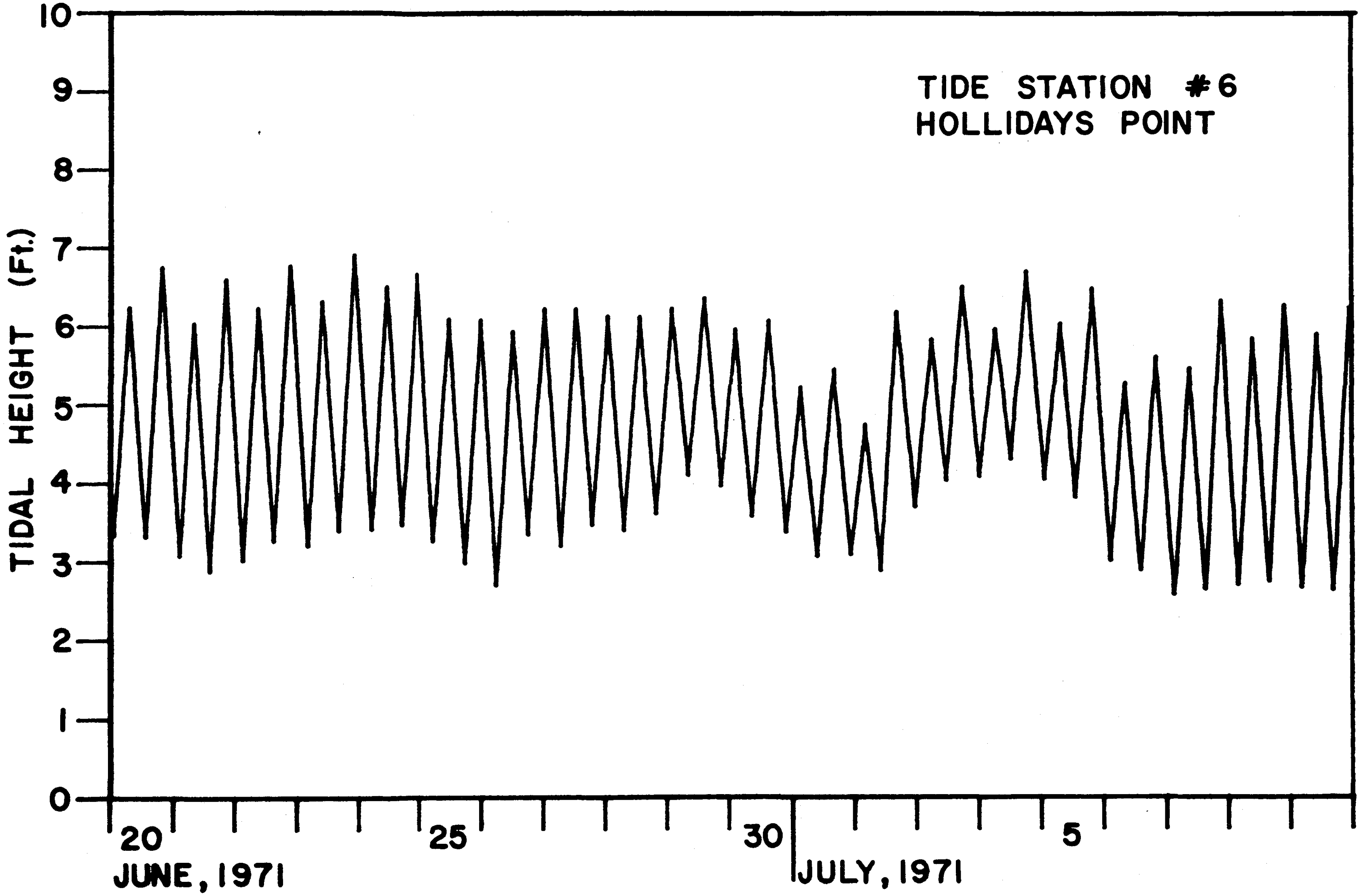

10
9
8
7
6
5
4
3
2
1
0
TIDAL HEIGHT (Ft.)
20
25
30
5
JUNE, 1971
JULY, 1971
TIDE STATION #5
PORTSMOUTH

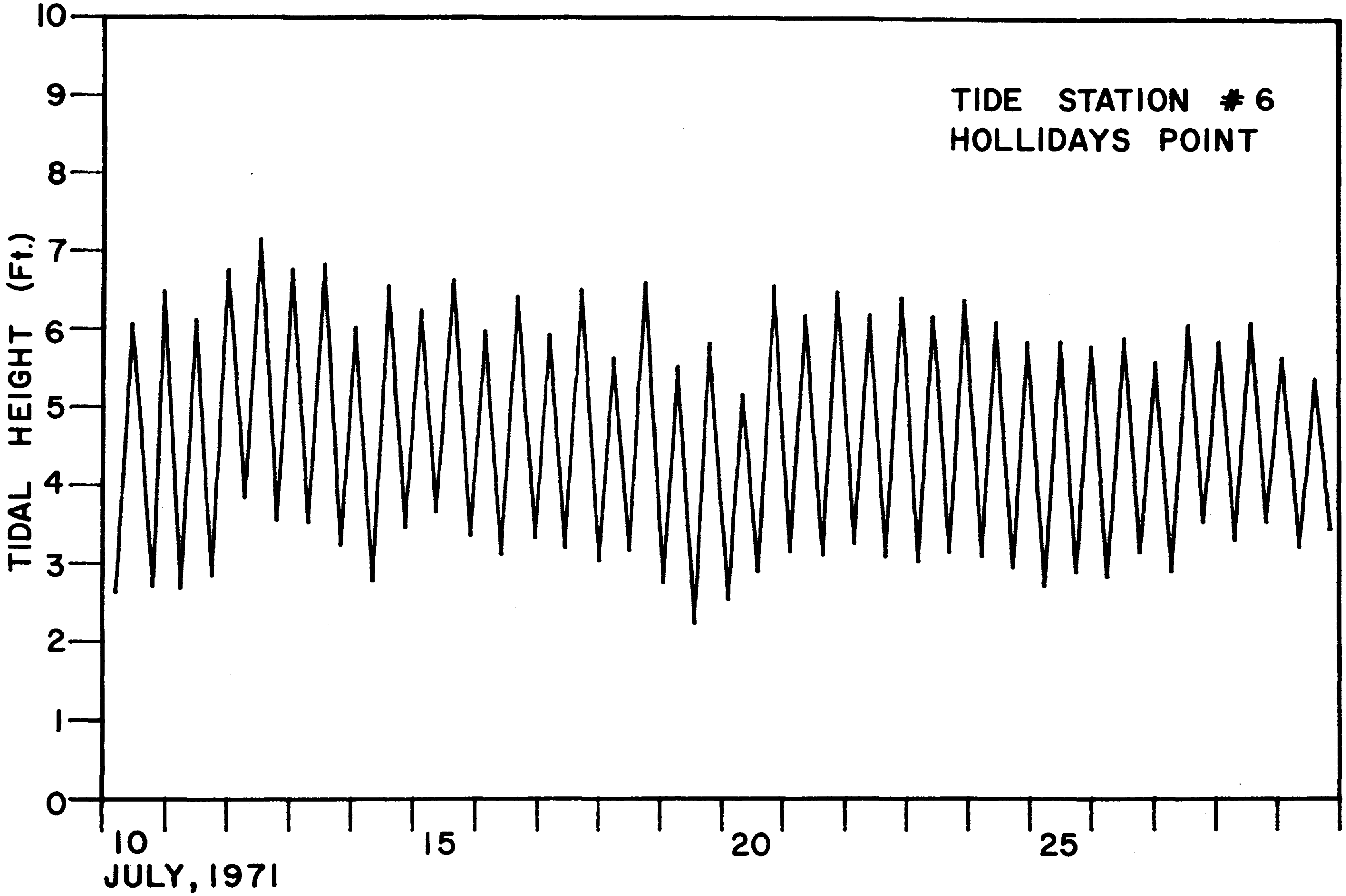

TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
25
JULY, 1971
TIDE STATION #5
PORTSMOUTH

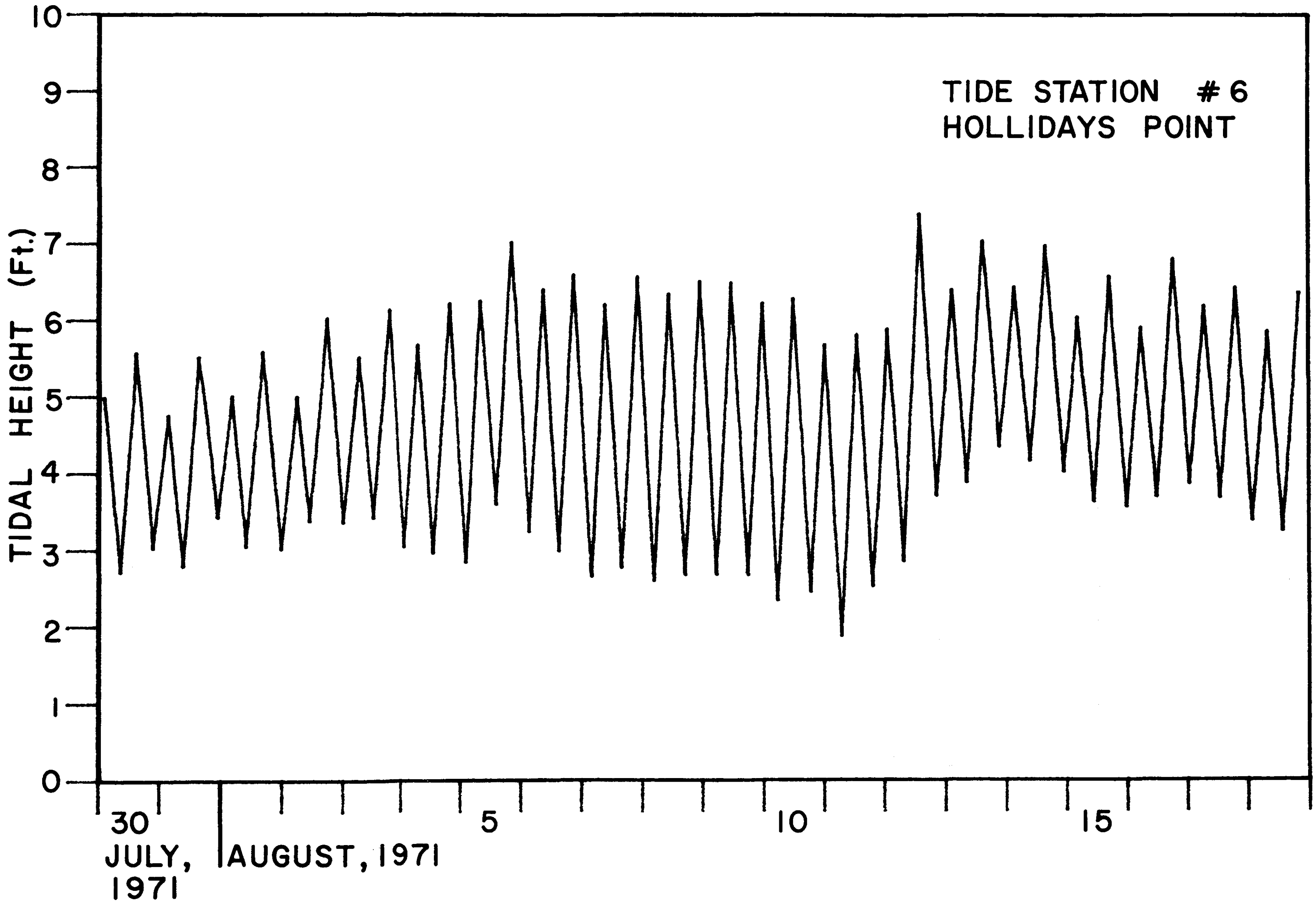


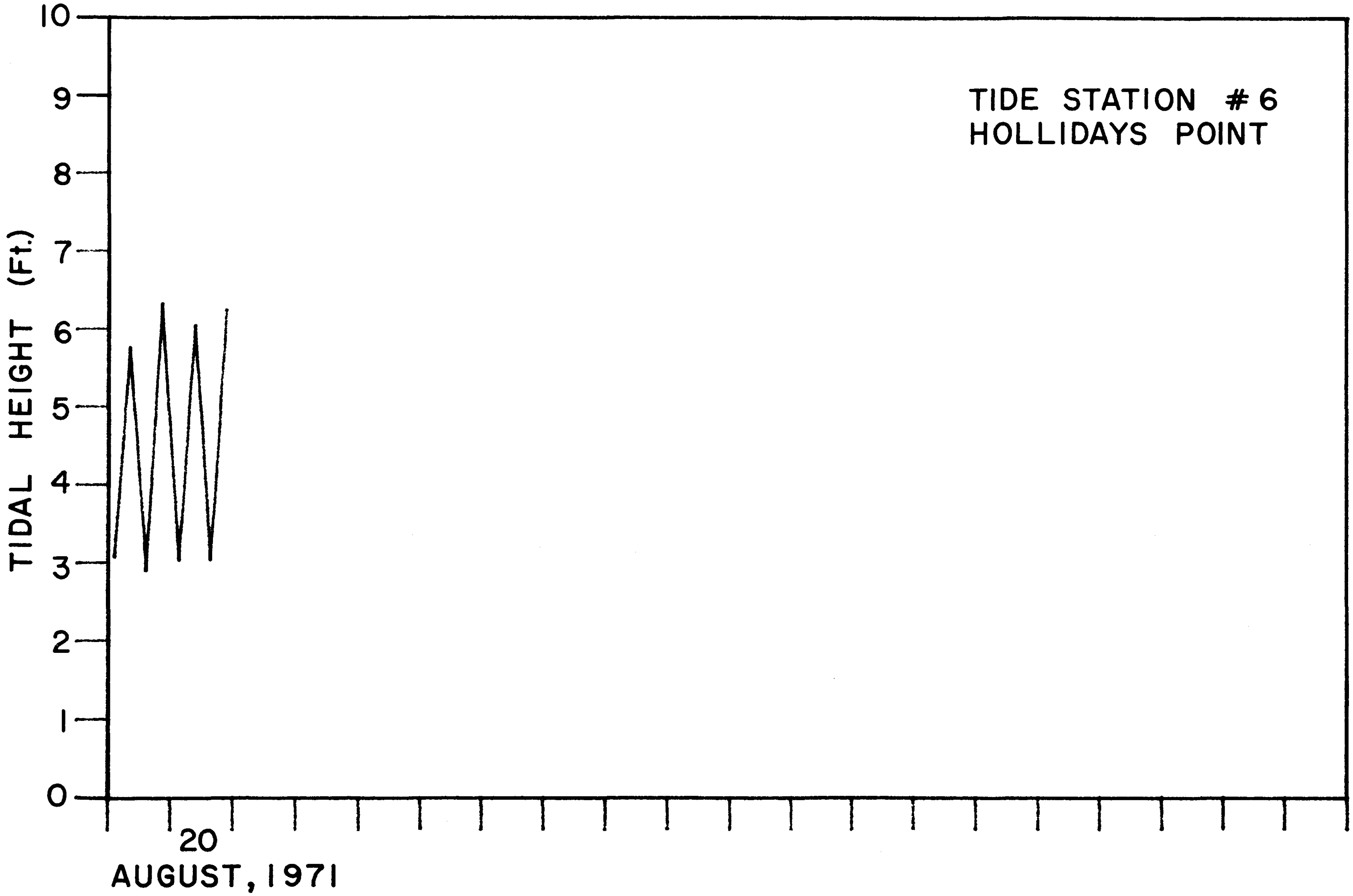
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
TIDE STATION # 5
PORTSMOUTH
30
5
10
15
JULY,
1971
AUGUST, 1971

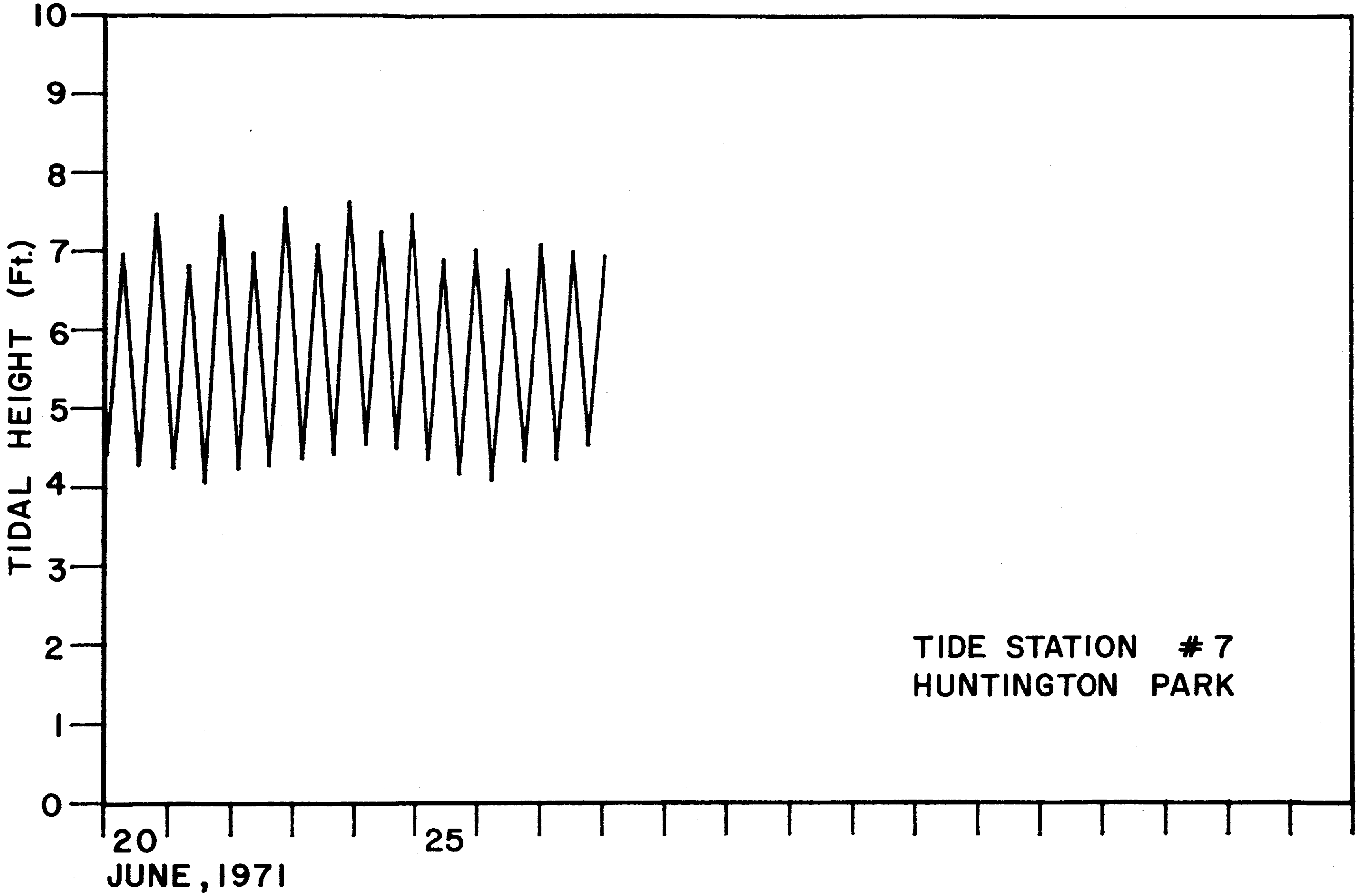

TIDAL HEIGHT (Ft.)
10
9
8
7
6
5
4
3
2
1
0
20
AUGUST, 1971
TIDE STATION # 5
PORTSMOUTH

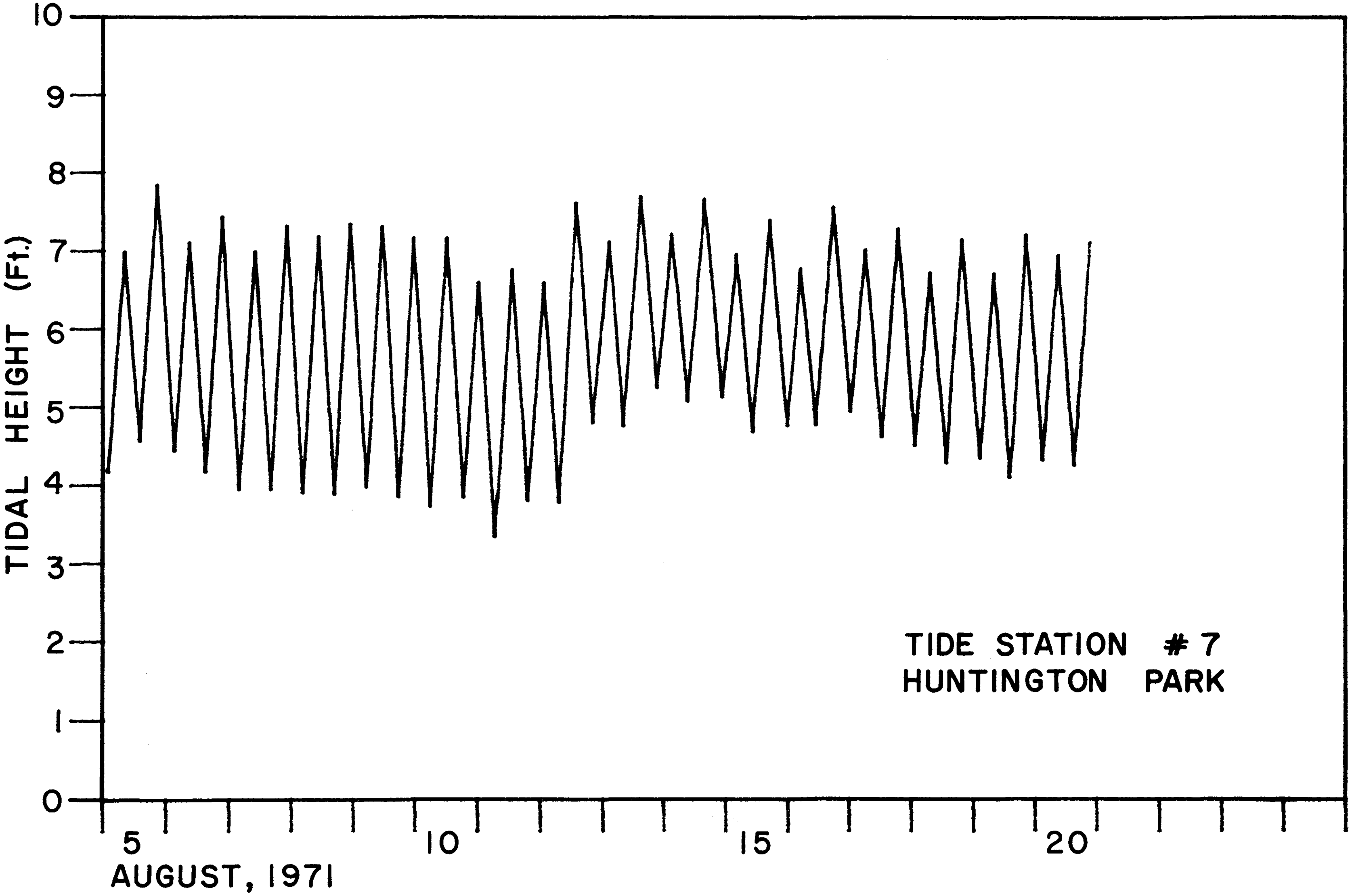

TIDE STATION #6
HOLLIDAYS POINT
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
20
25
30
5
JUNE, 1971
JULY, 1971

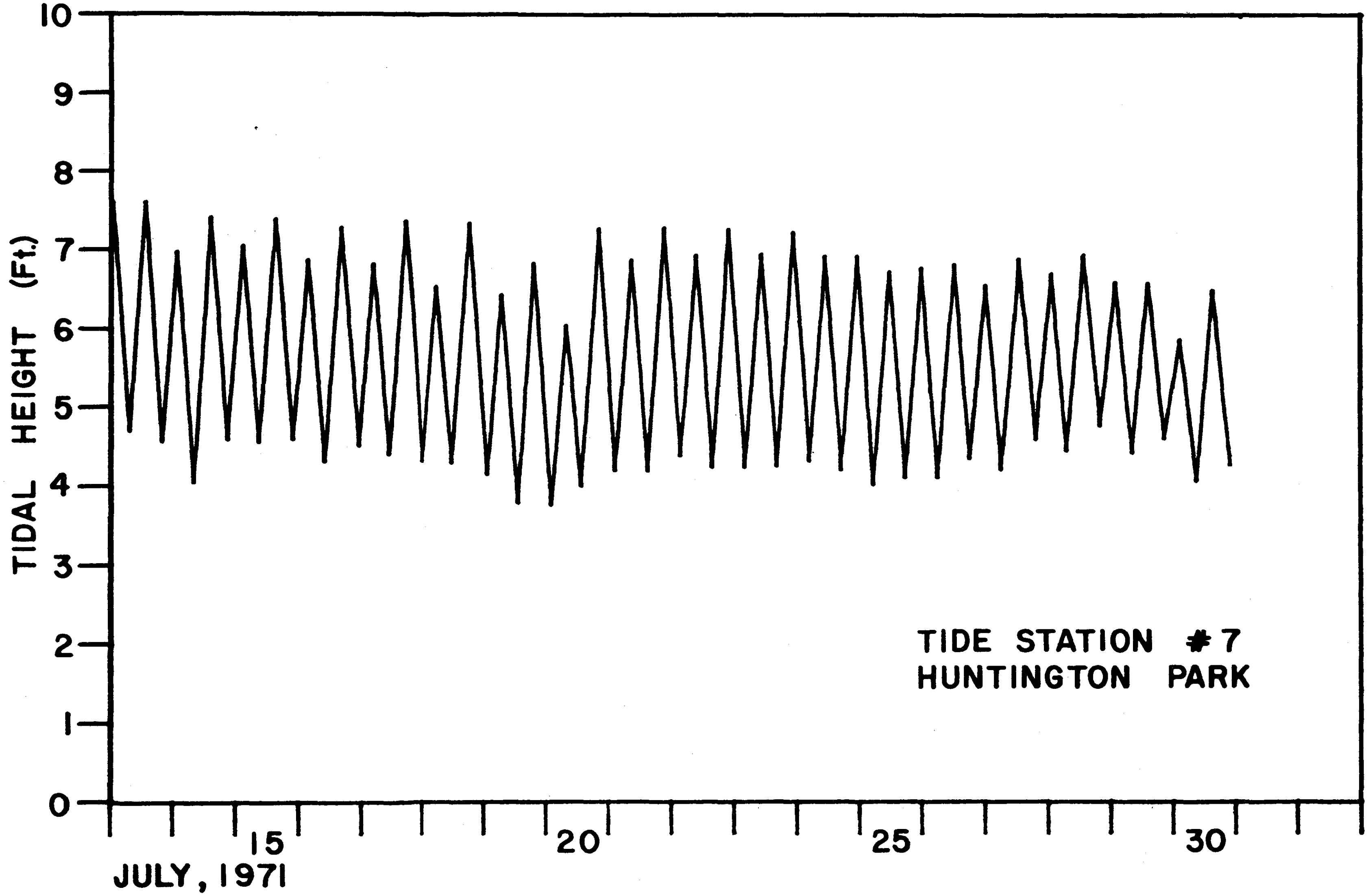

TIDE STATION # 6
HOLLIDAYS POINT
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
25
JULY, 1971

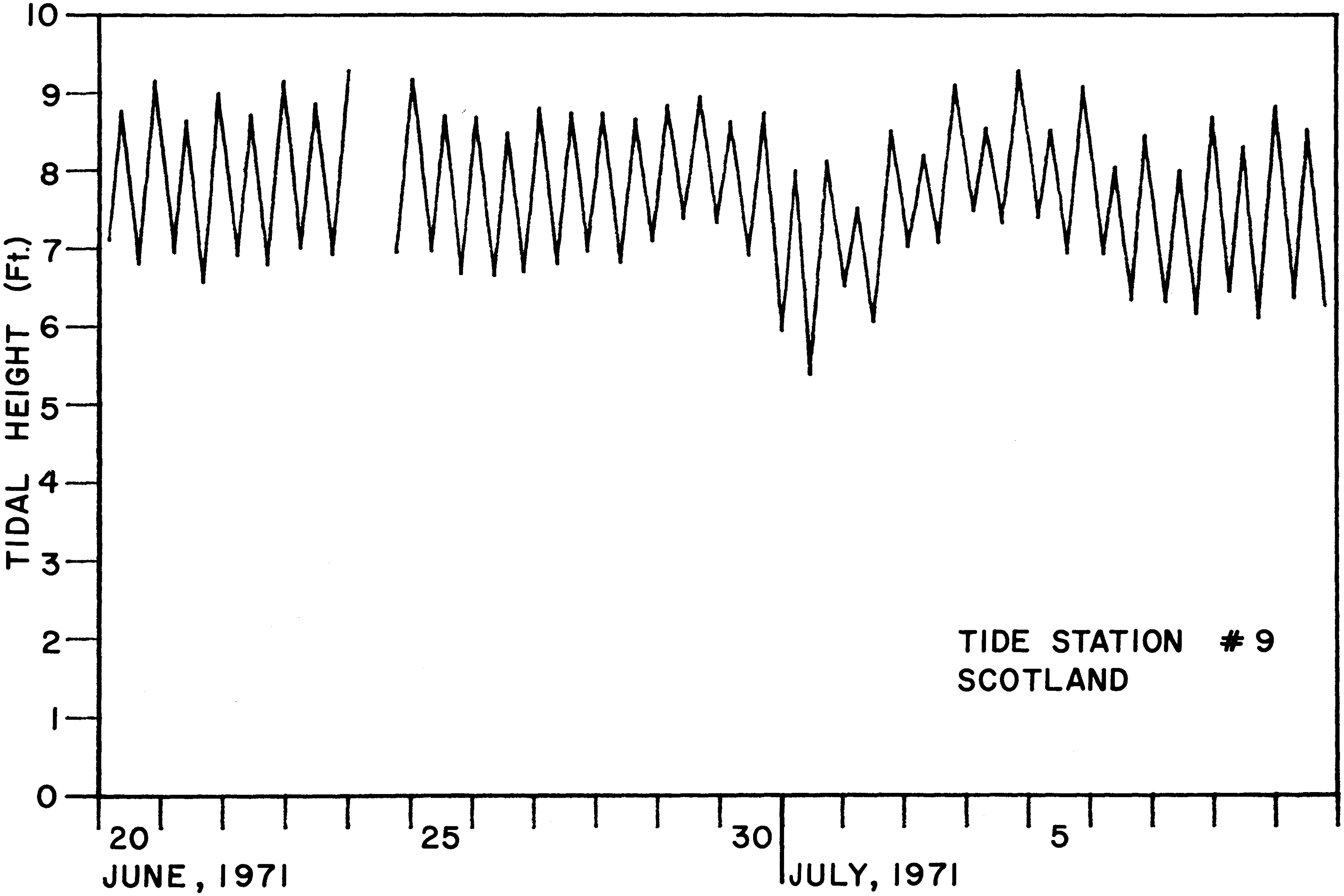

TIDE STATION # 6
HOLLIDAYS POINT
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
30
5
10
15
JULY, 1971
AUGUST, 1971

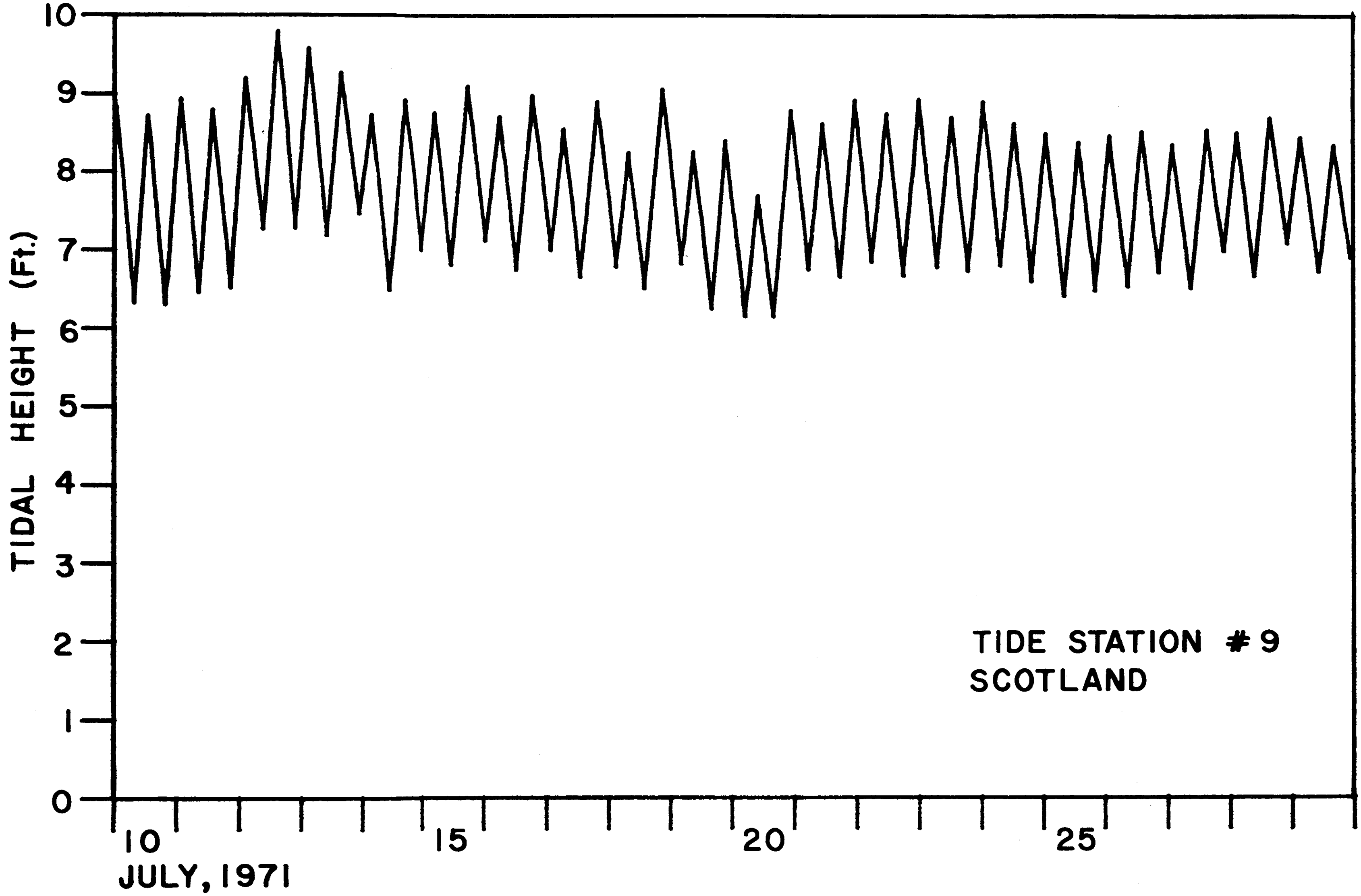

TIDE STATION # 6
HOLLIDAYS POINT
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
20
AUGUST, 1971

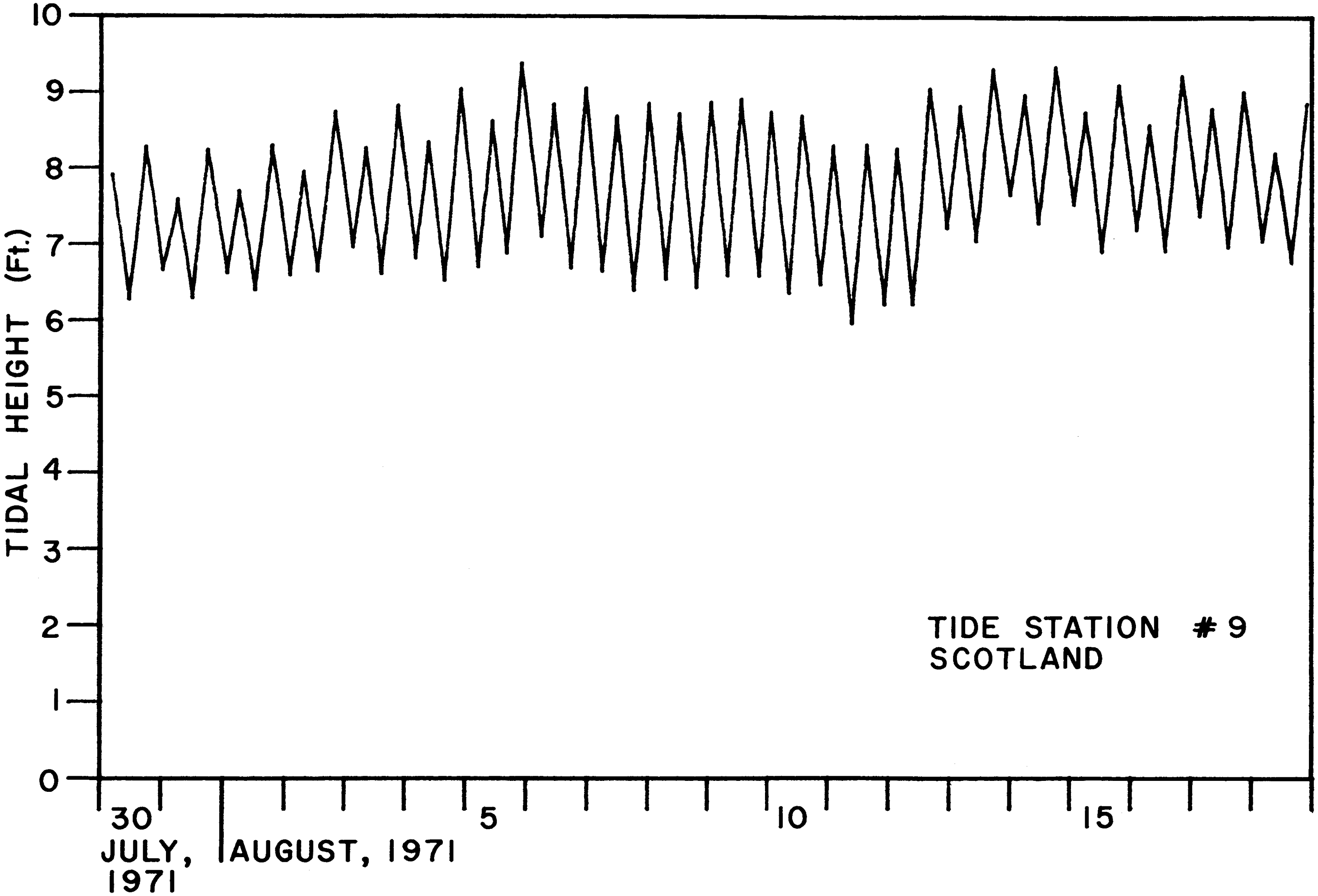

TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
20
25
JUNE, 1971
TIDE STATION # 7
HUNTINGTON PARK


TIDAL HEIGHT (Ft.)
10
9
8
7
6
5
4
3
2
1
0
5
10
15
20
AUGUST, 1971
TIDE STATION # 7
HUNTINGTON PARK

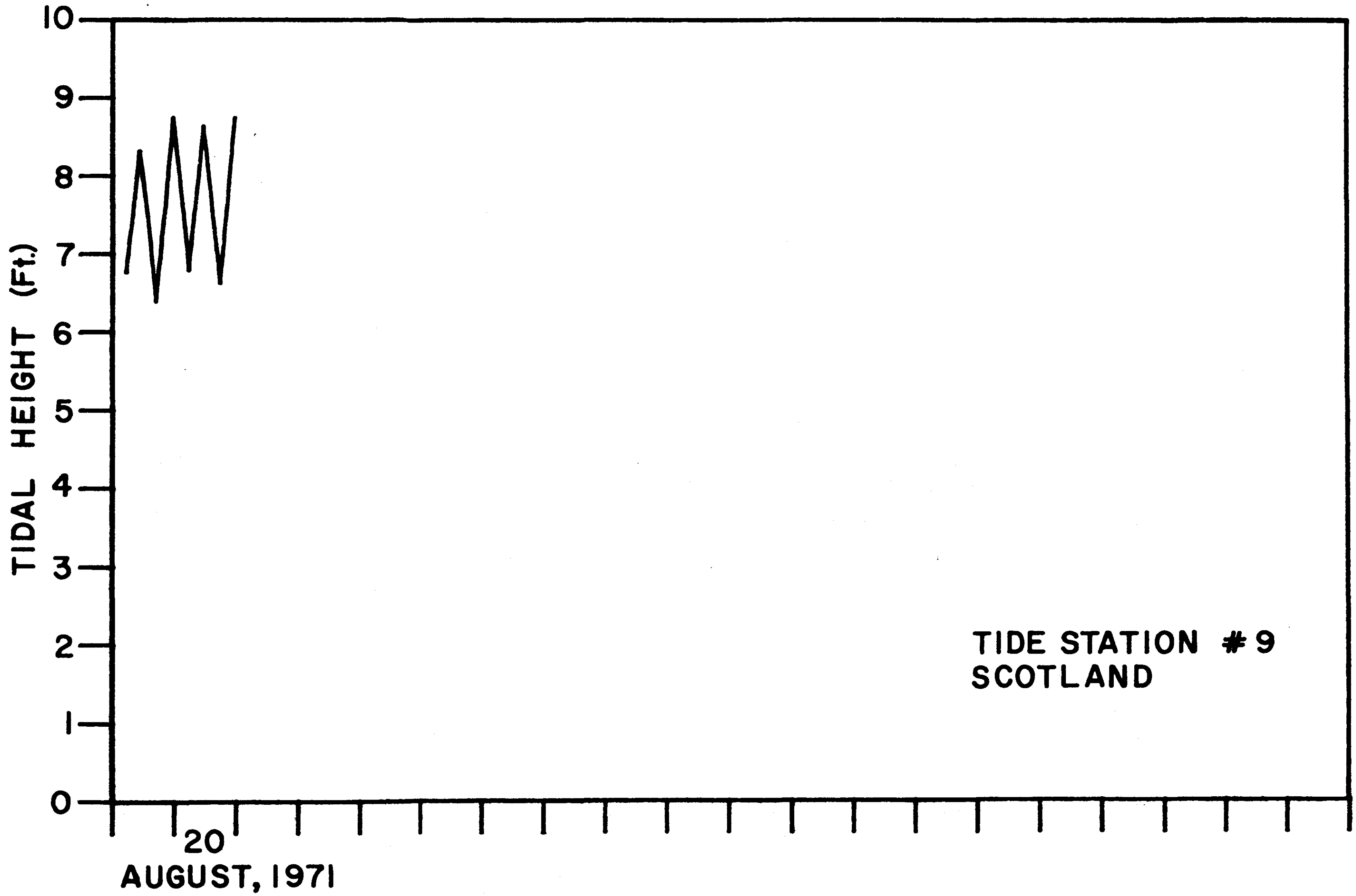

TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
15
20
25
30
JULY, 1971
TIDE STATION #7
HUNTINGTON PARK

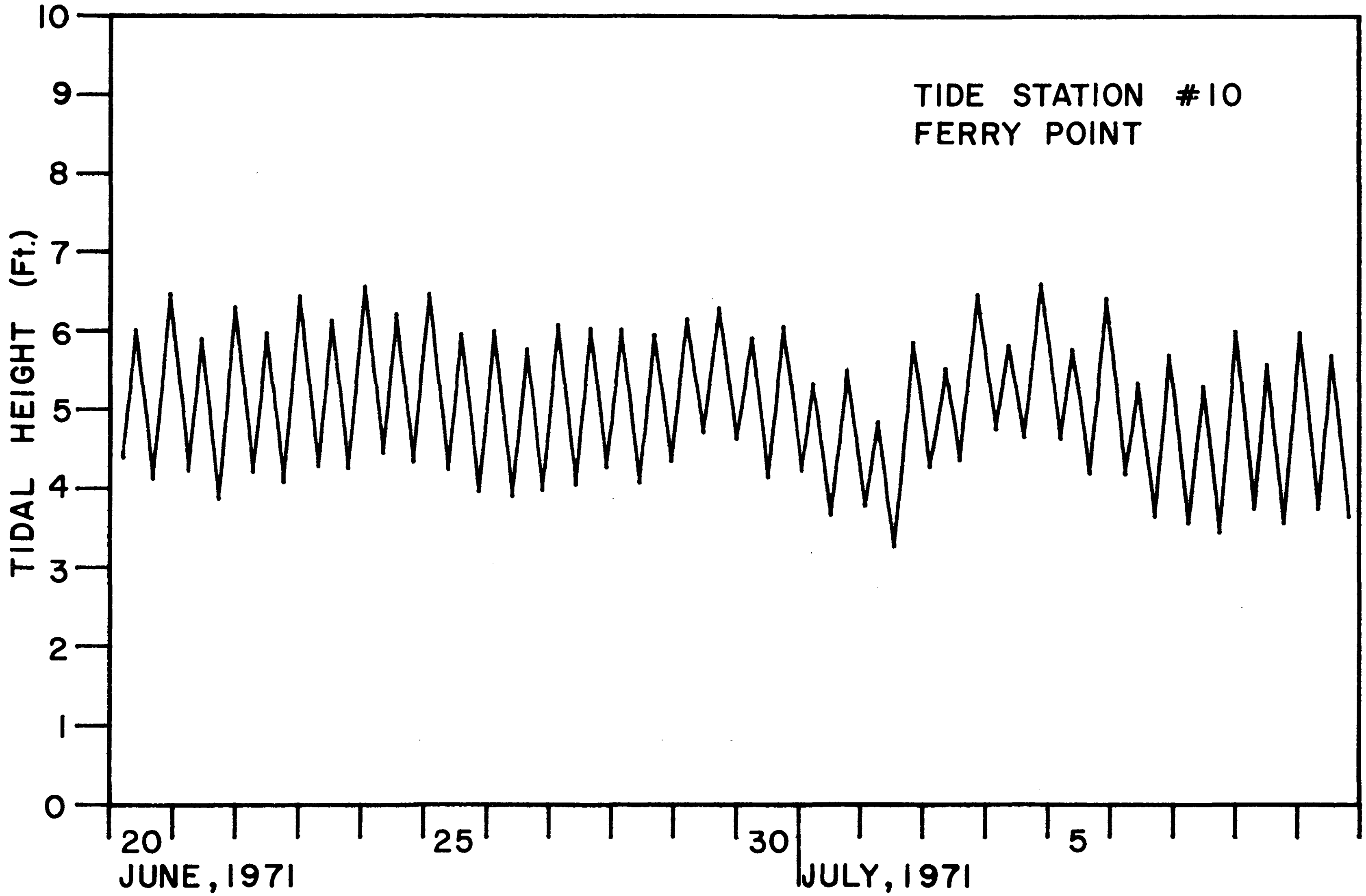

TIDAL HEIGHT (Ft.)
10
9
8
7
6
5
4
3
2
1
0
20
25
30
5
JUNE, 1971
JULY, 1971
TIDE STATION #9
SCOTLAND

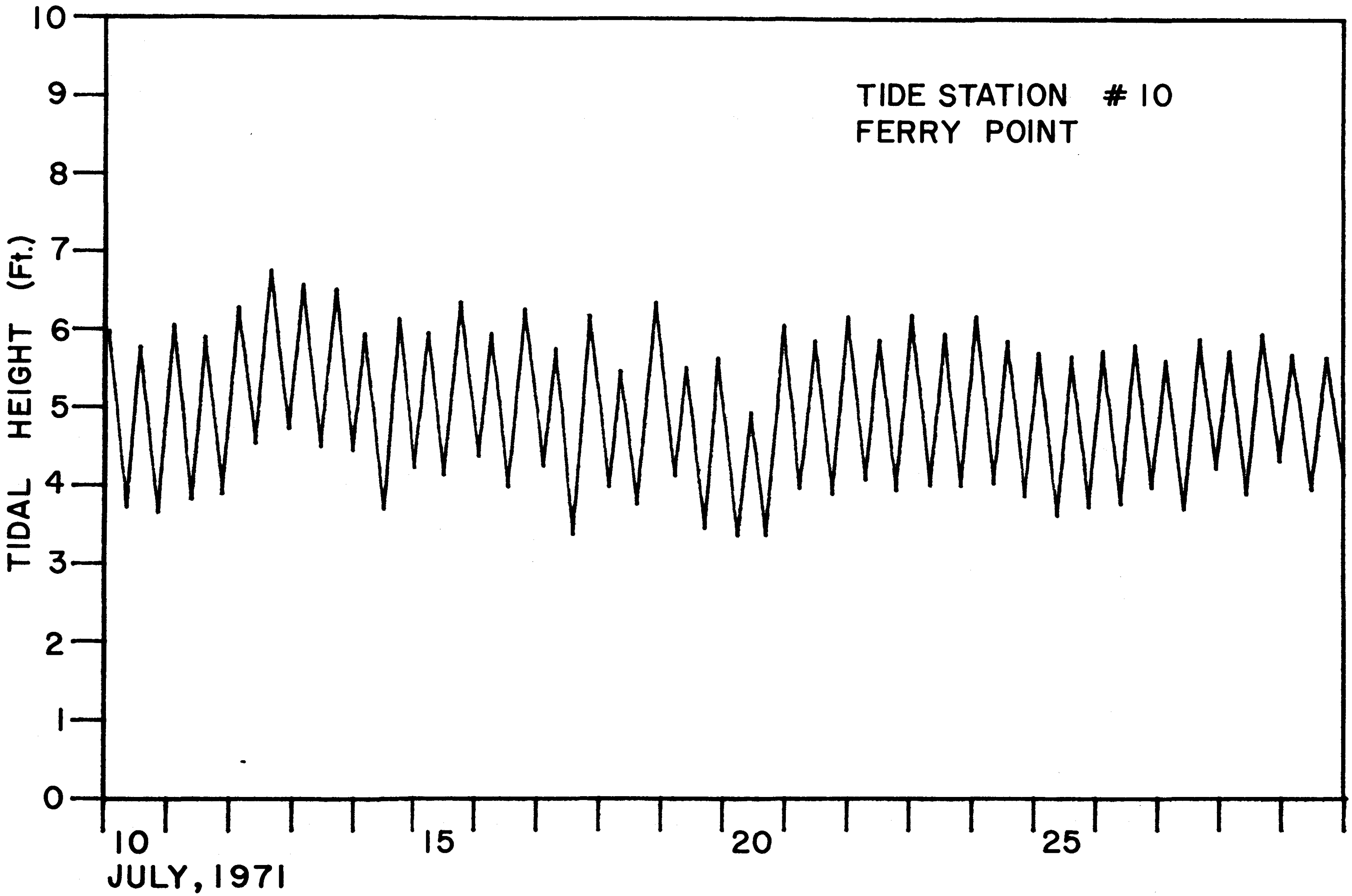

10
9
8
7
6
5
4
3
2
1
0
TIDAL HEIGHT (Ft.)
TIDE STATION #9
SCOTLAND
10
15
20
25
JULY, 1971



TIDAL HEIGHT (Ft.)
10
9
8
7
6
5
4
3
2
1
0
30
5
10
15
JULY, 1971
AUGUST, 1971
TIDE STATION # 9
SCOTLAND

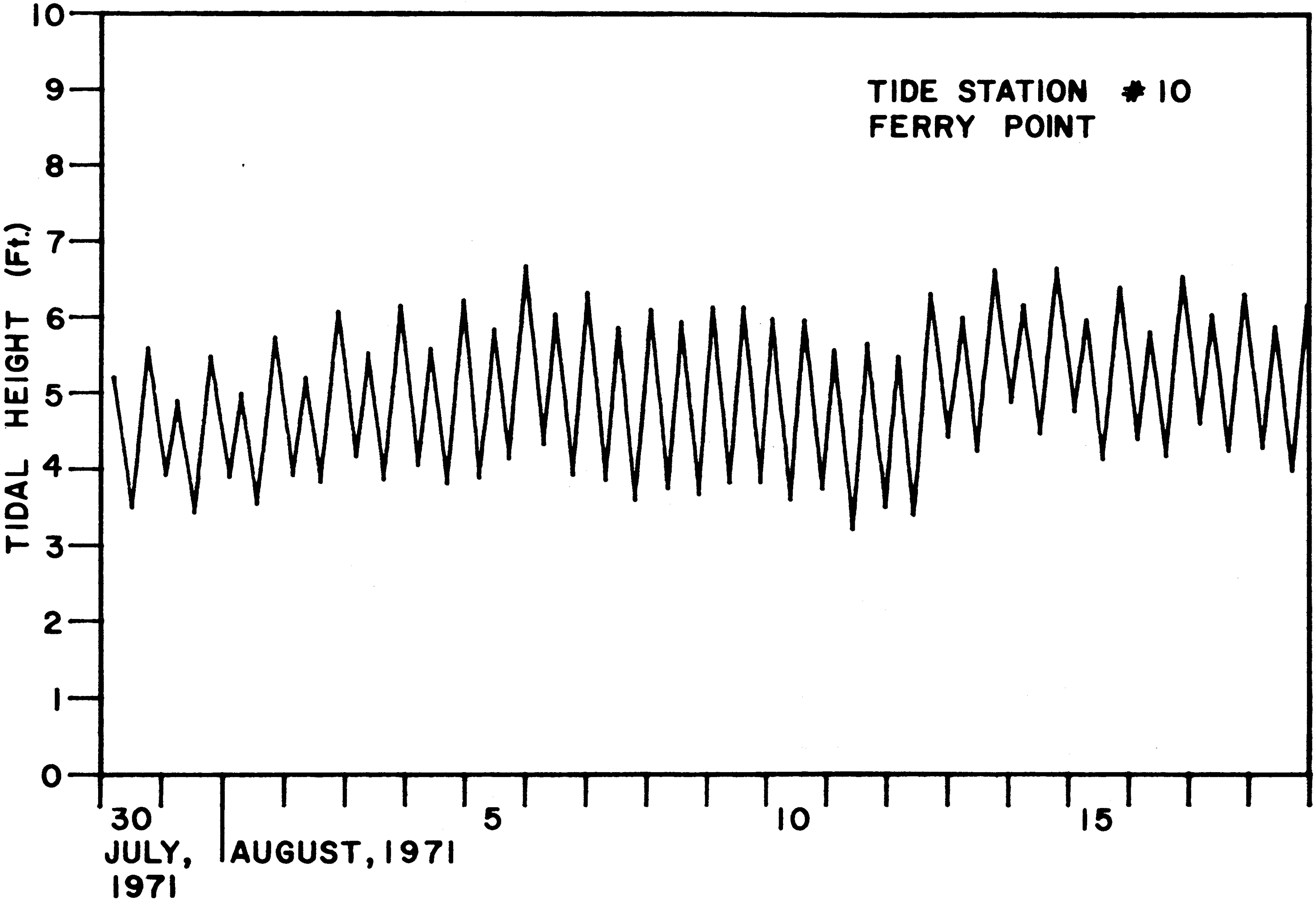

10
9
8
7
6
5
4
3
2
1
0
TIDAL HEIGHT (Ft.)
20
AUGUST, 1971
TIDE STATION #9
SCOTLAND

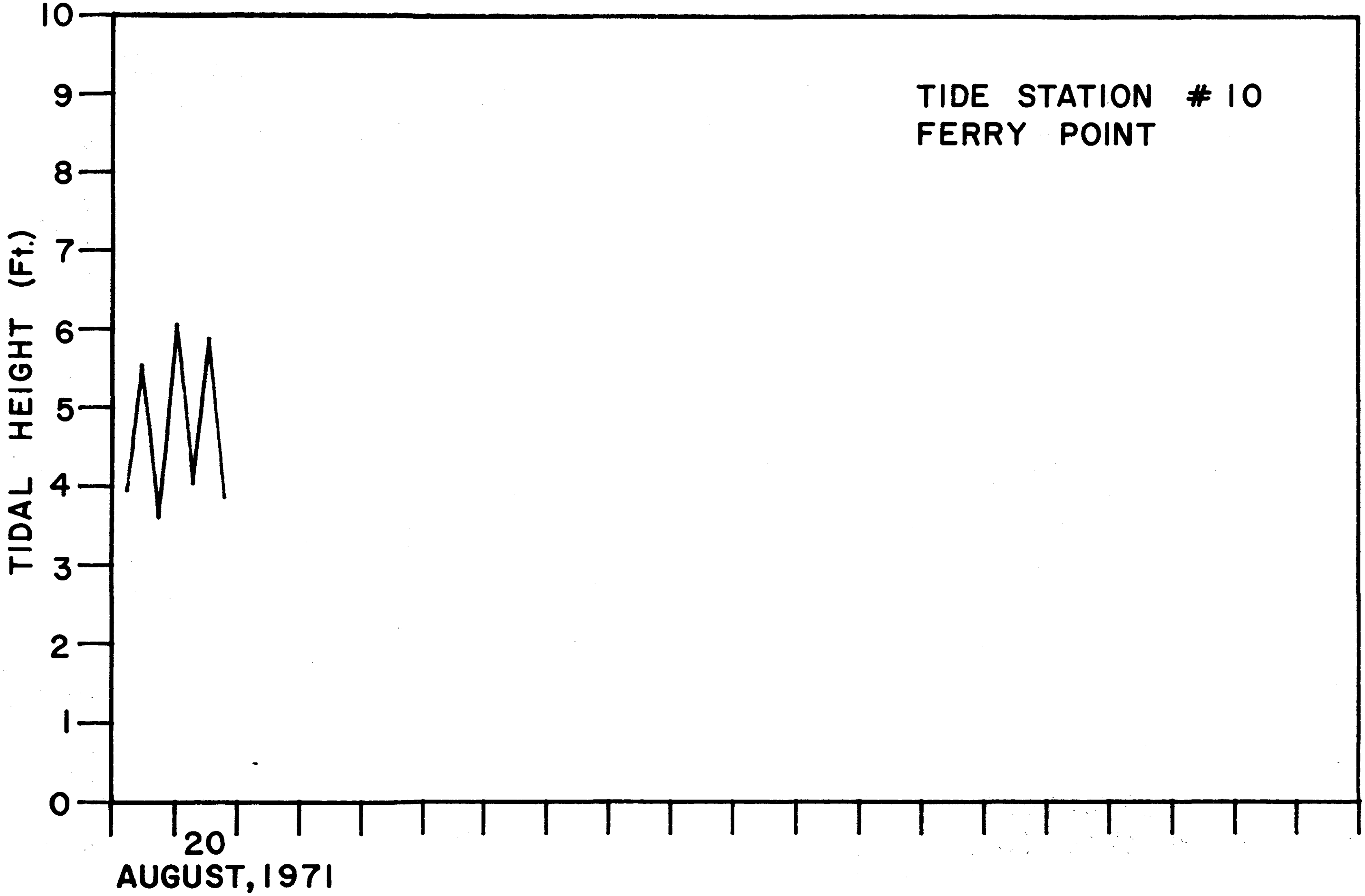

TIDE STATION #10
FERRY POINT
TIDAL HEIGHT (Ft.)
10
9
8
7
6
5
4
3
2
1
0
20
25
30
5
JUNE, 1971
JULY, 1971



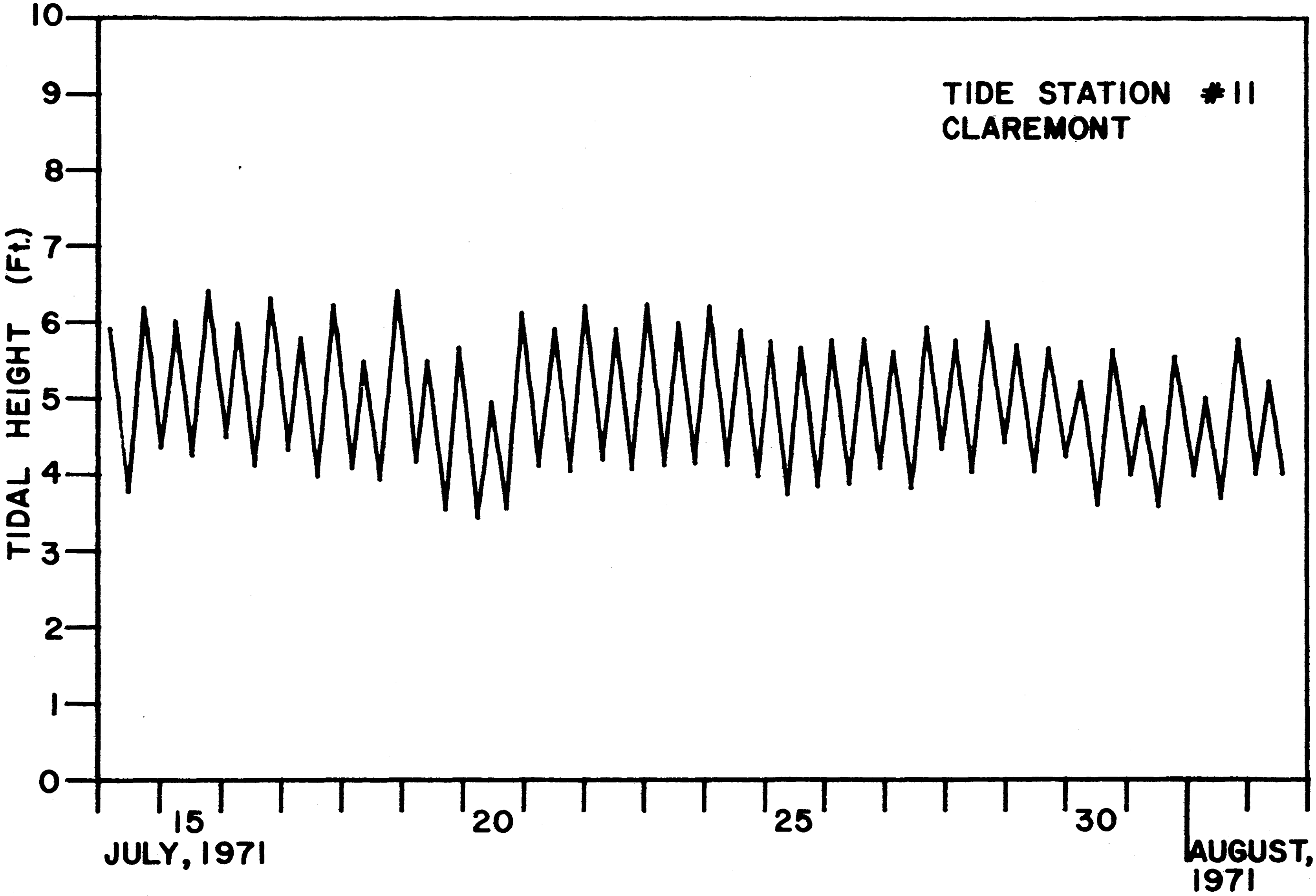
TIDE STATION # 10
FERRY POINT
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
25
JULY, 1971

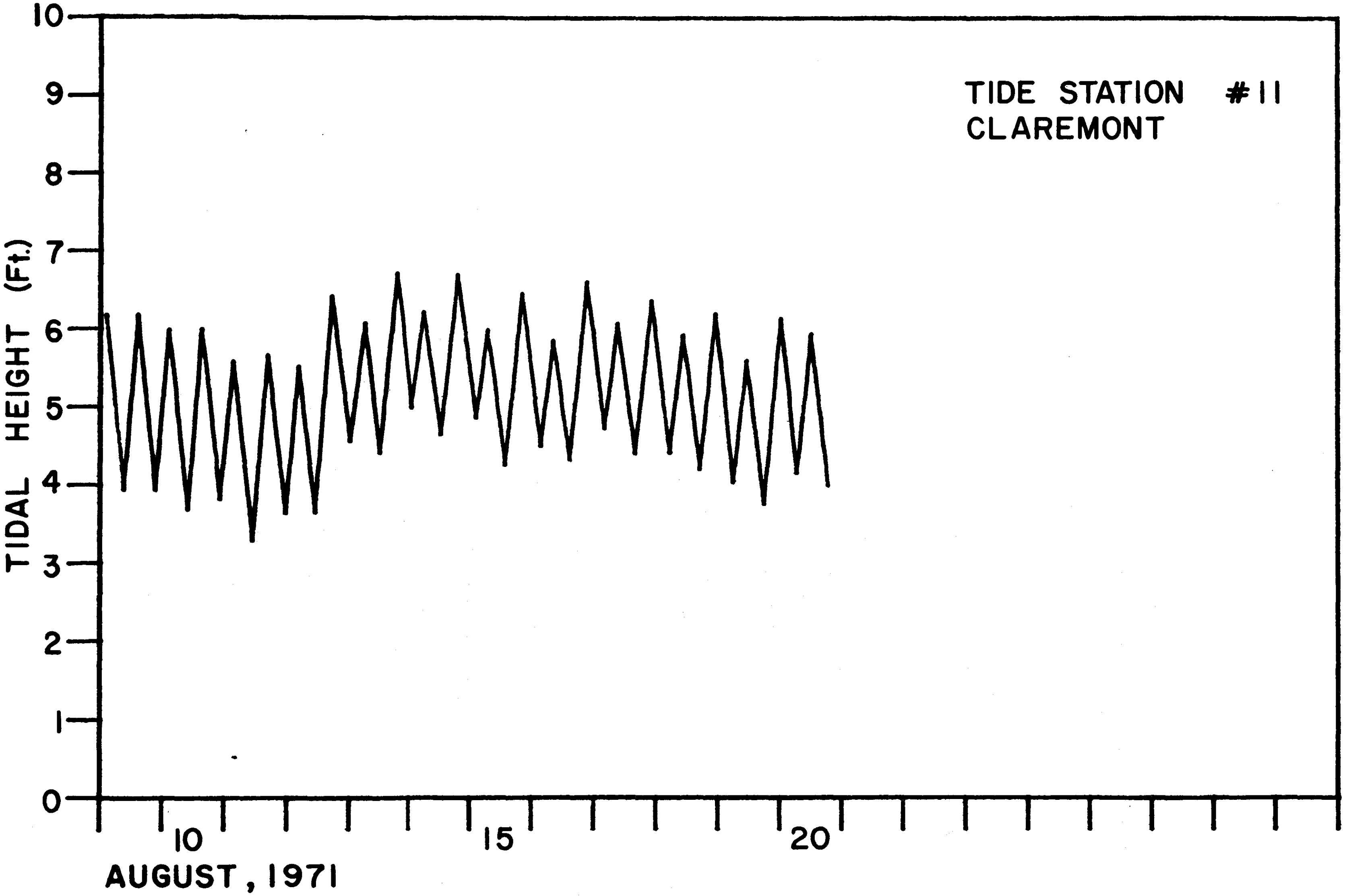
247

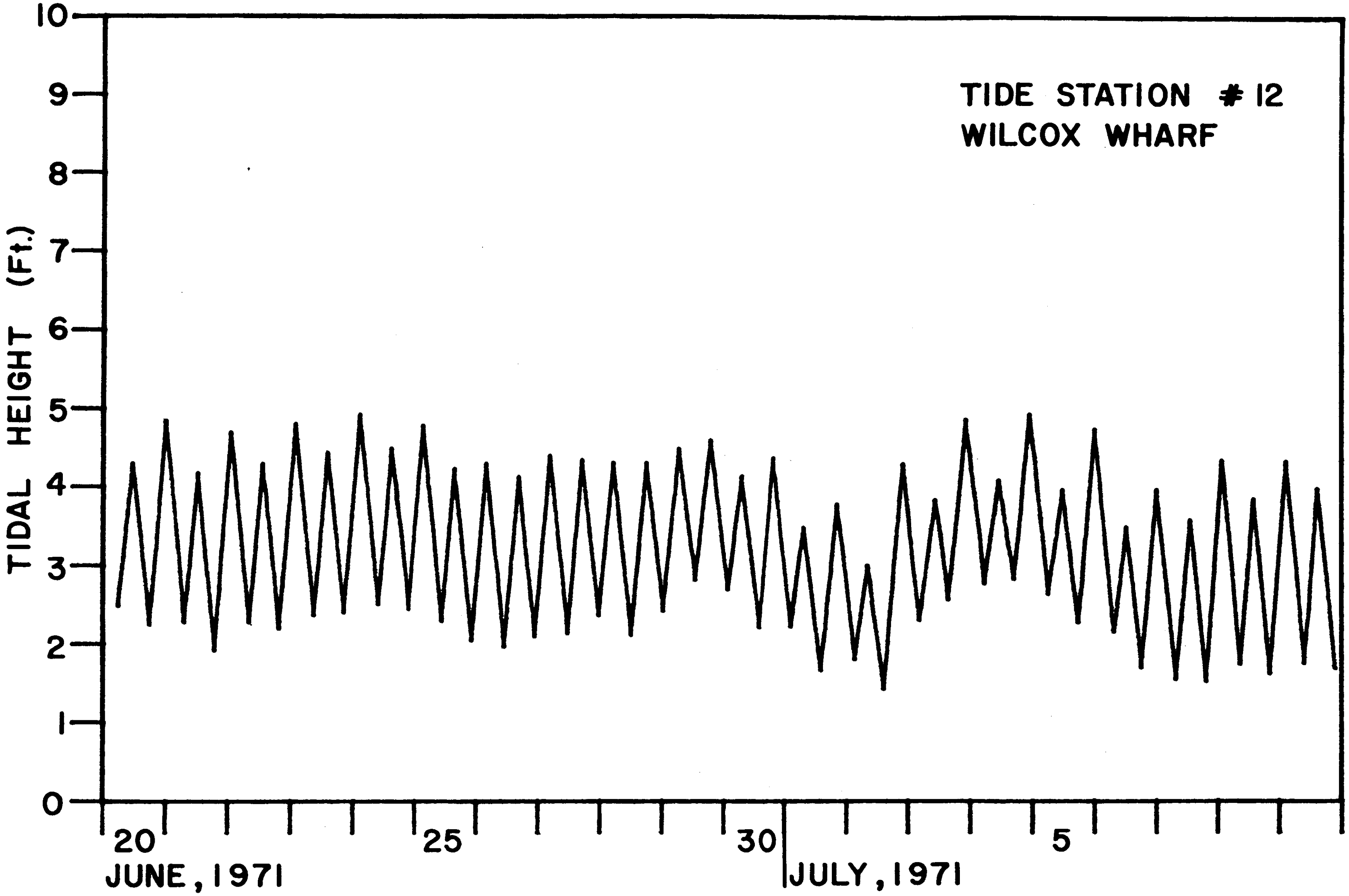

TIDE STATION # 10
FERRY POINT
TIDAL HEIGHT (Ft.)
10
9
8
7
6
5
4
3
2
1
0
30
5
10
15
JULY, 1971
AUGUST, 1971

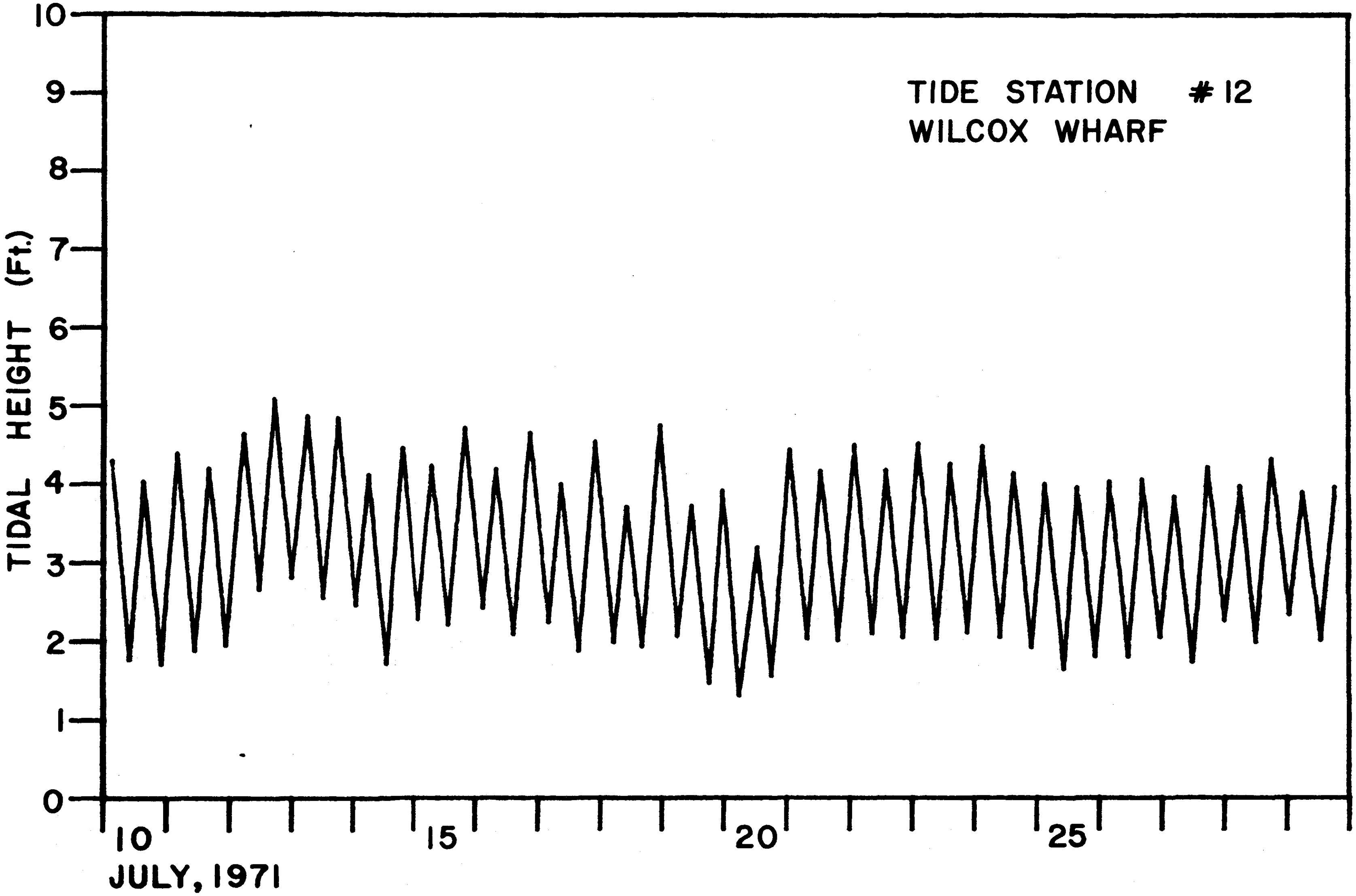


TIDE STATION # 10
FERRY POINT
TIDAL HEIGHT (Ft.)
10
9
8
7
6
5
4
3
2
1
0
20
AUGUST, 1971

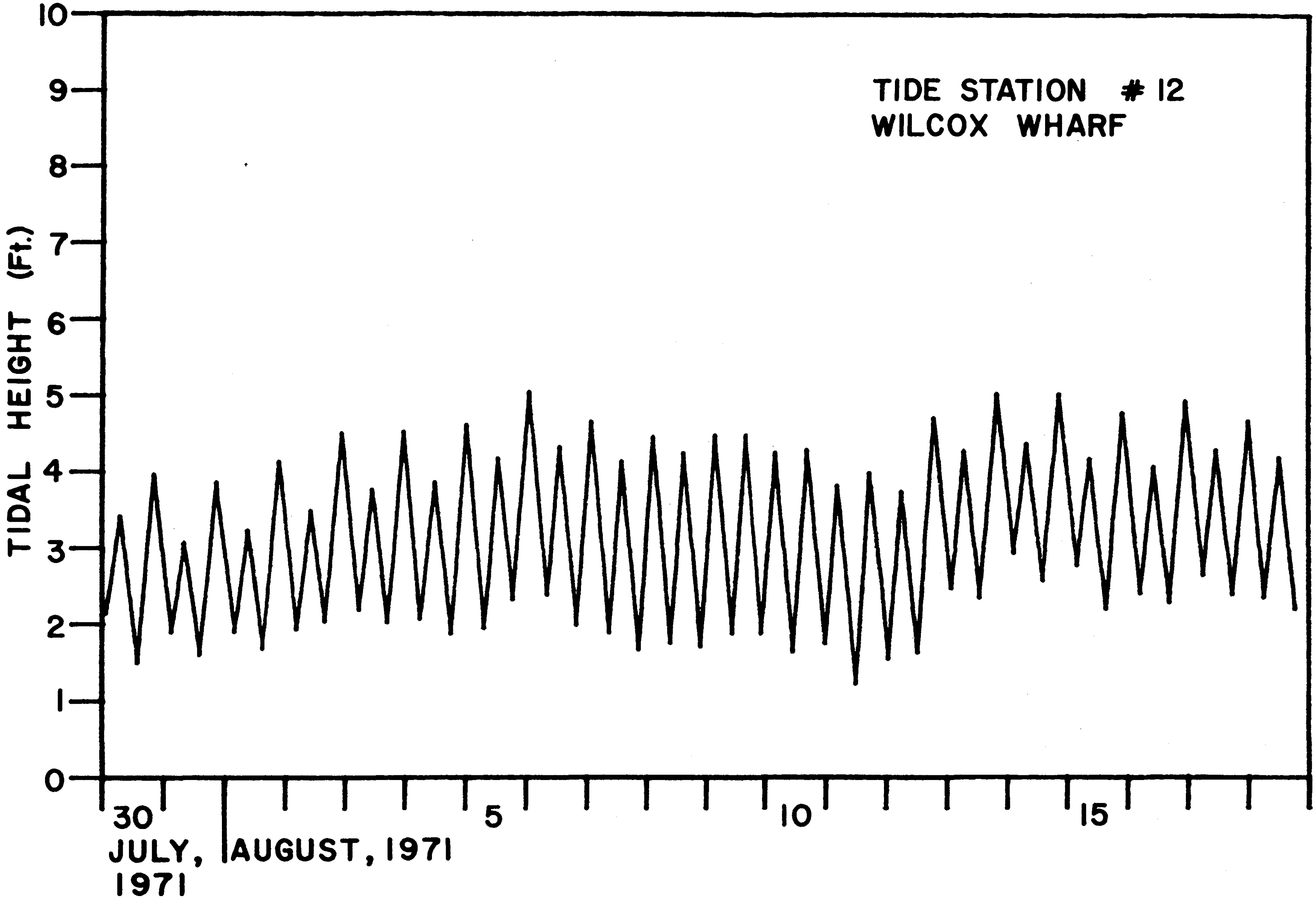

TIDE STATION #11
CLARAMONT
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
15
20
25
30
JULY, 1971
AUGUST, 1971

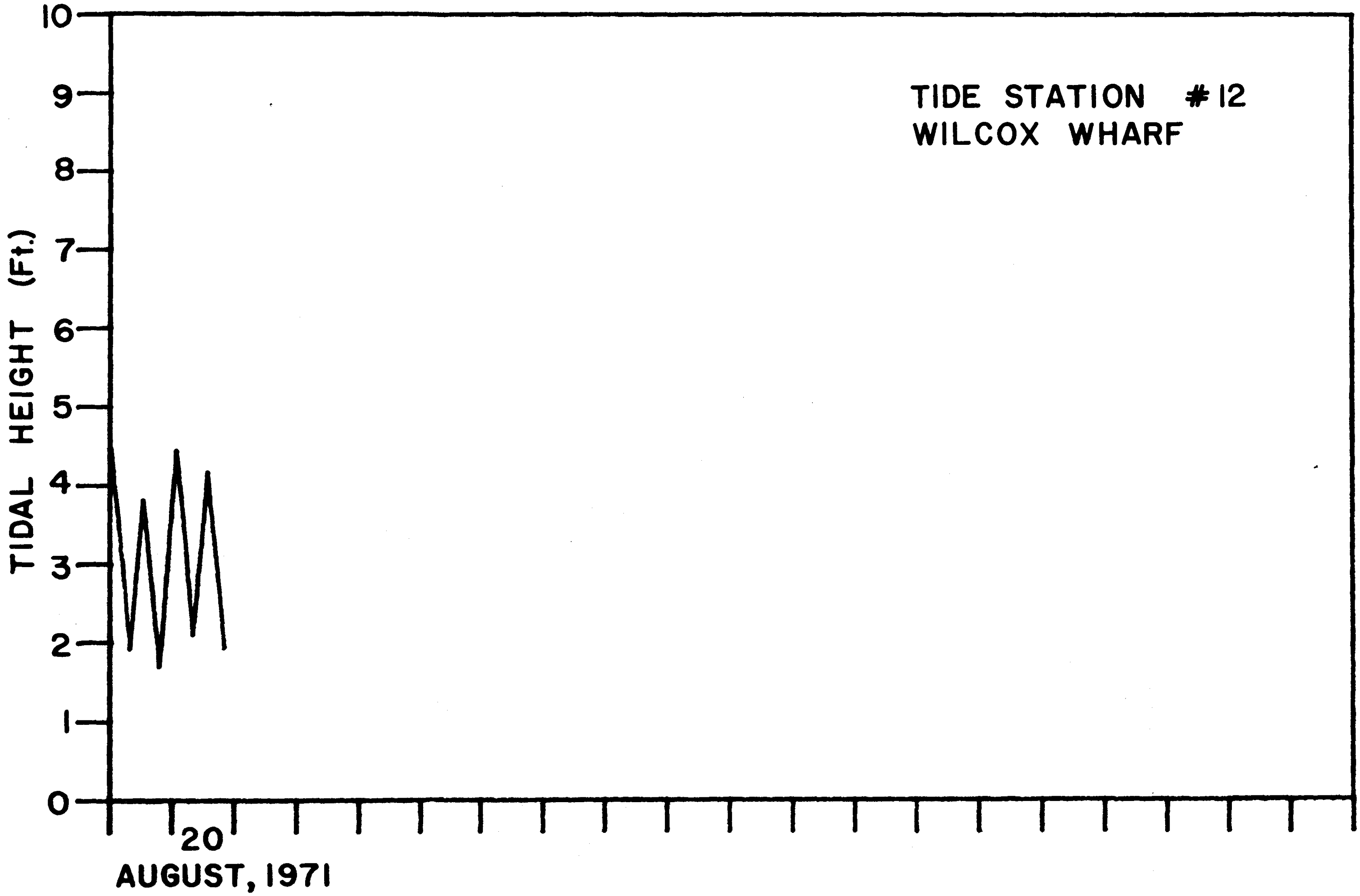

TIDE STATION #11
CLAREMONT
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
AUGUST, 1971

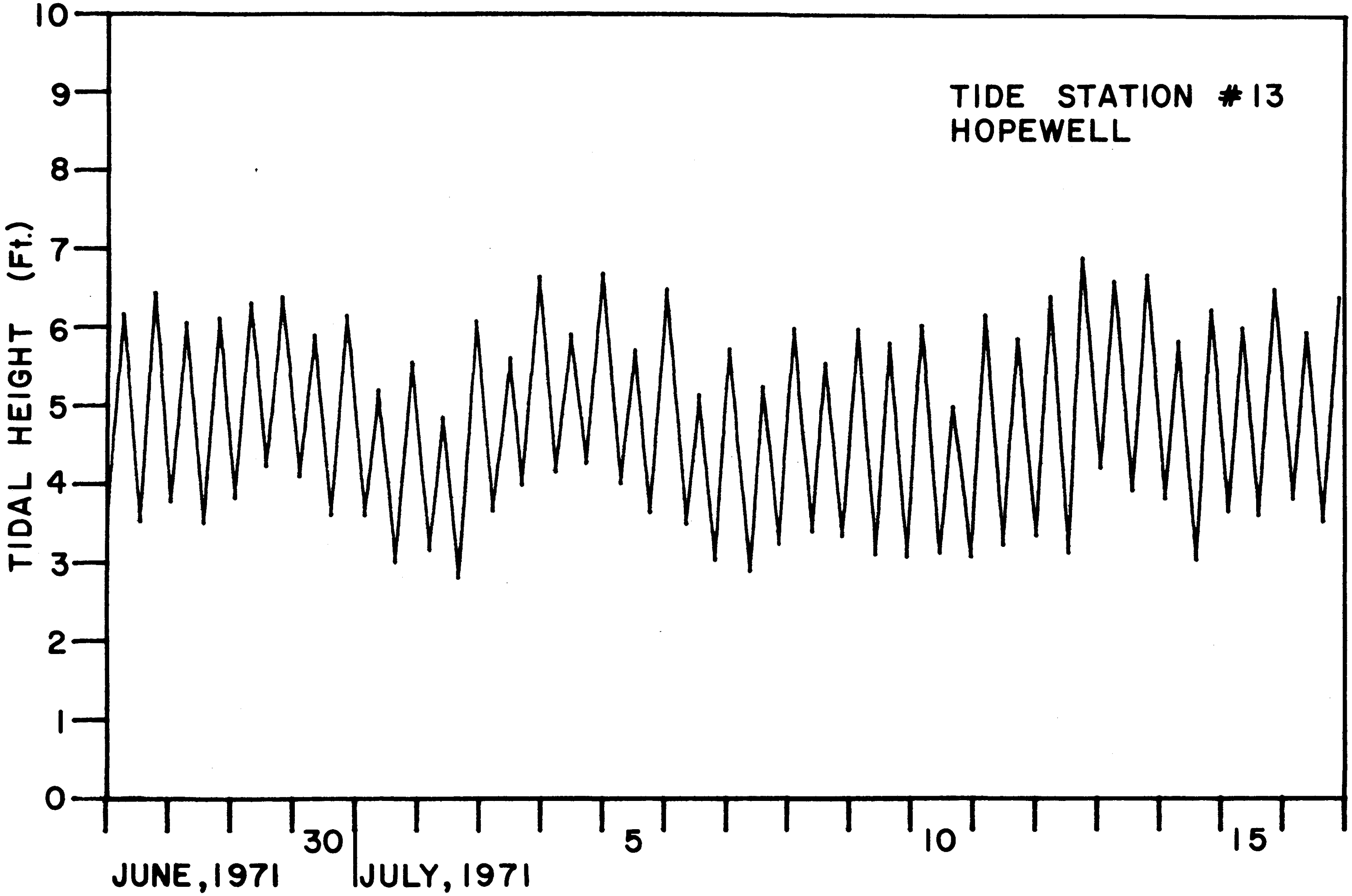

TIDE STATION # 12
WILCOX WHARF
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
20
25
30
5
JUNE, 1971
JULY, 1971

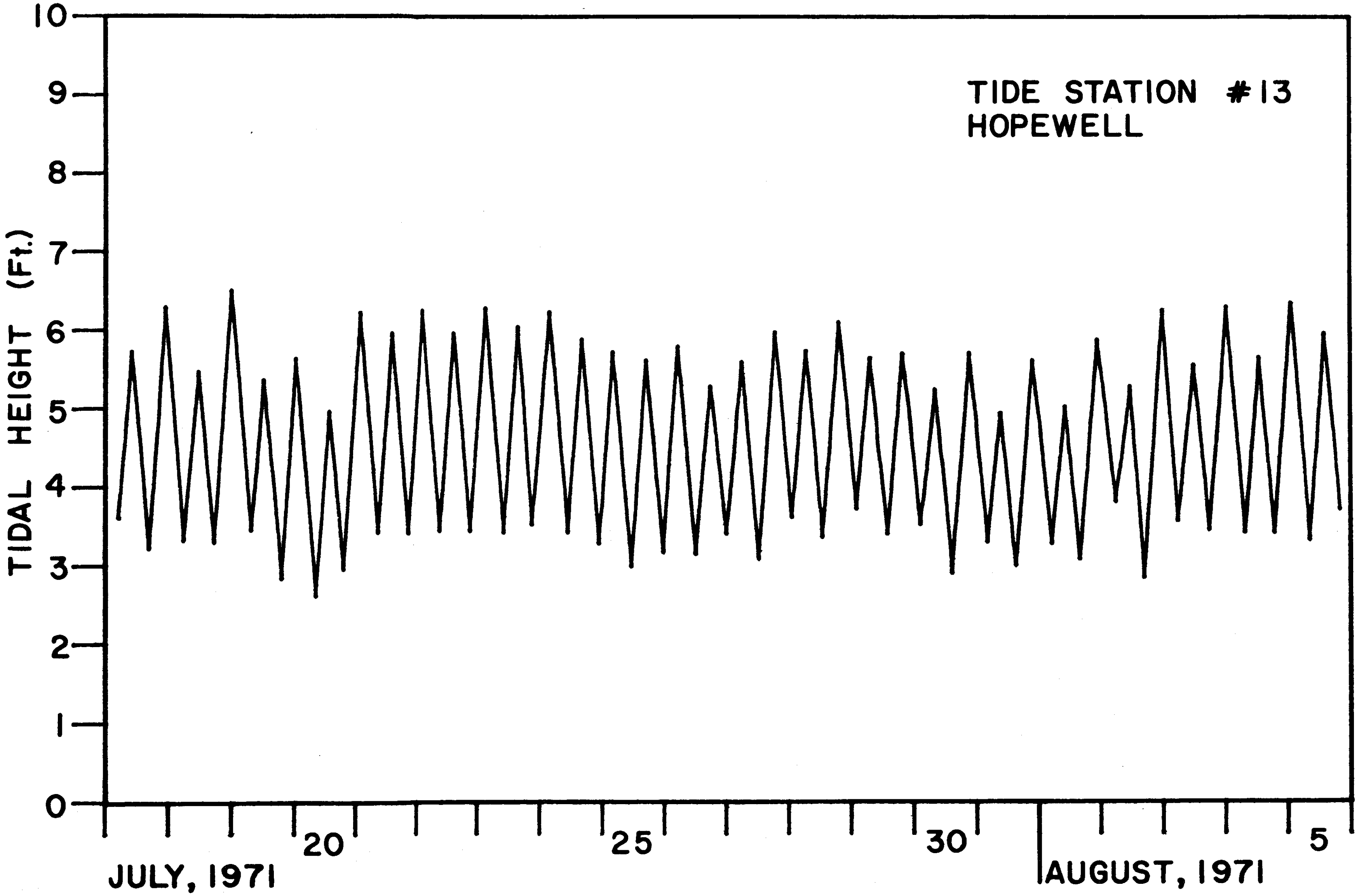


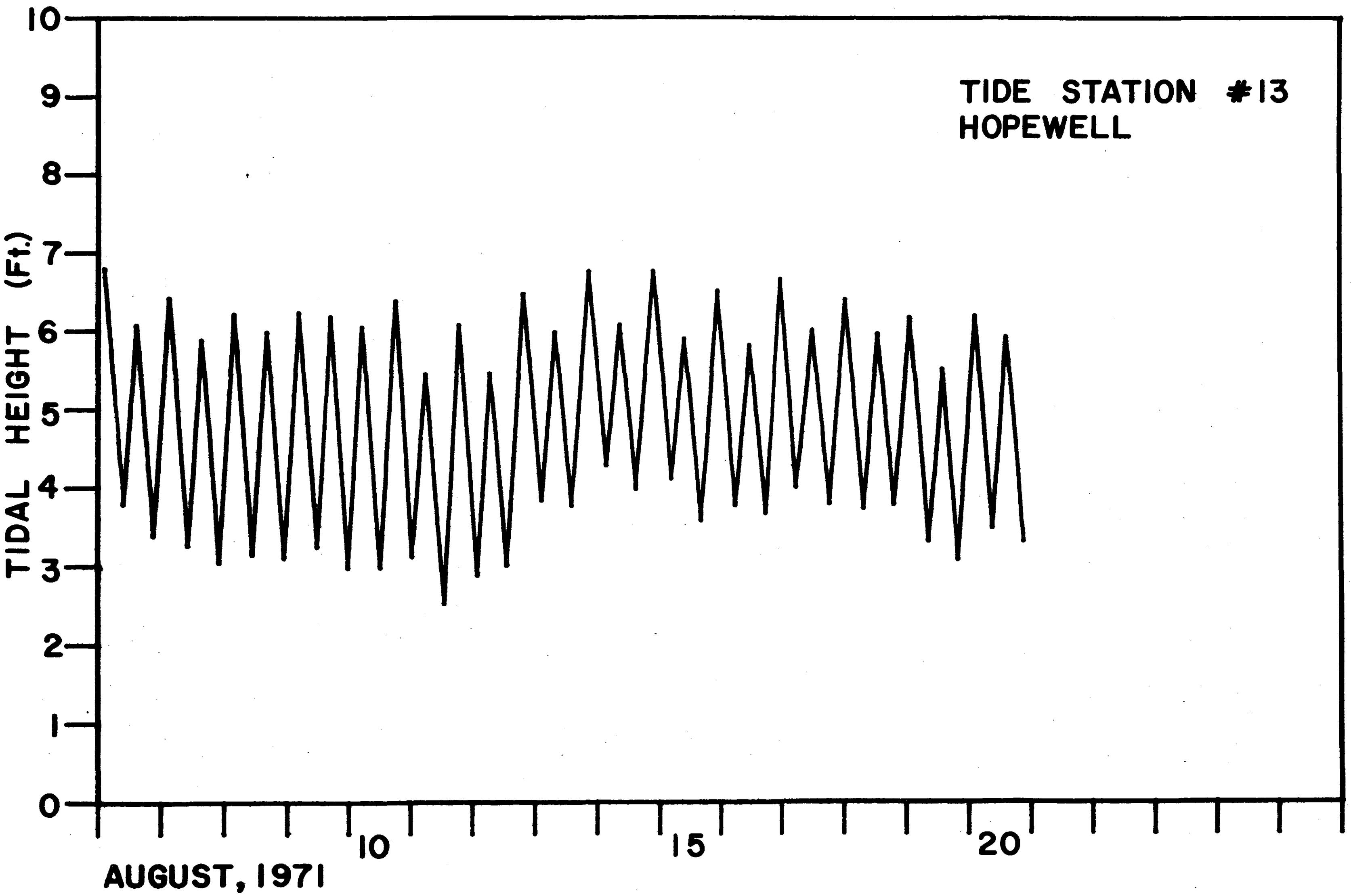
TIDE STATION # 12
WILCOX WHARF
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
25
JULY, 1971

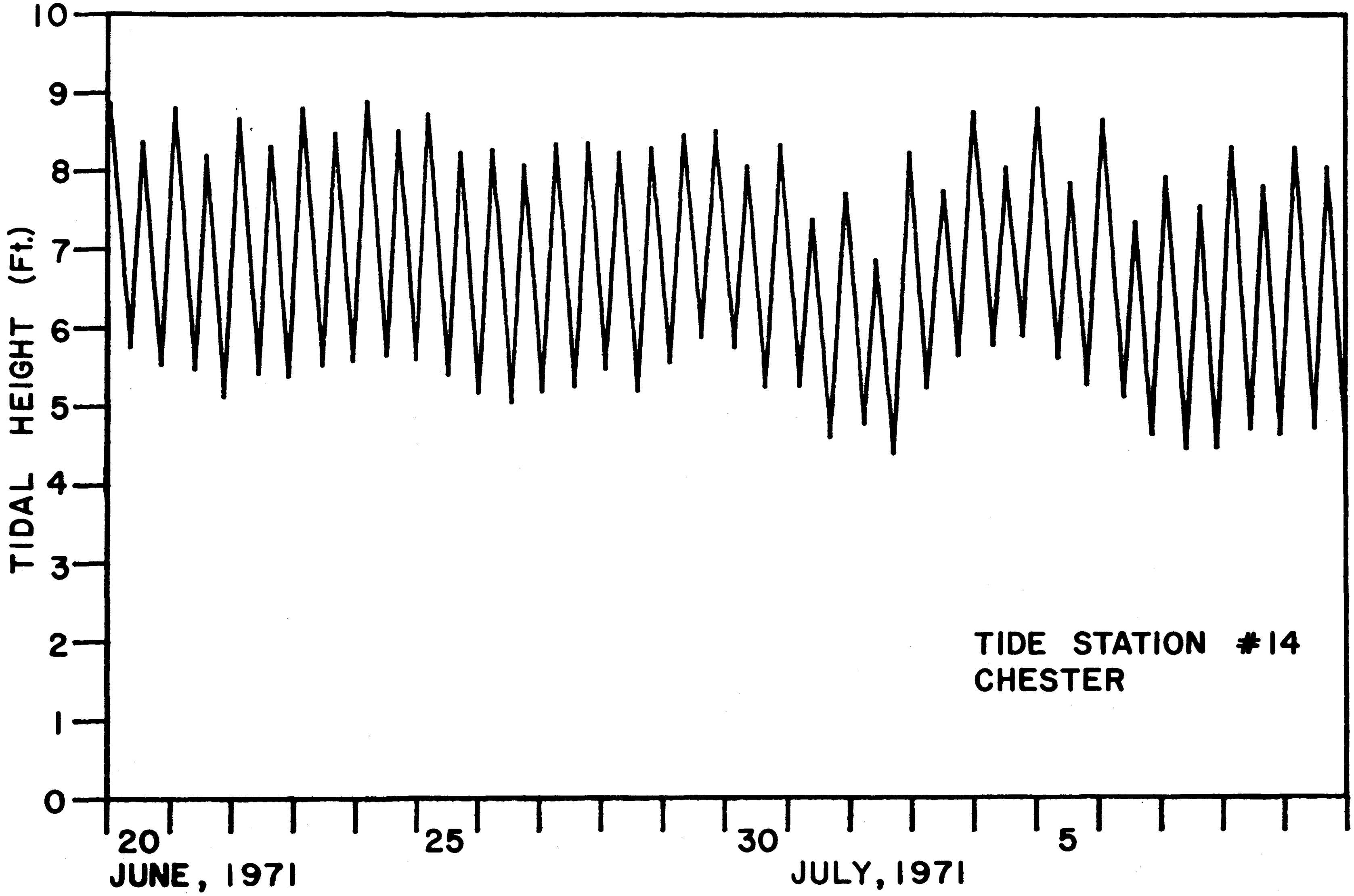

TIDE STATION # 12
WILCOX WHARF
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
30
5
10
15
JULY, 1971
AUGUST, 1971

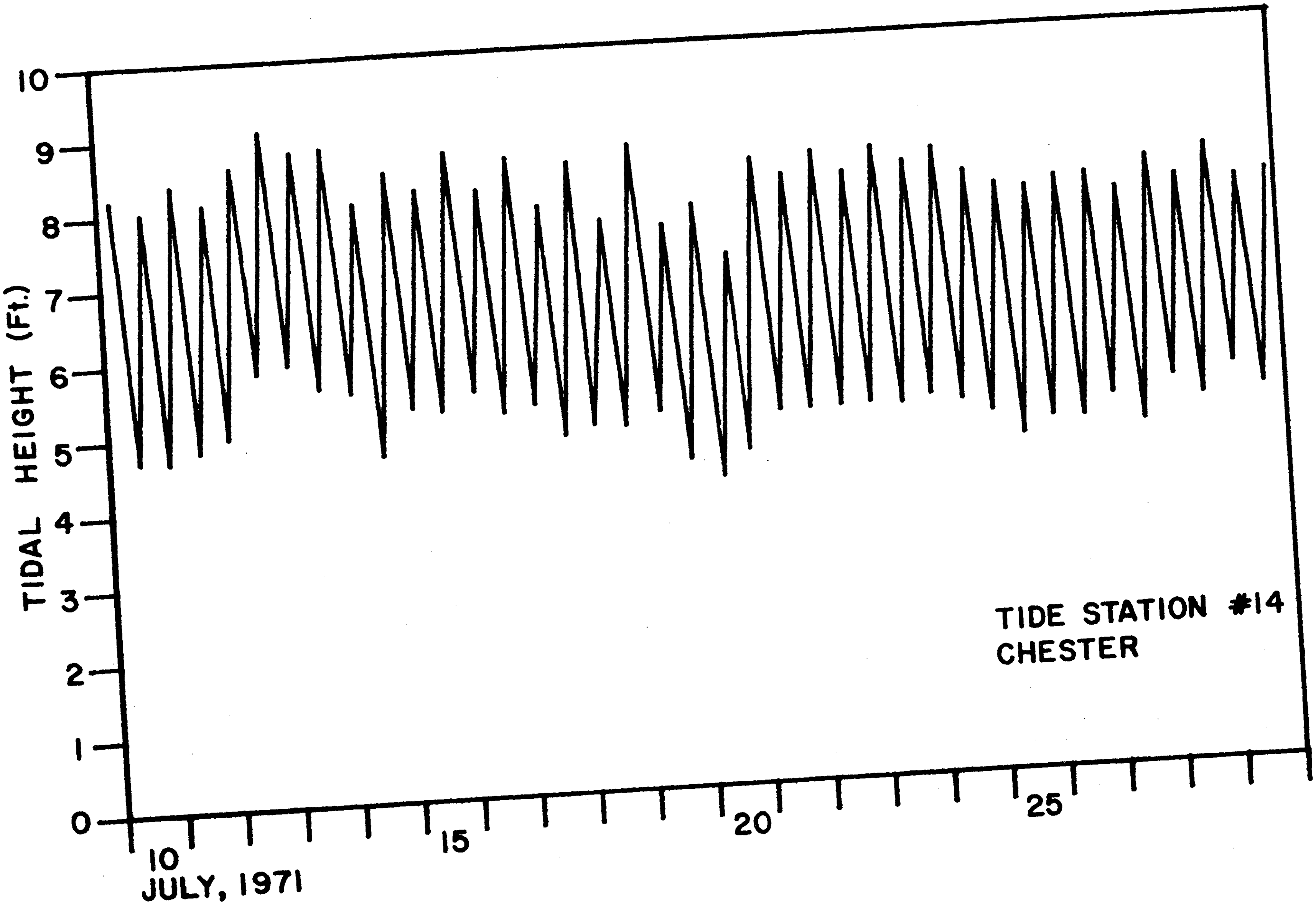

TIDE STATION #12
WILCOX WHARF
TIDAL HEIGHT (Ft.)
10
9
8
7
6
5
4
3
2
1
0
20
AUGUST, 1971


TIDE STATION # 13
HOPEWELL
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
30
5
10
15
JUNE, 1971
JULY, 1971

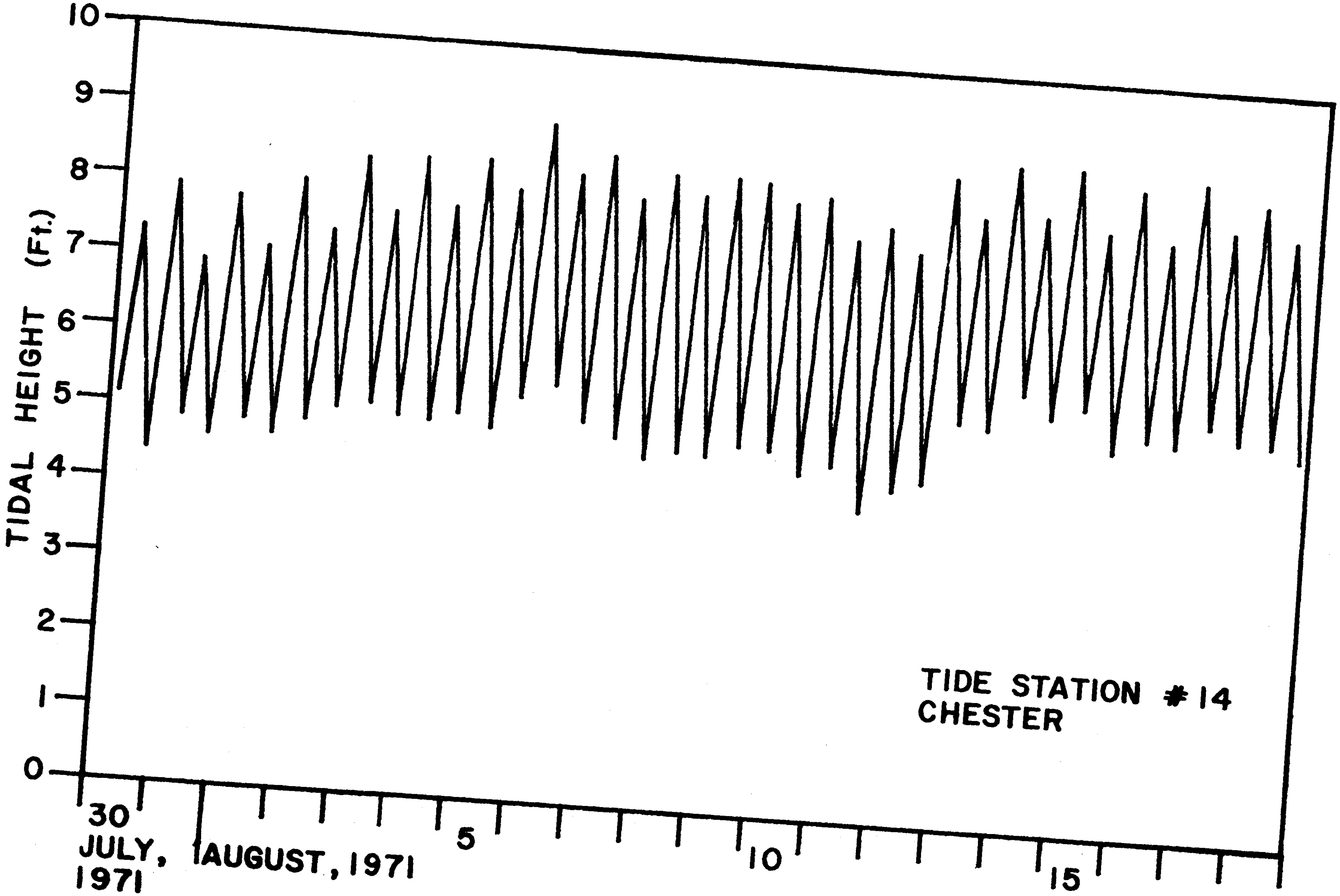

TIDE STATION #13
HOPEWELL
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
20
25
30
5
JULY, 1971
AUGUST, 1971

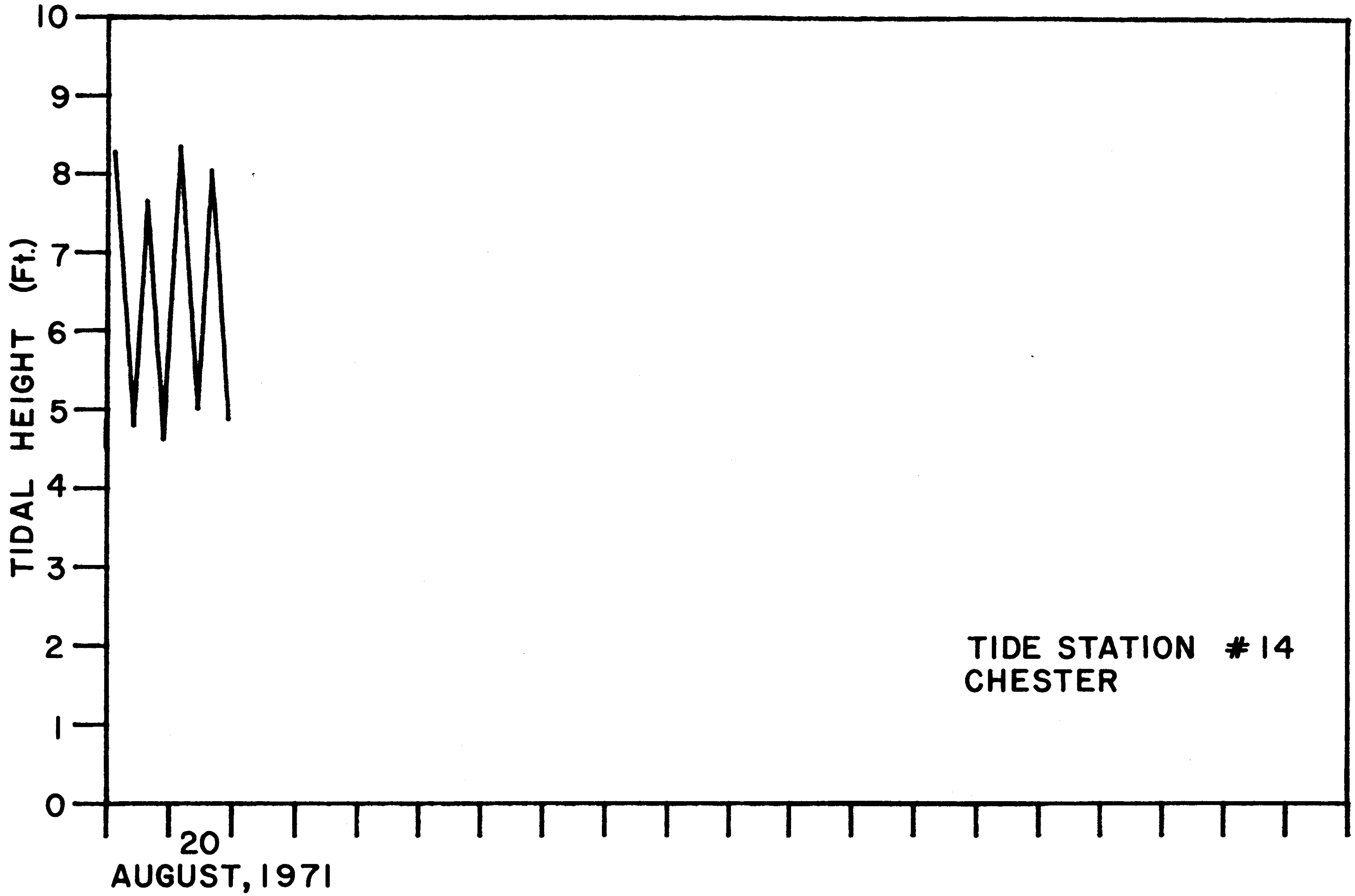

TIDE STATION #13
HOPEWELL
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
AUGUST, 1971

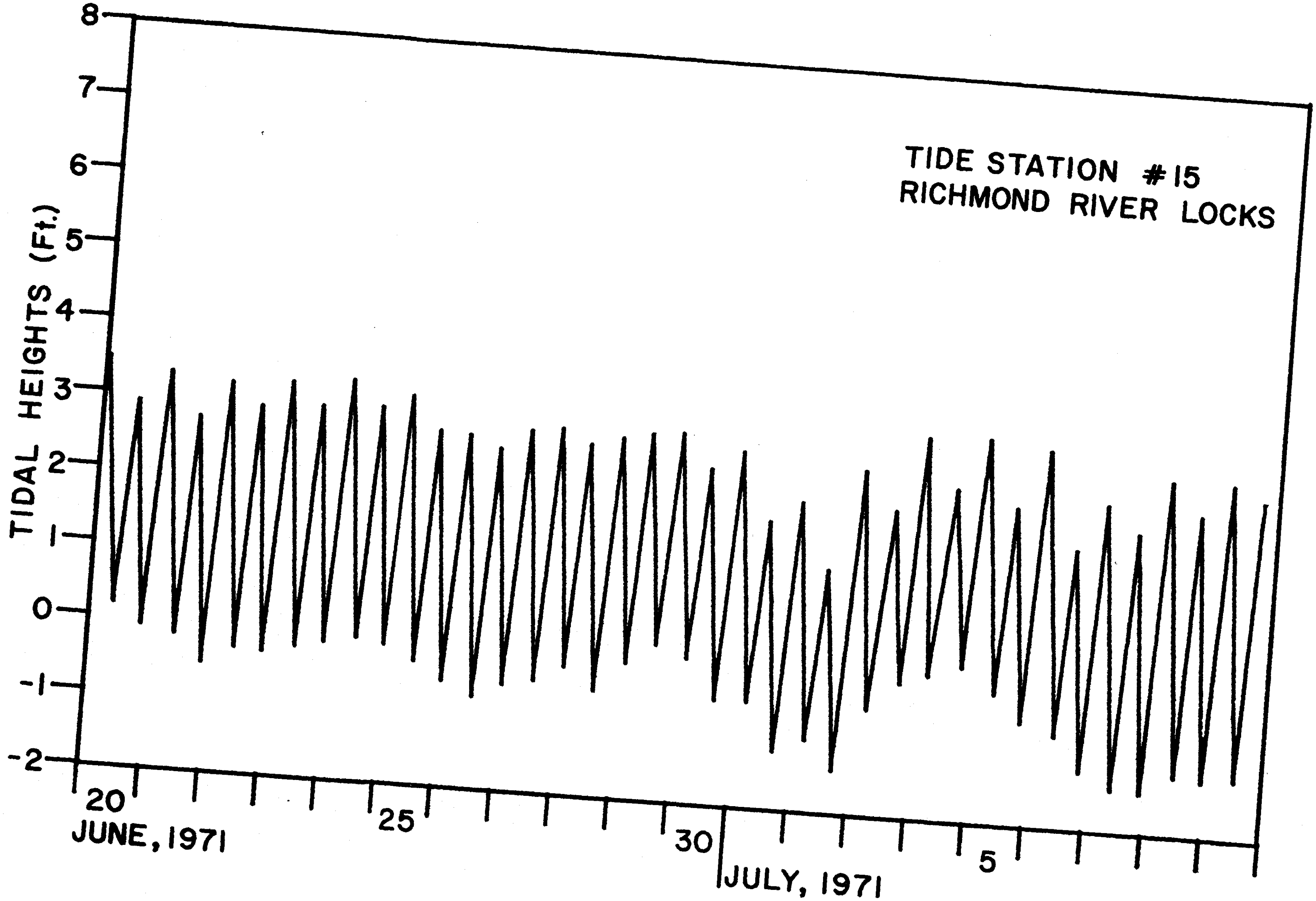

TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
20
25
30
5
JUNE, 1971
JULY, 1971
TIDE STATION #14
CHESTER

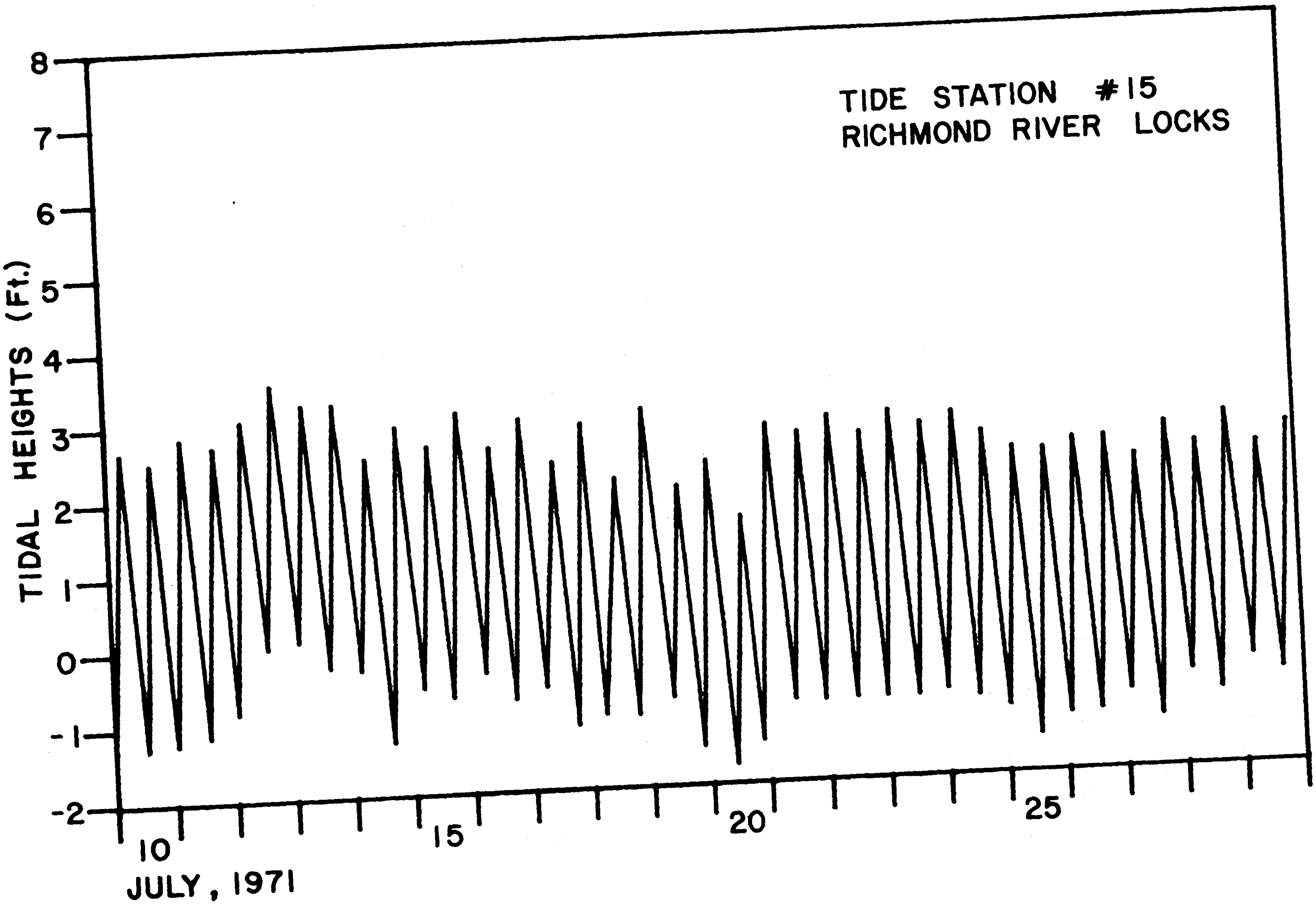


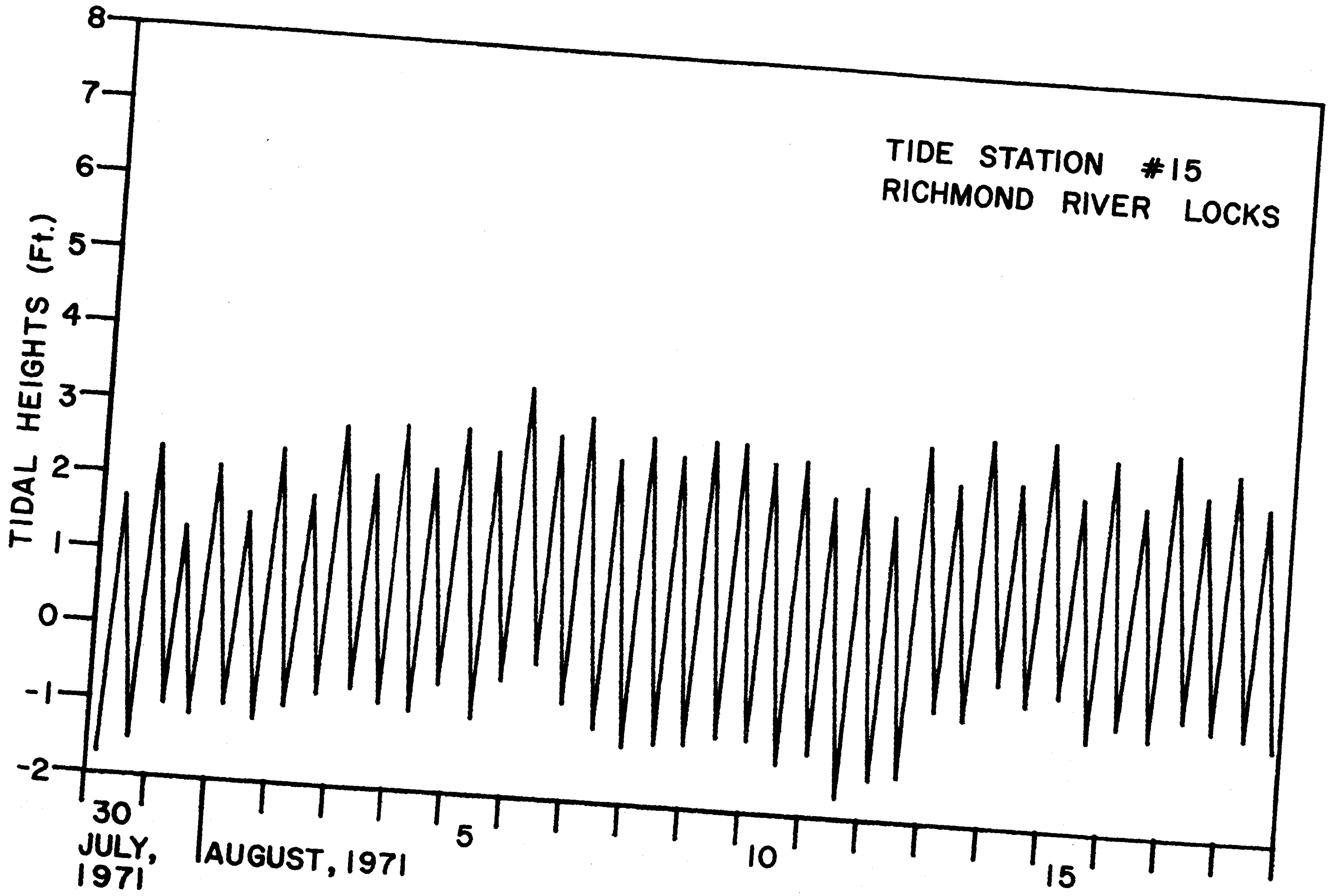
TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
10
15
20
25
JULY, 1971
TIDE STATION #14
CHESTER

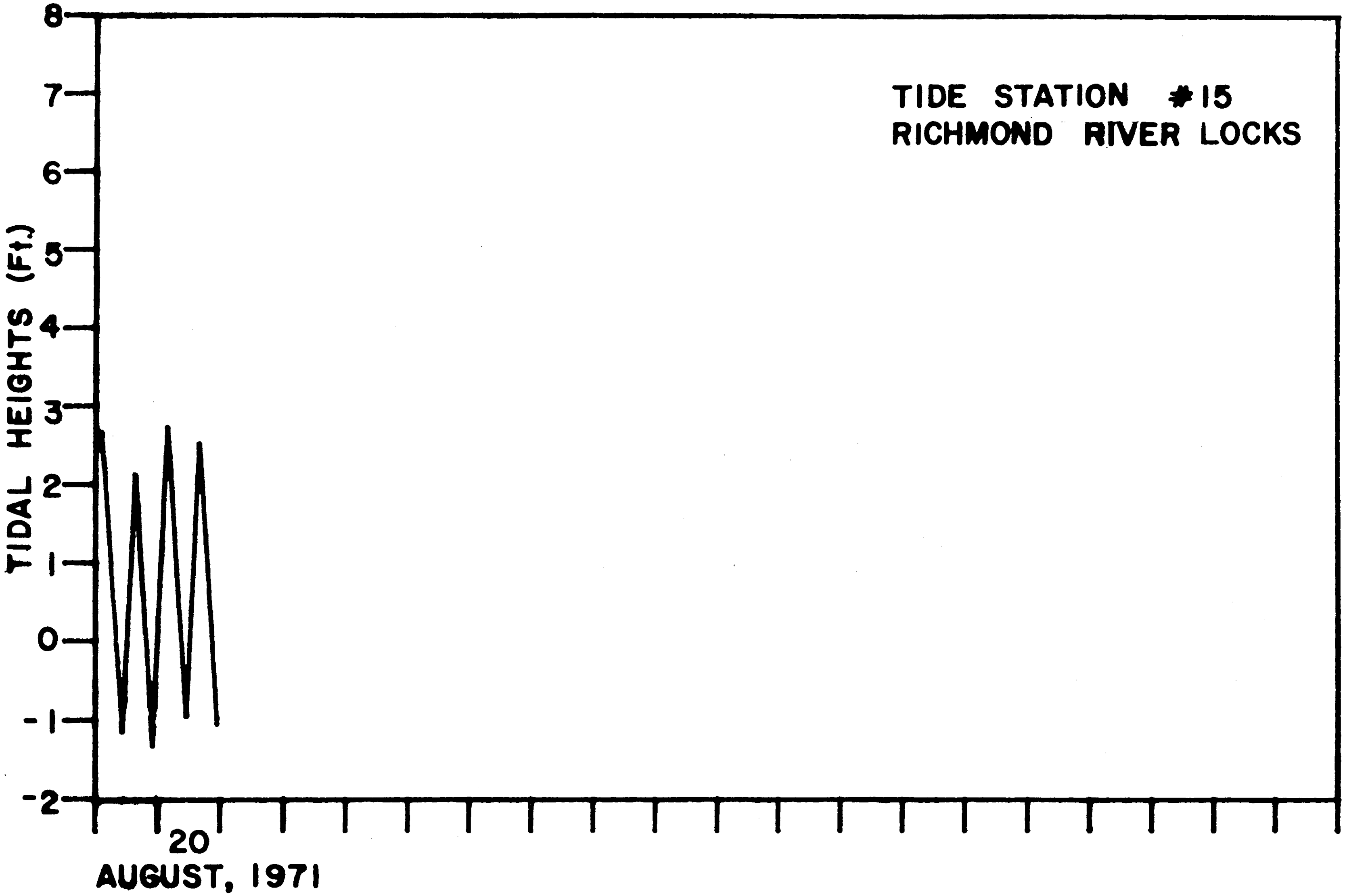

TIDAL HEIGHT (Ft.)
0
1
2
3
4
5
6
7
8
9
10
TIDE STATION # 14
CHESTER
30
JULY,
1971
AUGUST, 1971
5
10
15


10
9
8
7
6
5
4
3
2
1
0
TIDAL HEIGHT (Ft.)
20
AUGUST, 1971
TIDE STATION #14
CHESTER


TIDE STATION #15
RICHMOND RIVER LOCKS
TIDAL HEIGHTS (Ft.)
8
7
6
5
4
3
2
1
0
-1
-2
20
25
30
5
JUNE, 1971
JULY, 1971

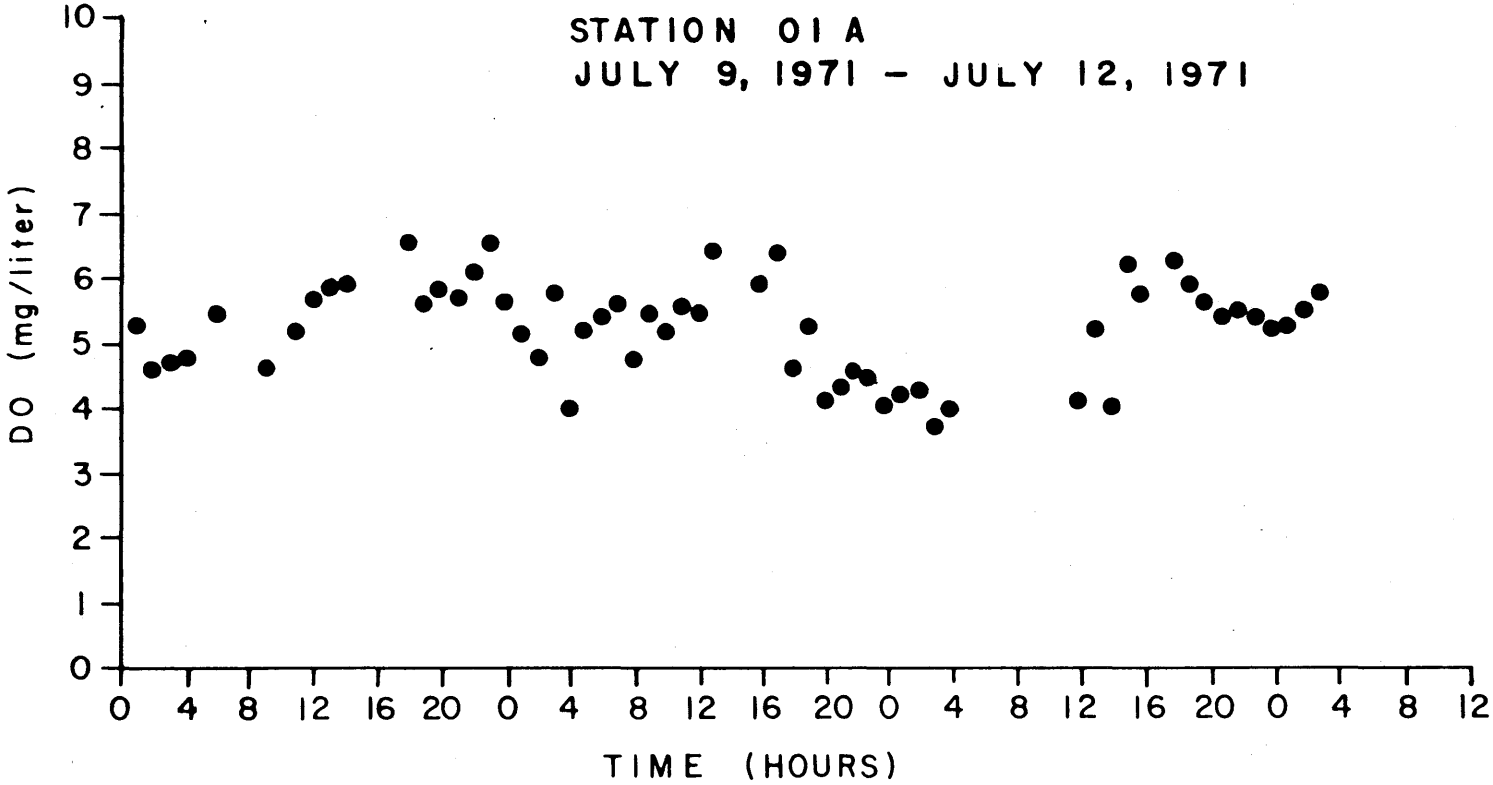

TIDE STATION #15
RICHMOND RIVER LOCKS
TIDAL HEIGHTS (Ft.)
8
7
6
5
4
3
2
1
0
-1
-2
10
15
20
25
JULY, 1971

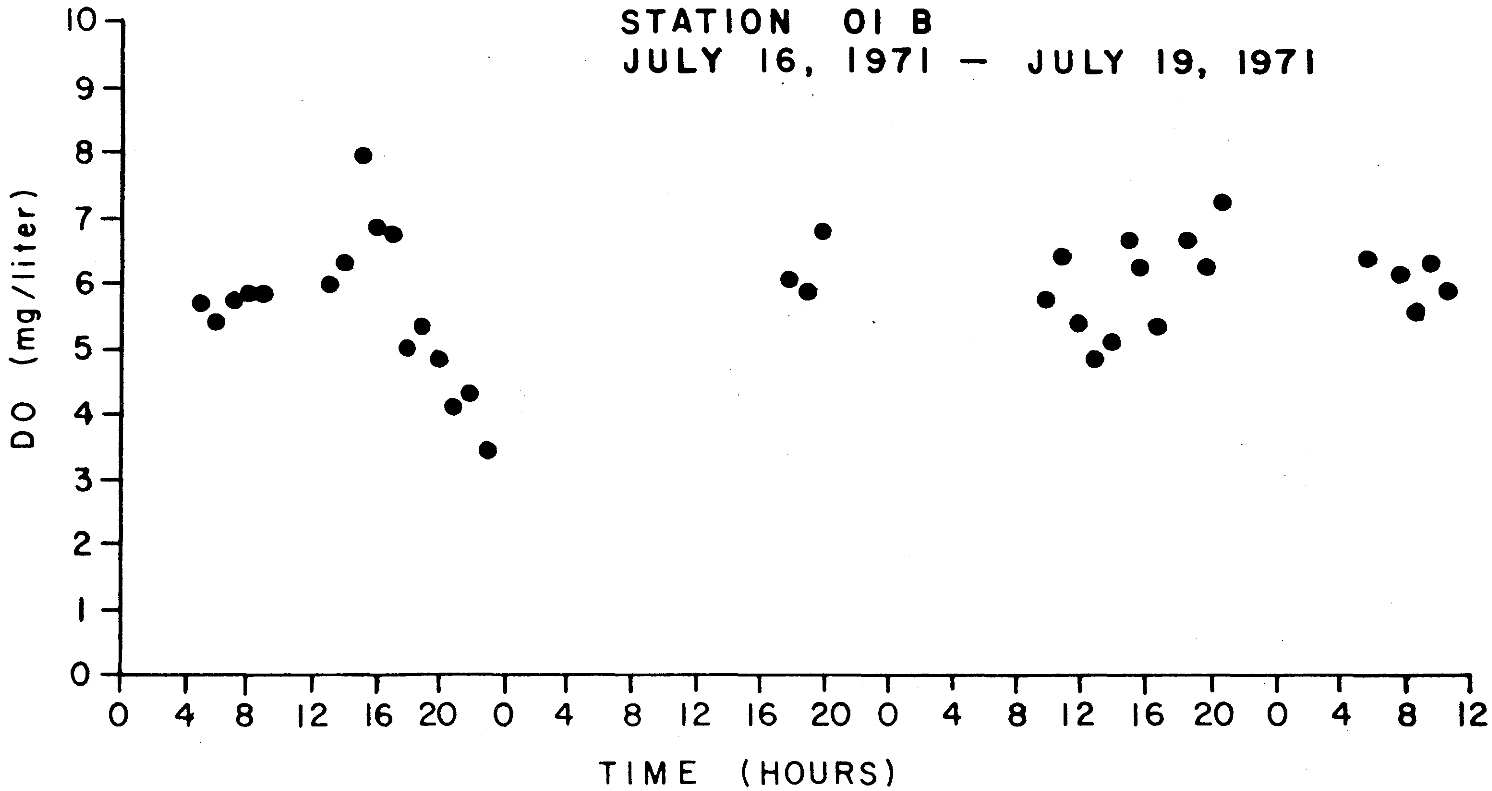

TIDE STATION #15
RICHMOND RIVER LOCKS
TIDAL HEIGHTS (Ft.)
8
7
6
5
4
3
2
1
0
-1
-2
30
JULY, 1971
AUGUST, 1971
5
10
15

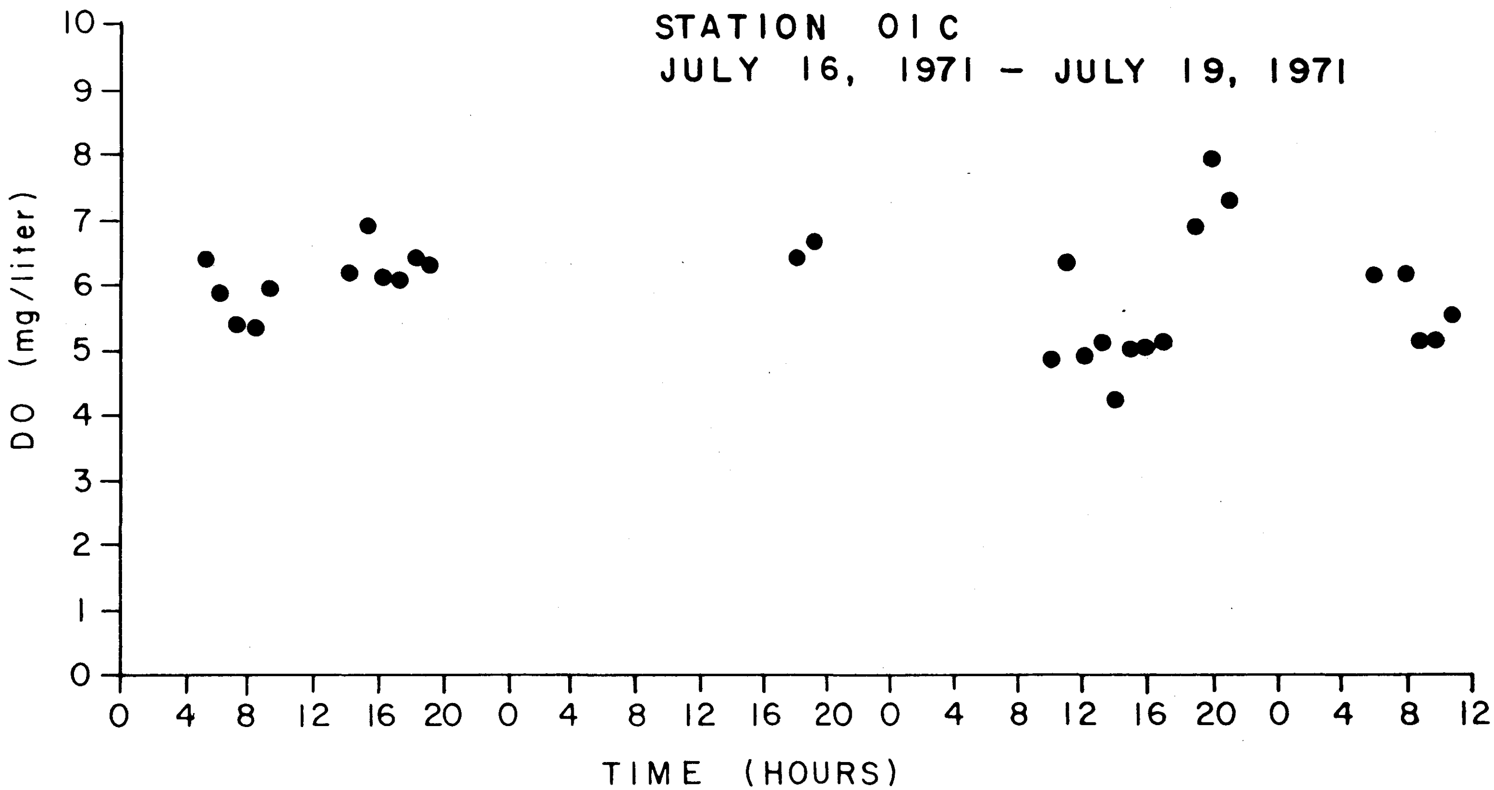

TIDE STATION #15
RICHMOND RIVER LOCKS
TIDAL HEIGHTS (Ft.)
8
7
6
5
4
3
2
1
0
-1
-2
20
AUGUST, 1971

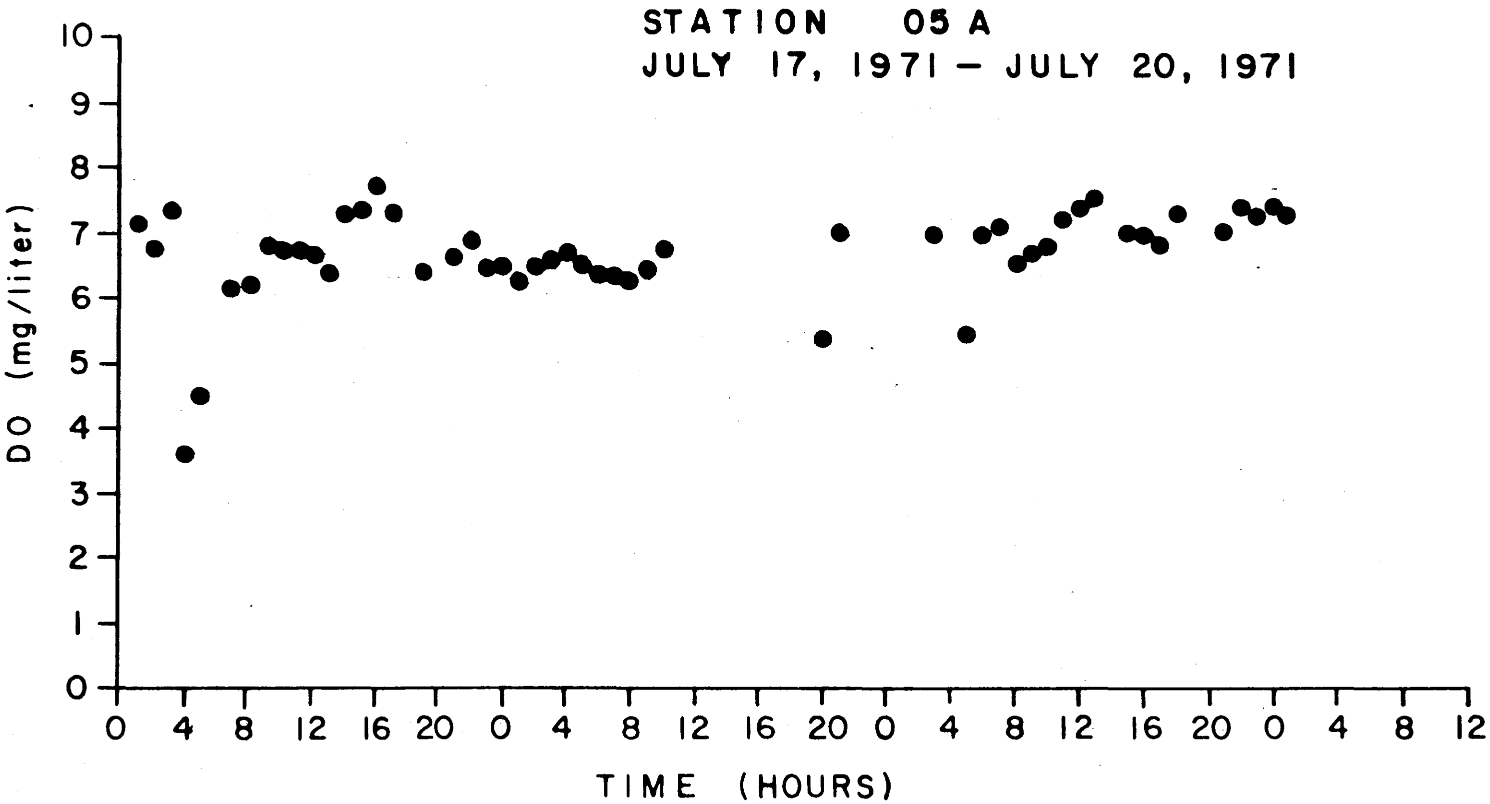
APPENDIX D

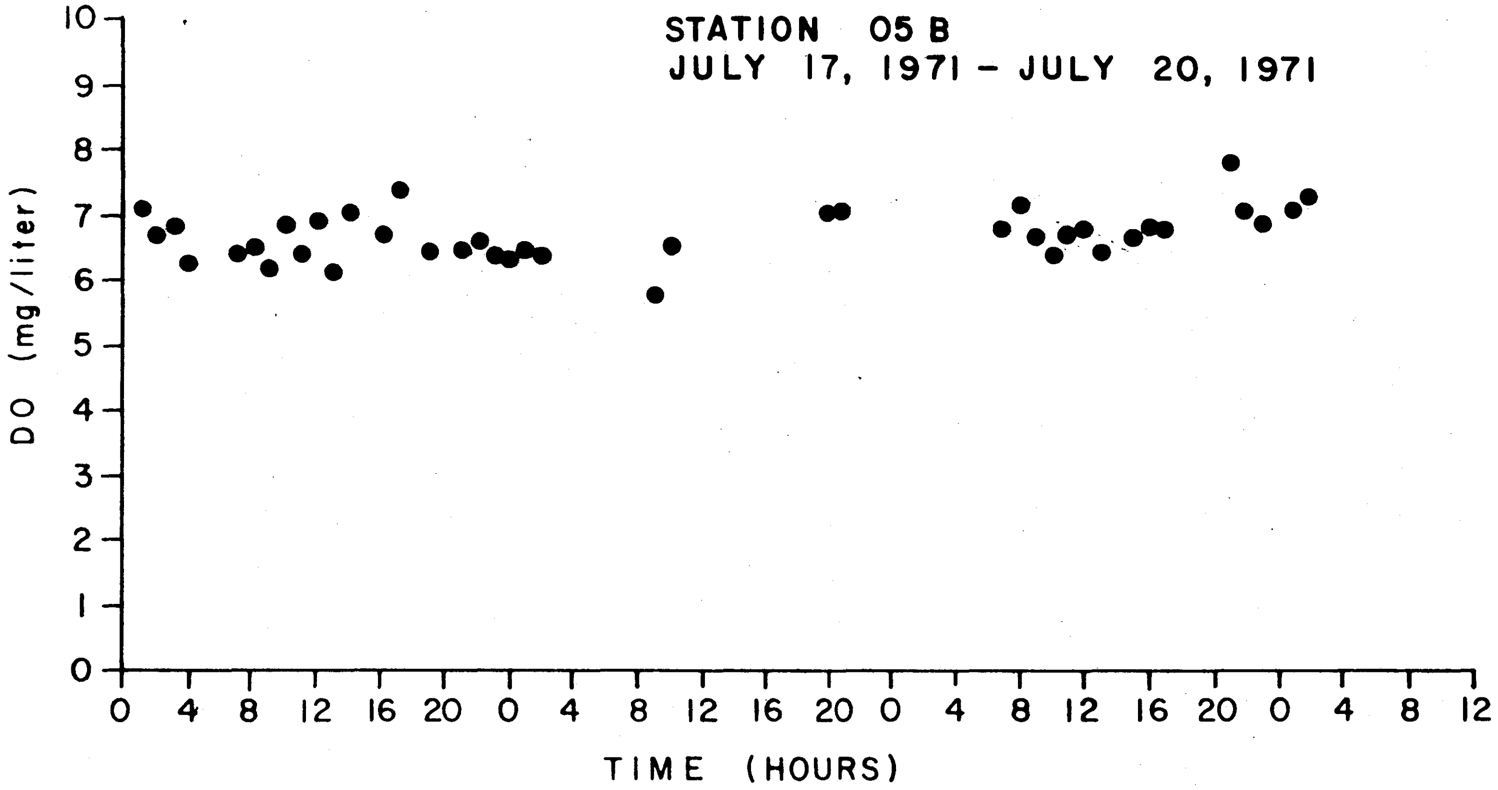
Samples of Graphical Summary of Data Collected During OJR '71

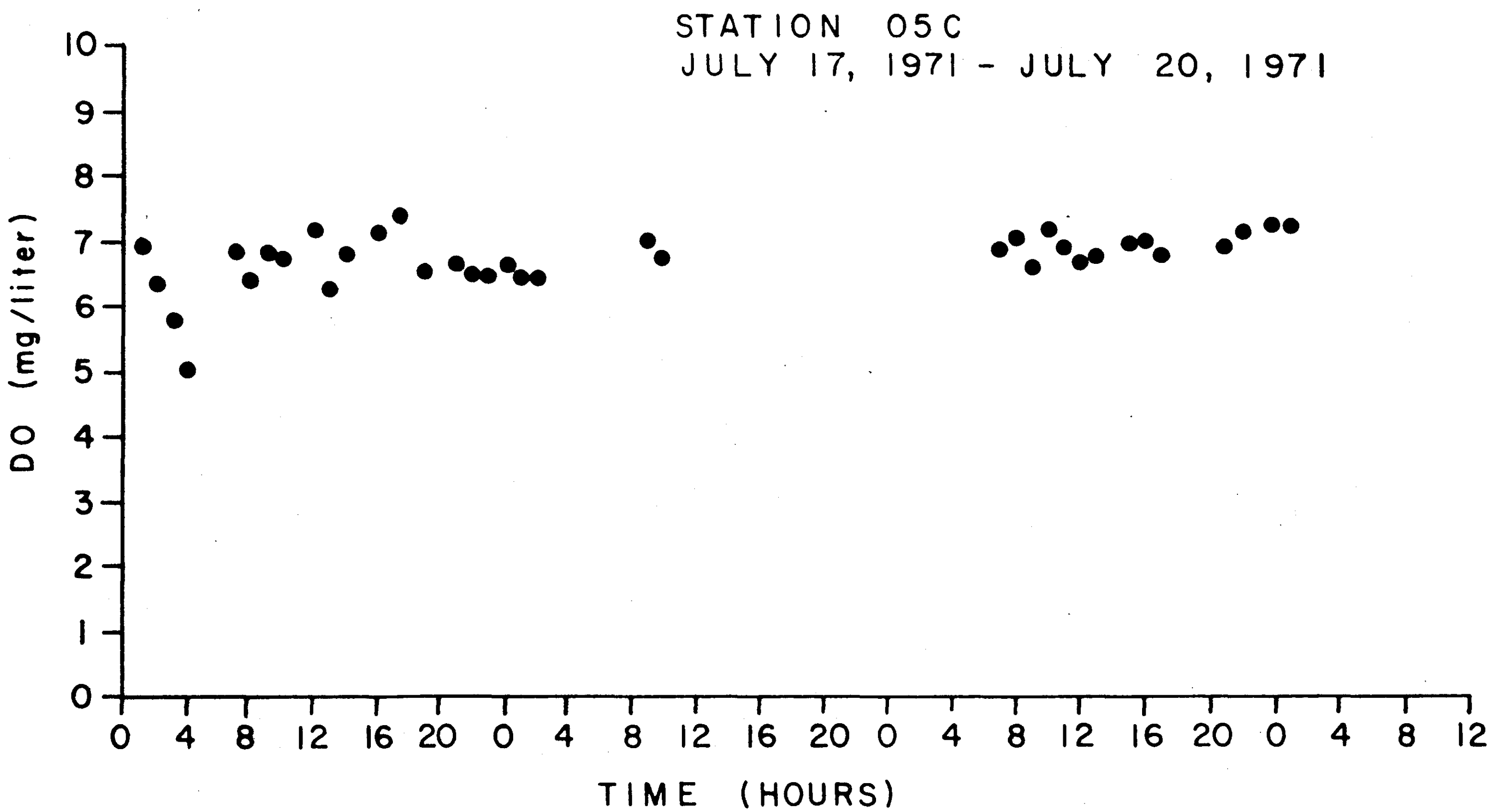

STATION 01 A
JULY 9, 1971 - JULY 12, 1971
DO (mg/liter)
10
9
8
7
6
5
4
3
2
1
0
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

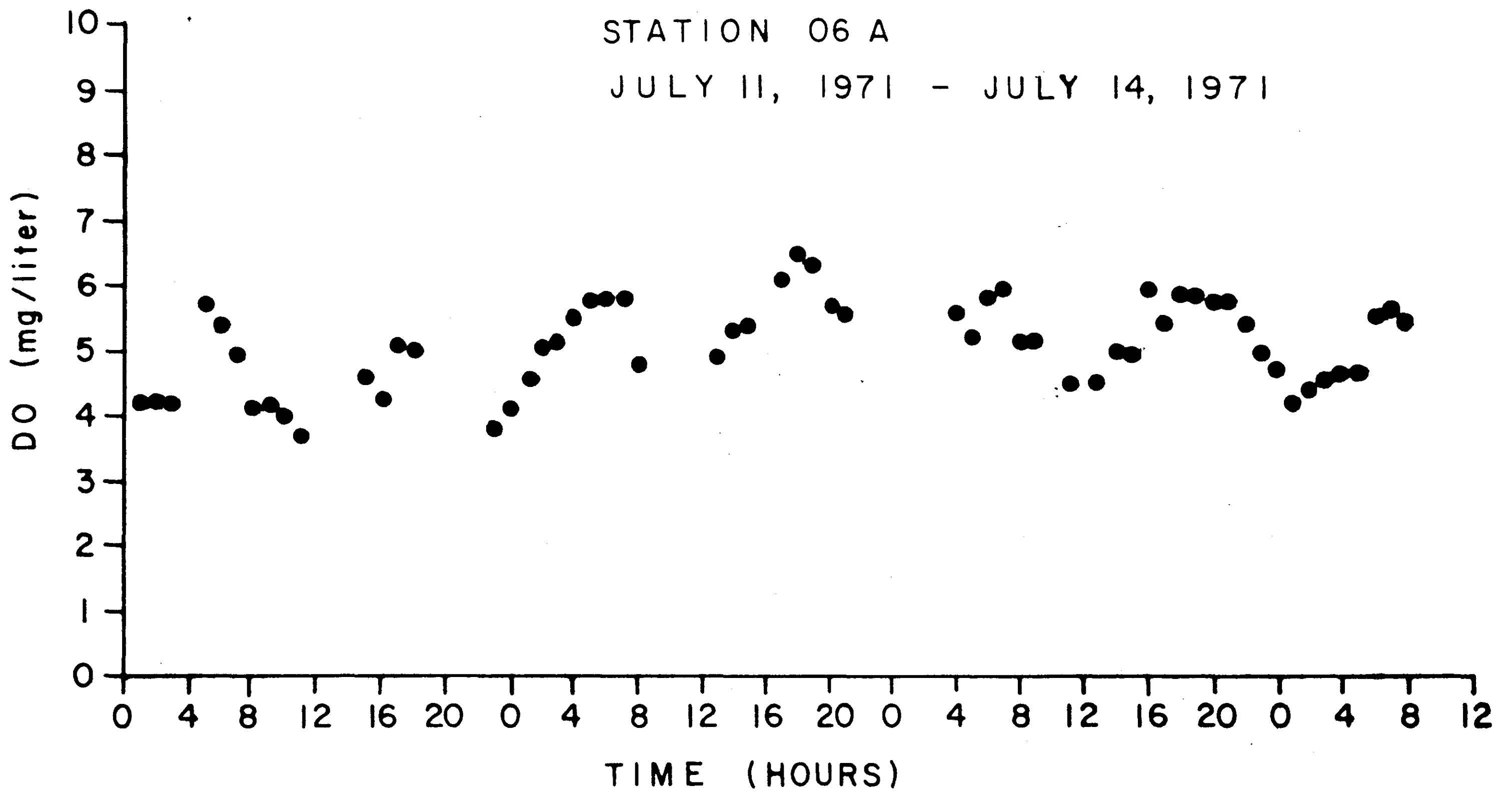

STATION 01 B
JULY 16, 1971 — JULY 19, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

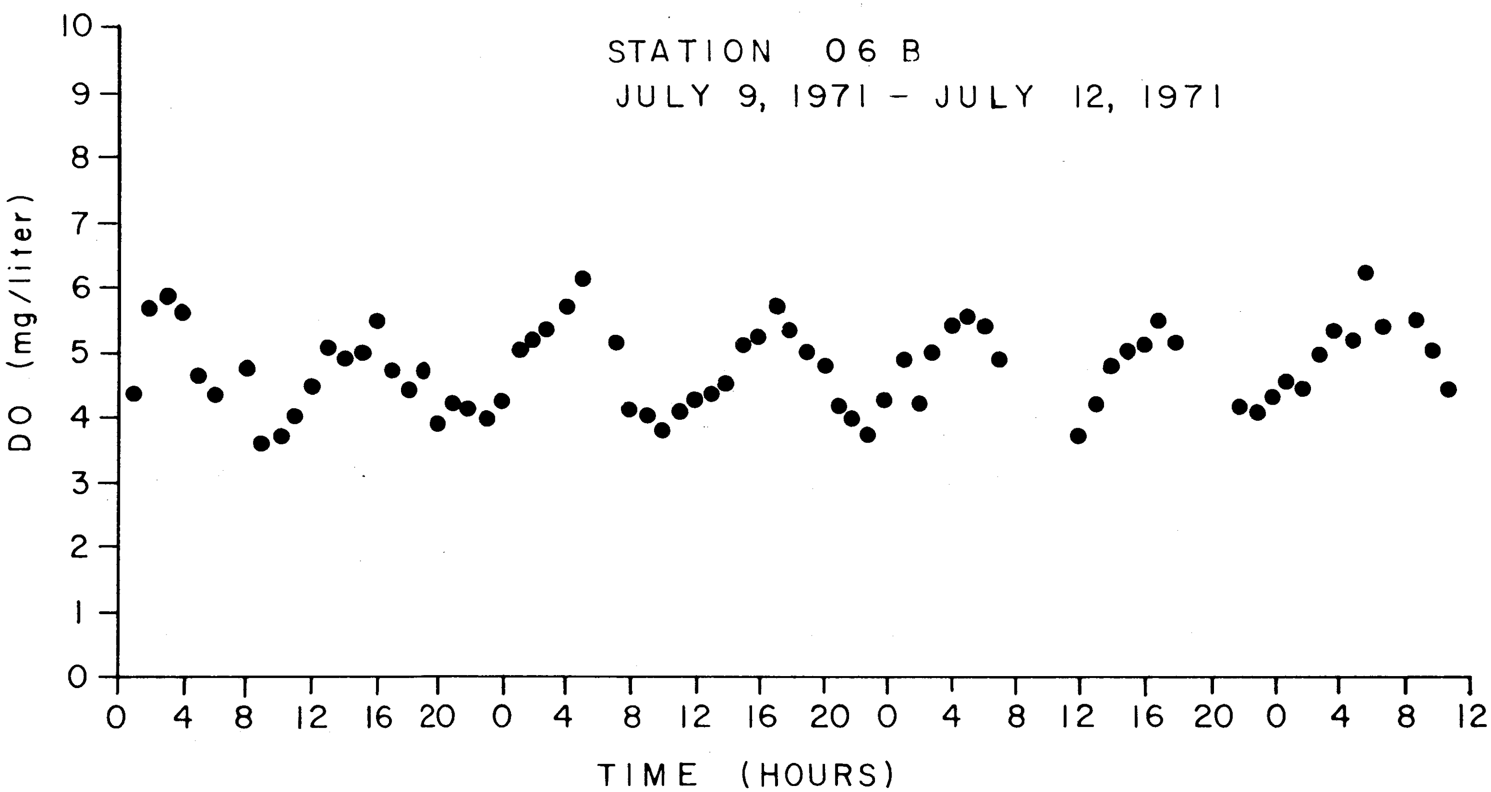

STATION 01C
JULY 16, 1971 – JULY 19, 1971
DO (mg/liter)
TIME (HOURS)
0 1 2 3 4 5 6 7 8 9 10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12

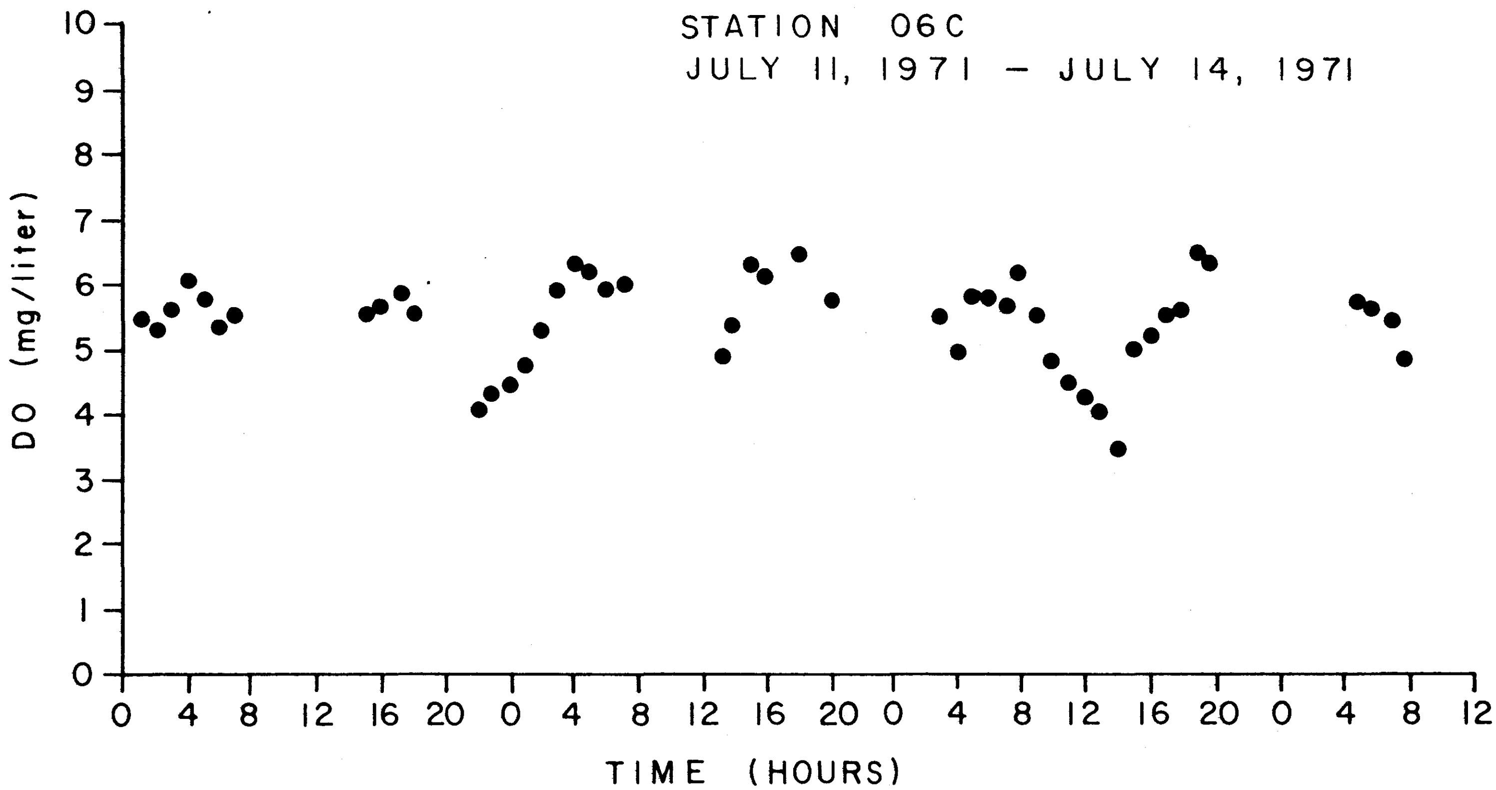

STATION 05 A
JULY 17, 1971 – JULY 20, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

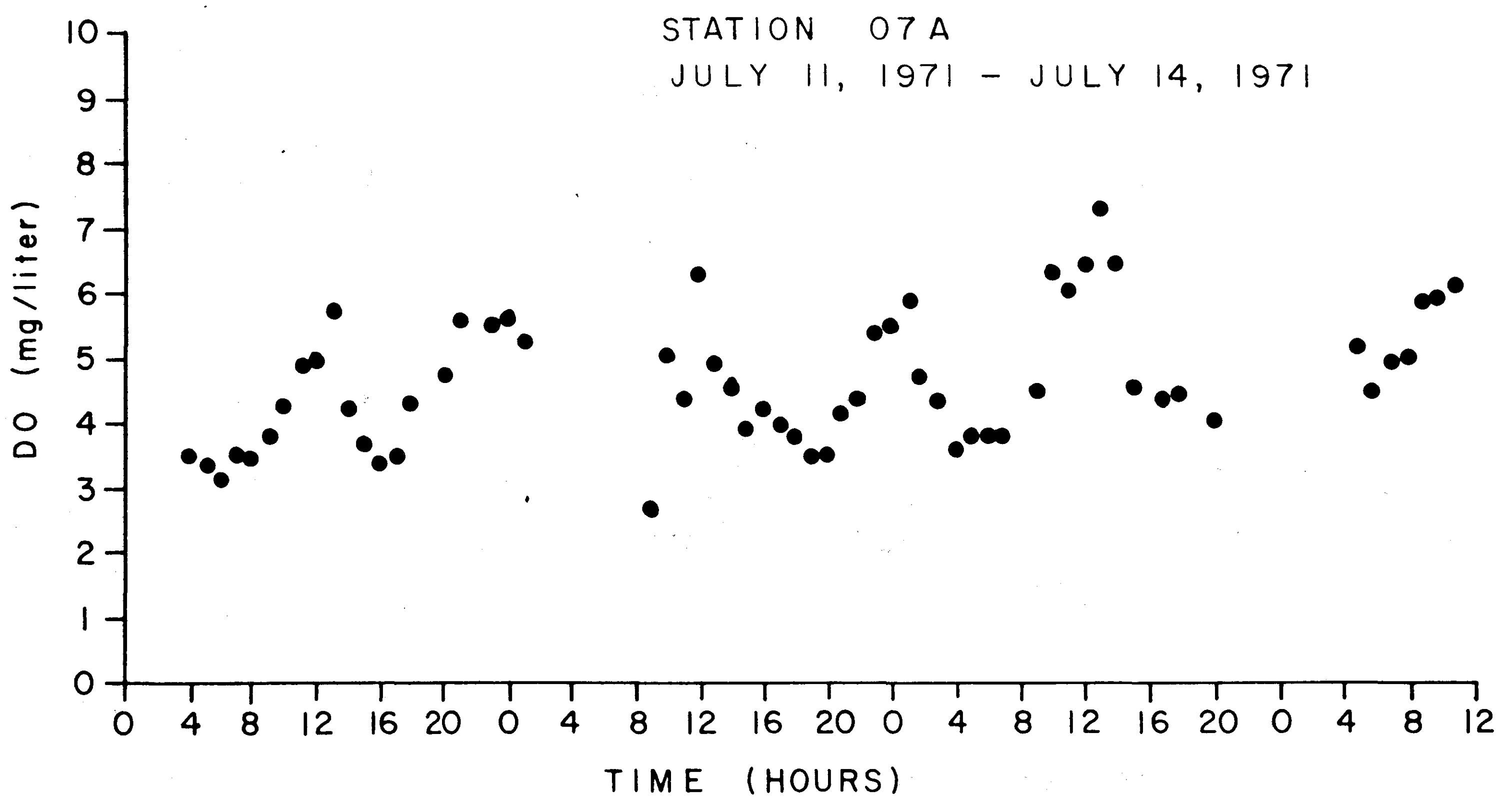

STATION 05 B
JULY 17, 1971 - JULY 20, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

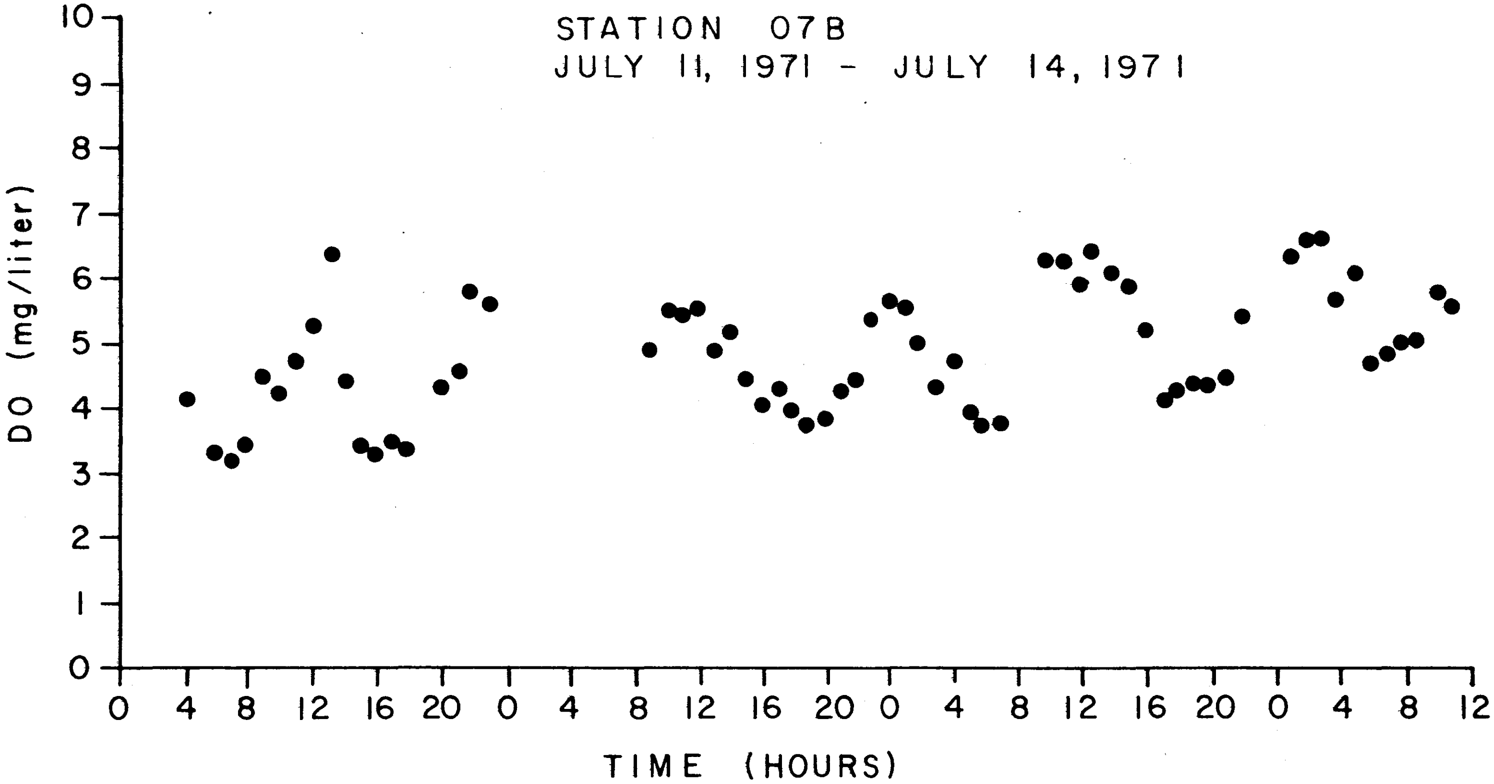

STATION 05C
JULY 17, 1971 - JULY 20, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

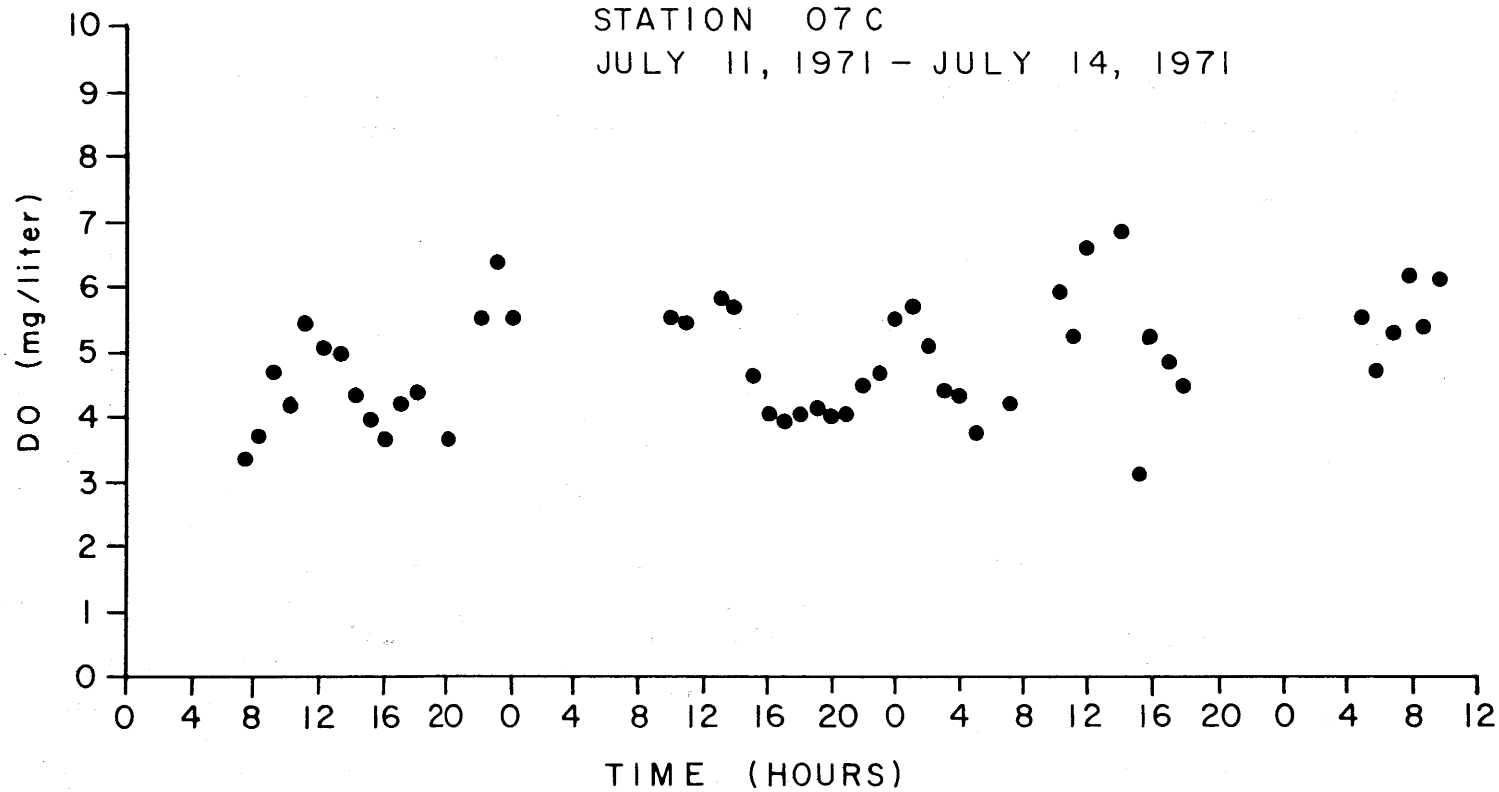

STATION 06 A
JULY 11, 1971 - JULY 14, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

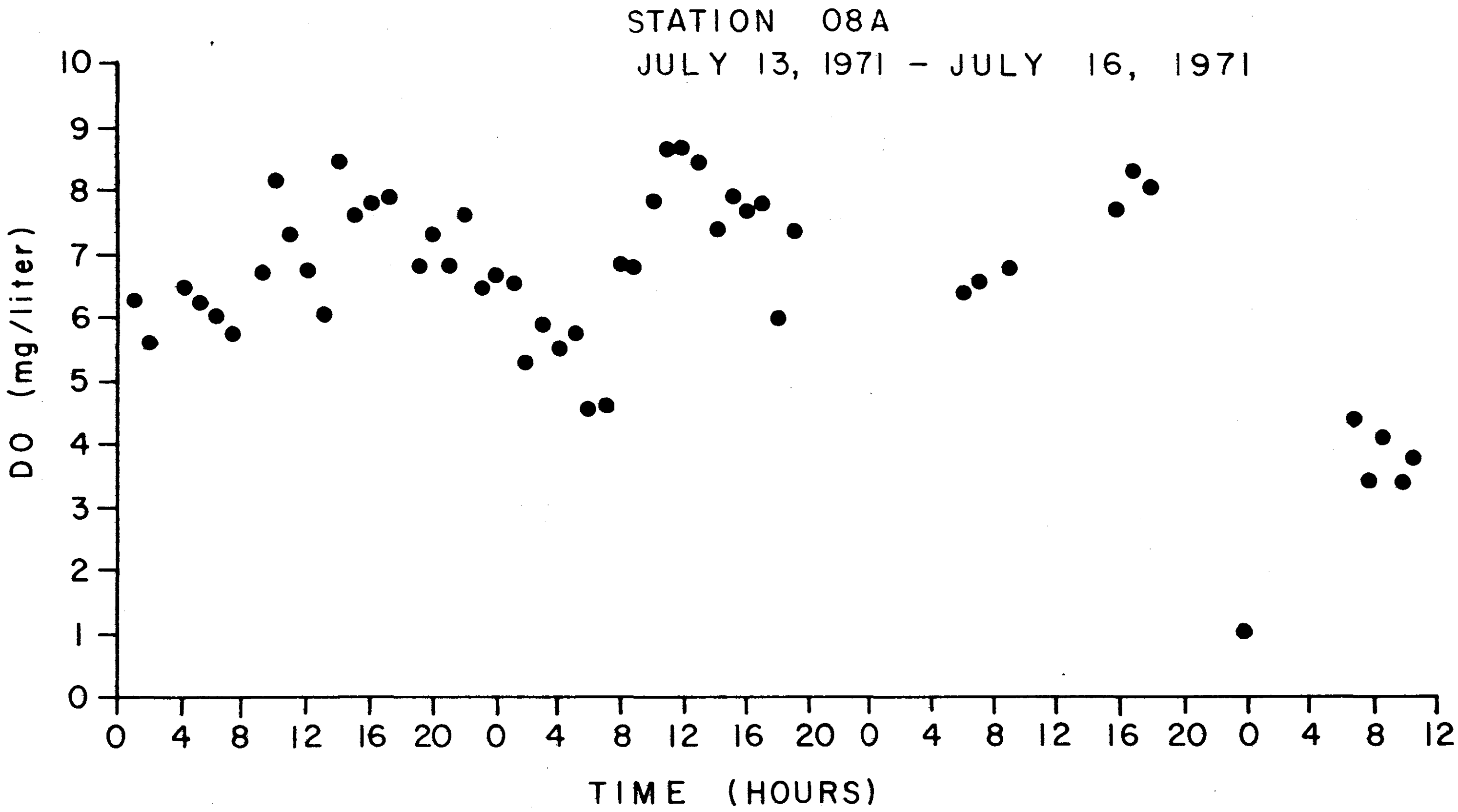

STATION 06 B
JULY 9, 1971 – JULY 12, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

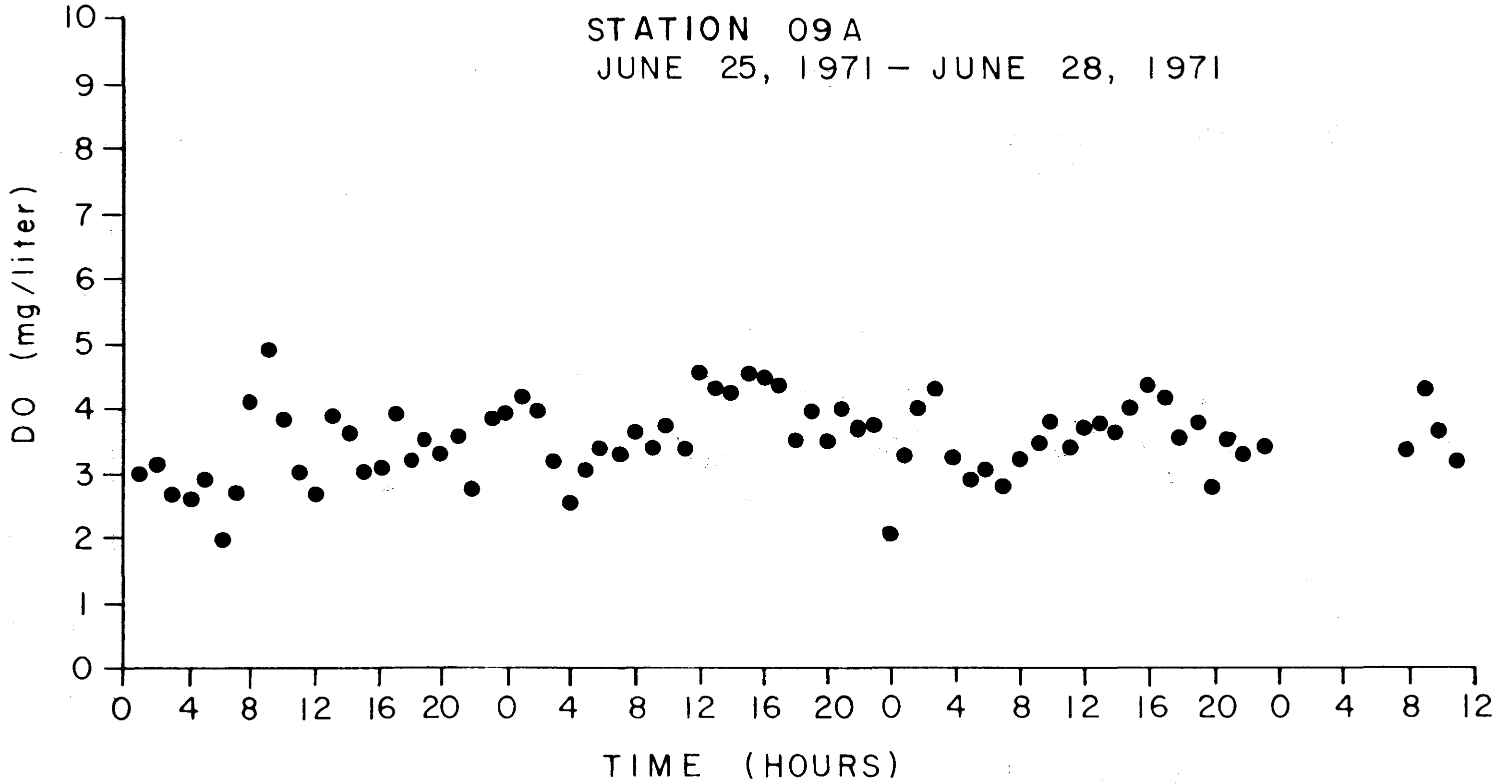

STATION 06C
JULY 11, 1971 – JULY 14, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

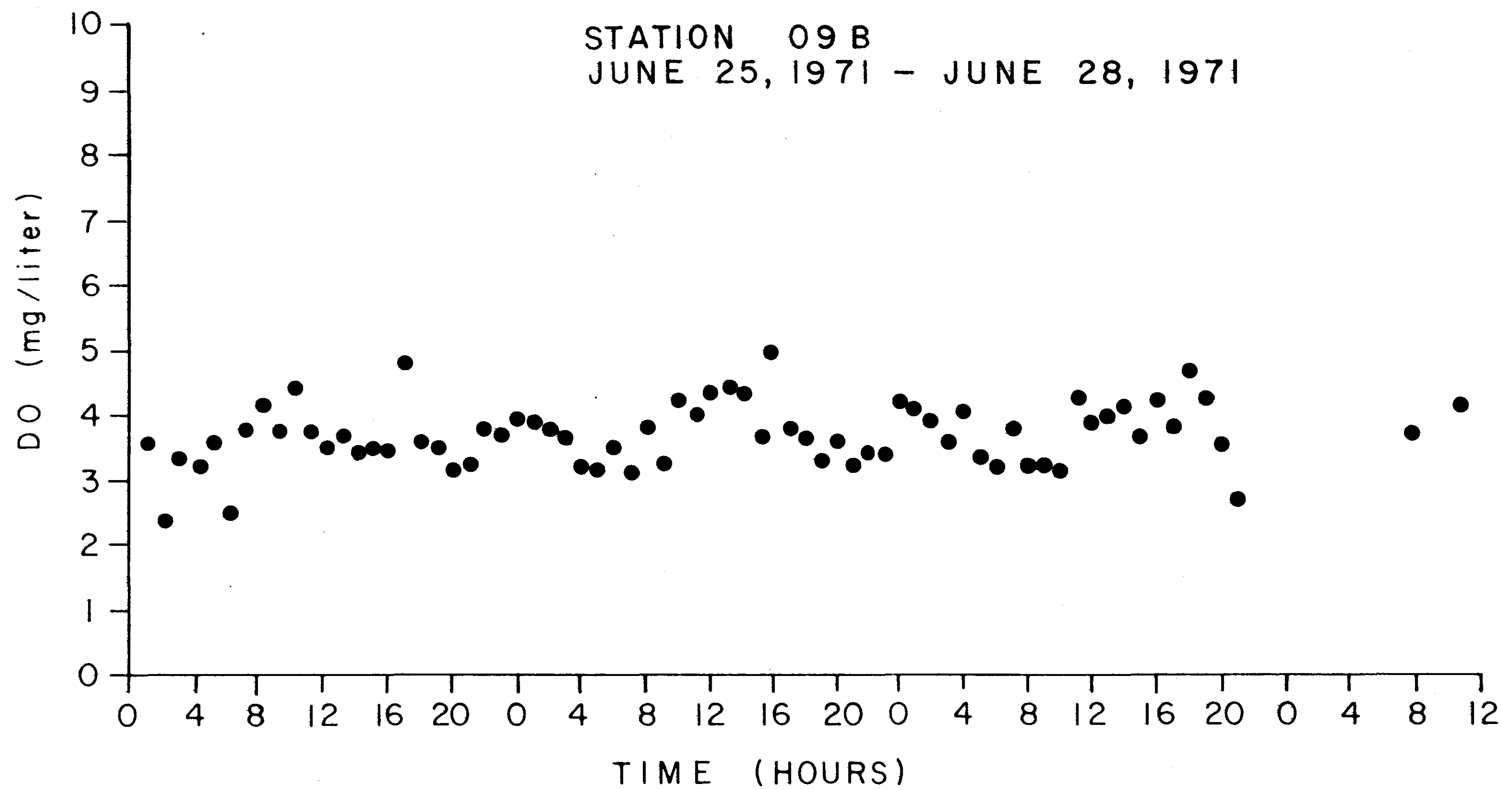

STATION 07A
JULY 11, 1971 - JULY 14, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

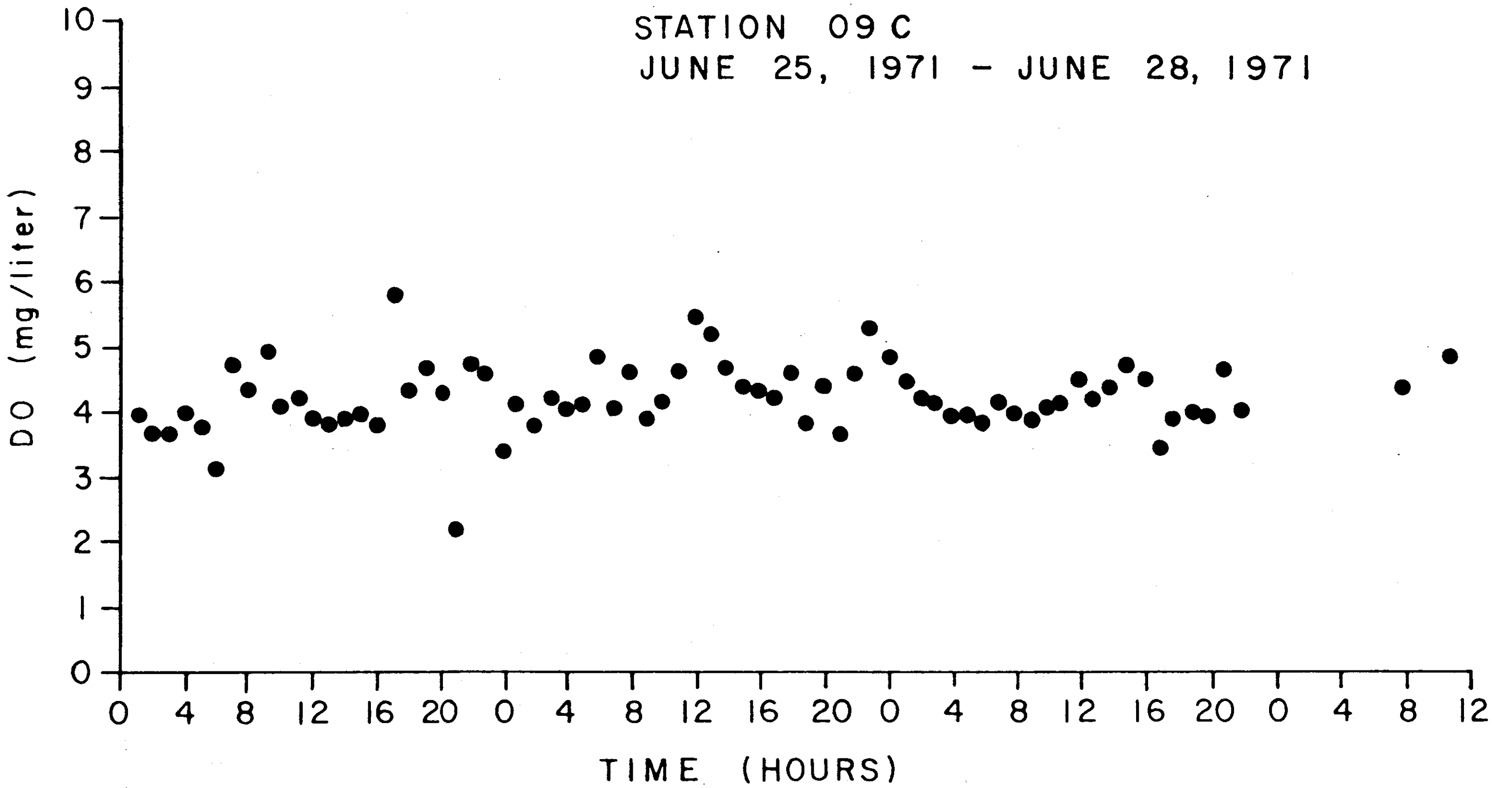

STATION 07B
JULY 11, 1971 - JULY 14, 1971
DO (mg/liter)
10
9
8
7
6
5
4
3
2
1
0
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)


STATION 07C
JULY 11, 1971 – JULY 14, 1971
DO (mg/liter)
10
9
8
7
6
5
4
3
2
1
0
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

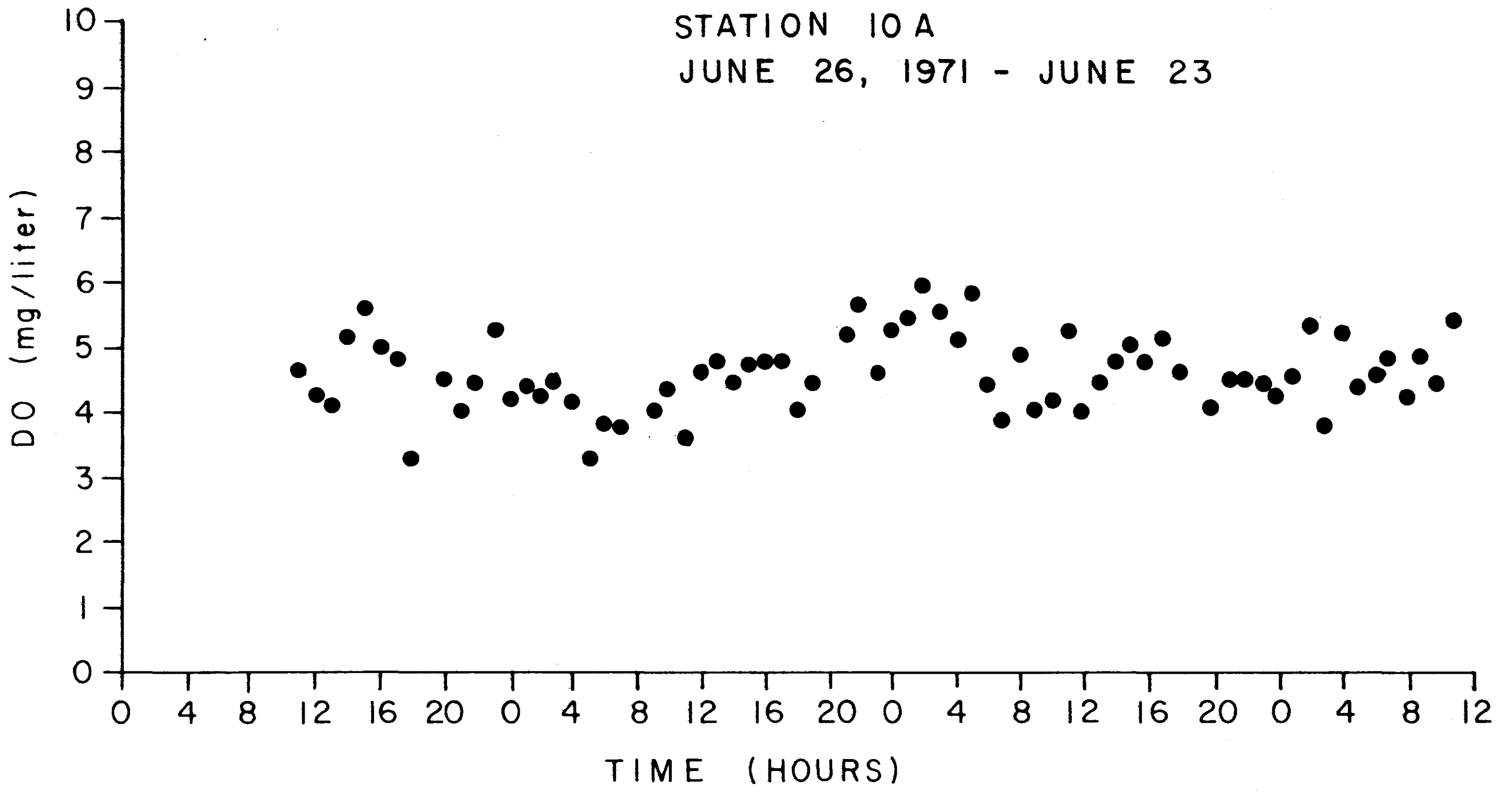

STATION 08A
JULY 13, 1971 - JULY 16, 1971
DO (mg/liter)
0 1 2 3 4 5 6 7 8 9 10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

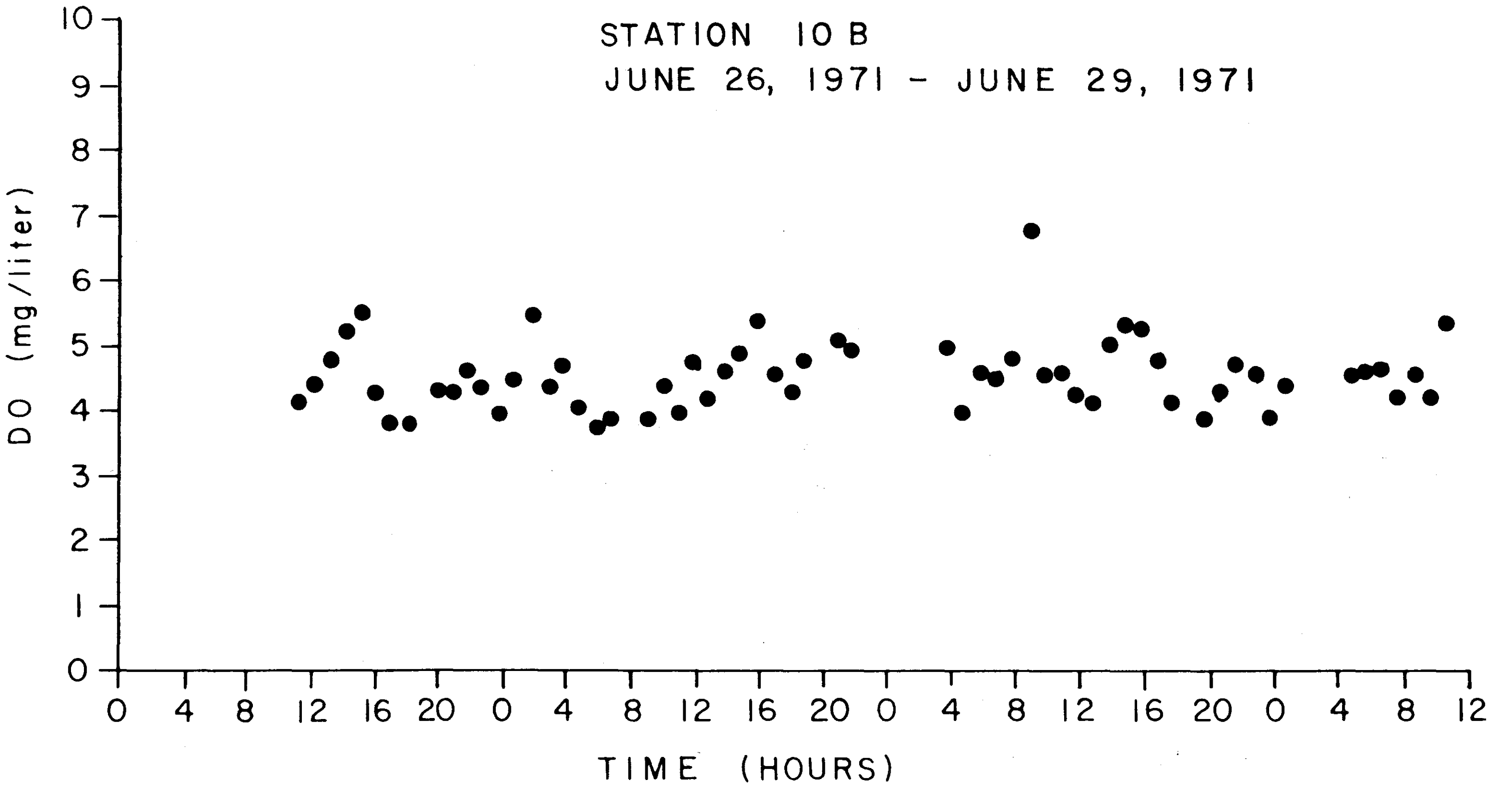

STATION 09A
JUNE 25, 1971 – JUNE 28, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

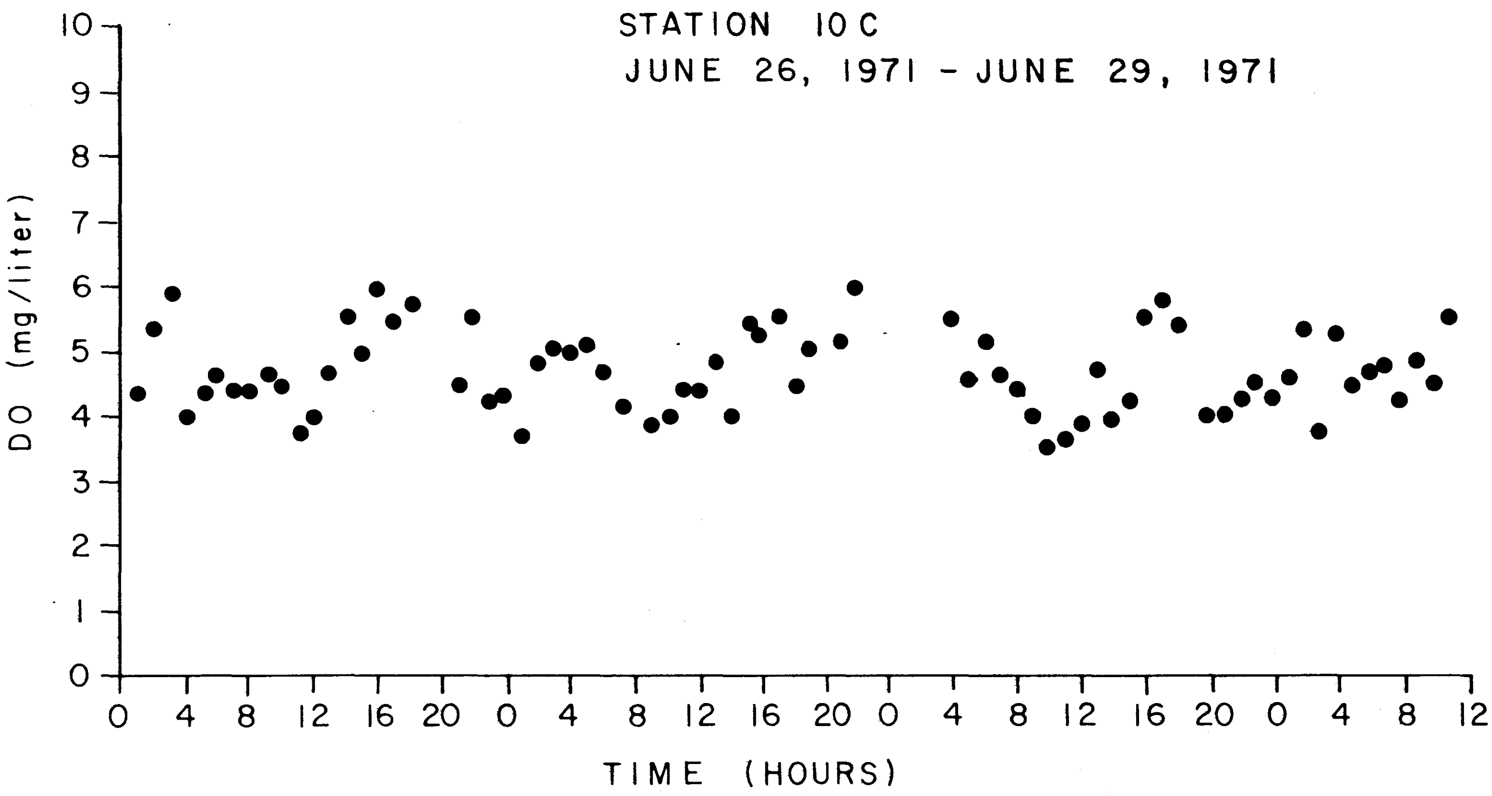

STATION 09 B
JUNE 25, 1971 - JUNE 28, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

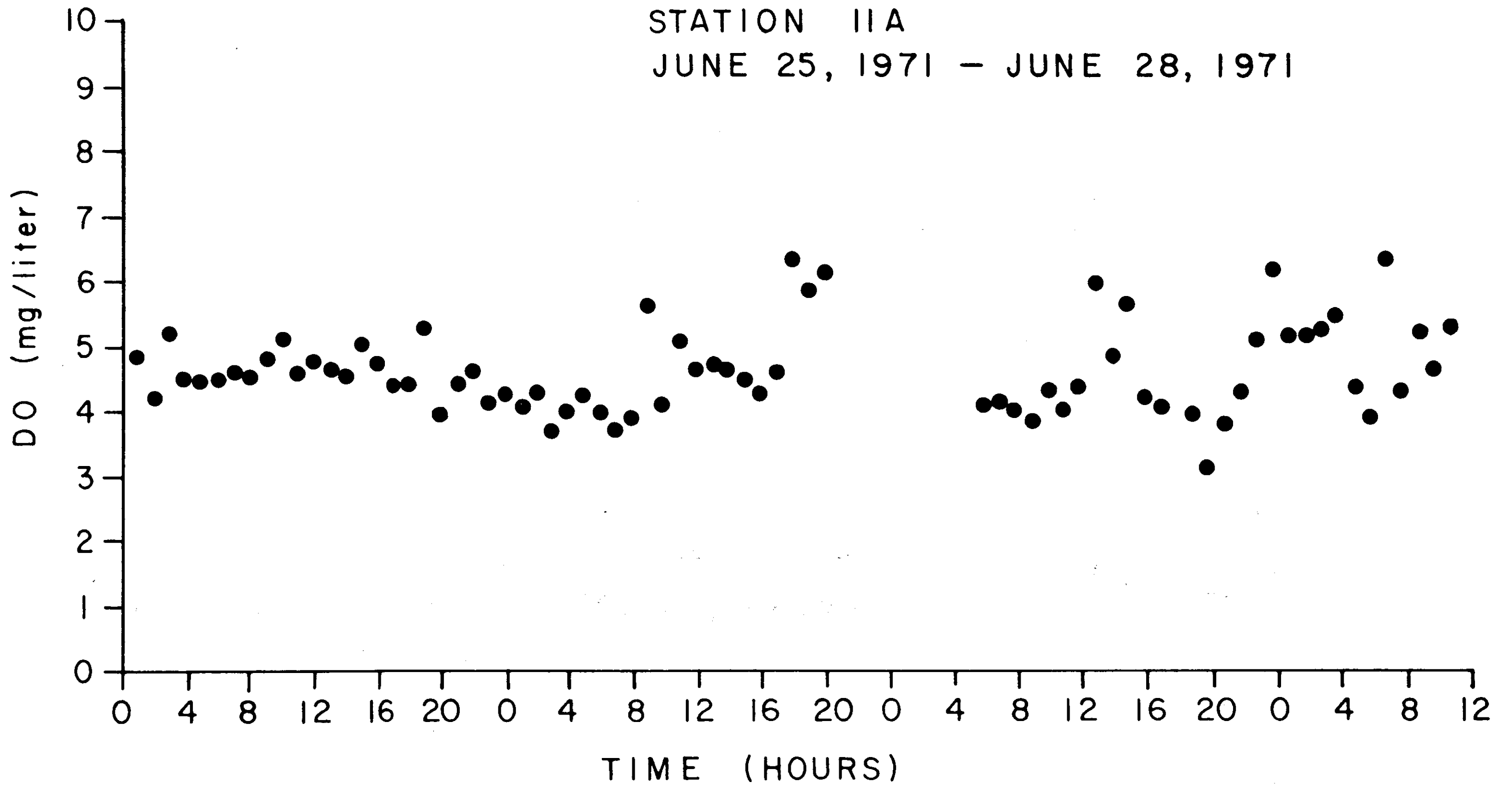


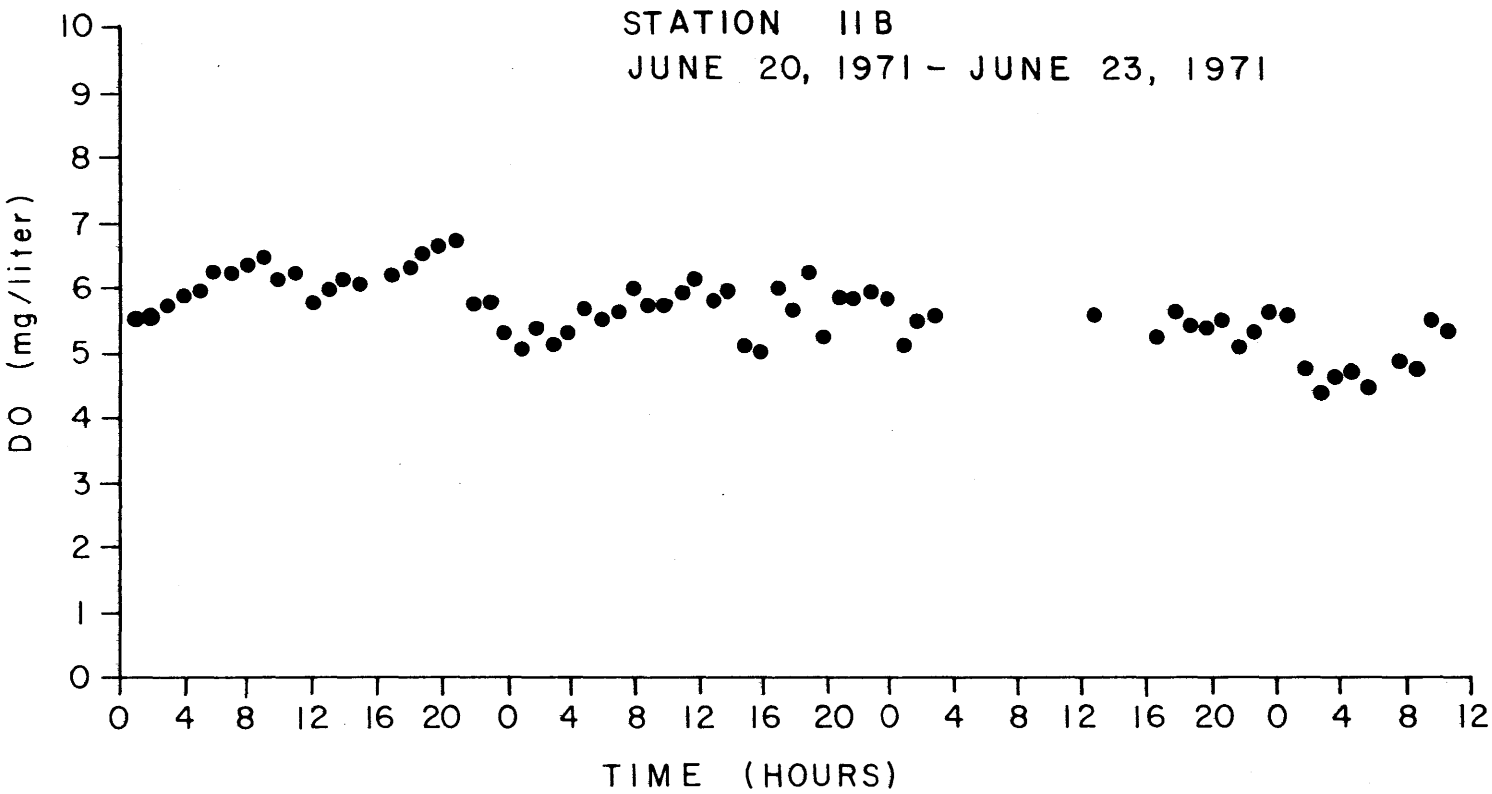
STATION 09 C
JUNE 25, 1971 - JUNE 28, 1971
DO (mg/liter)
TIME (HOURS)

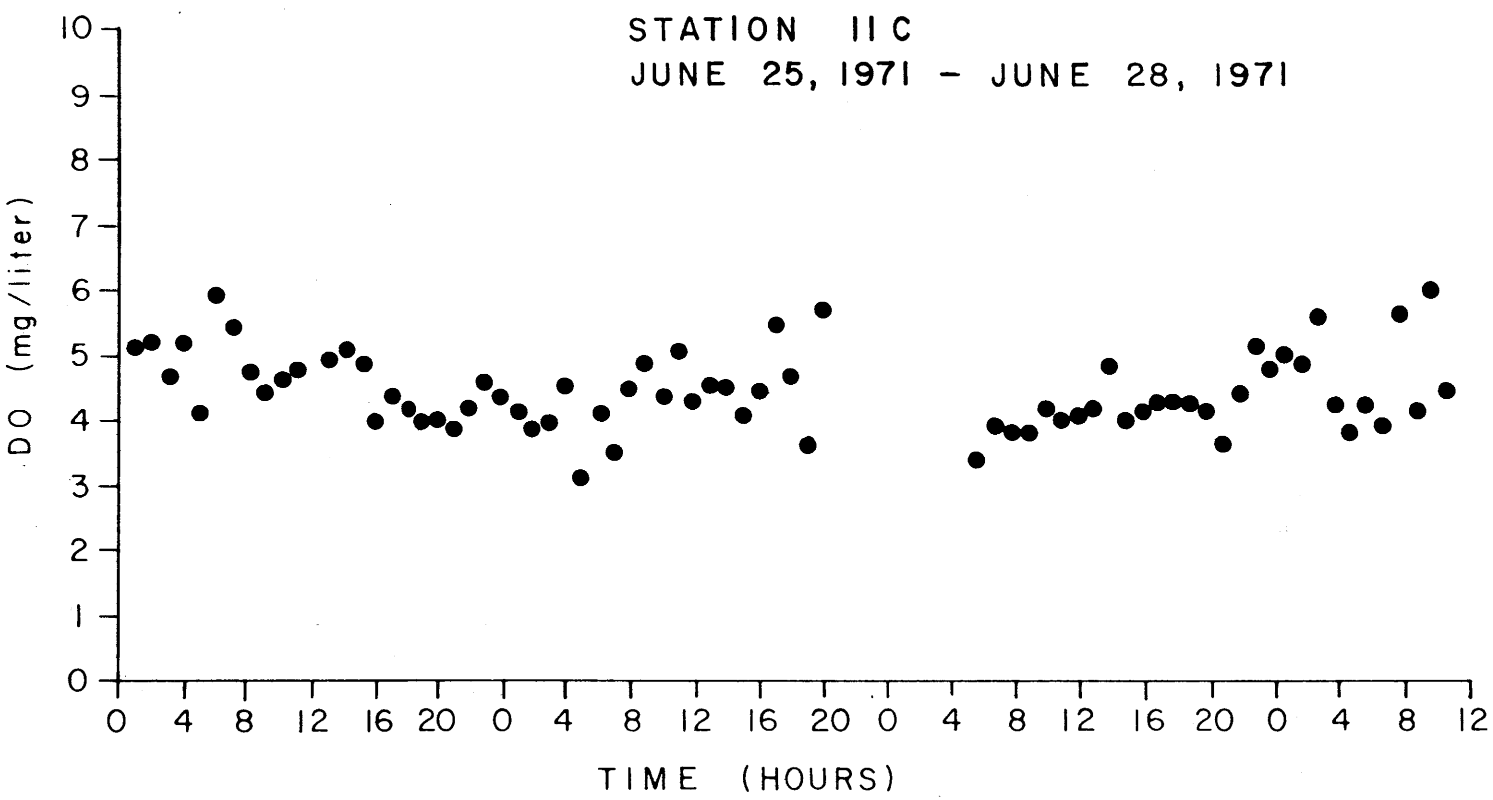

STATION 10 A
JUNE 26, 1971 - JUNE 23
DO (mg/liter)
10
9
8
7
6
5
4
3
2
1
0
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)


STATION 10 B
JUNE 26, 1971 - JUNE 29, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

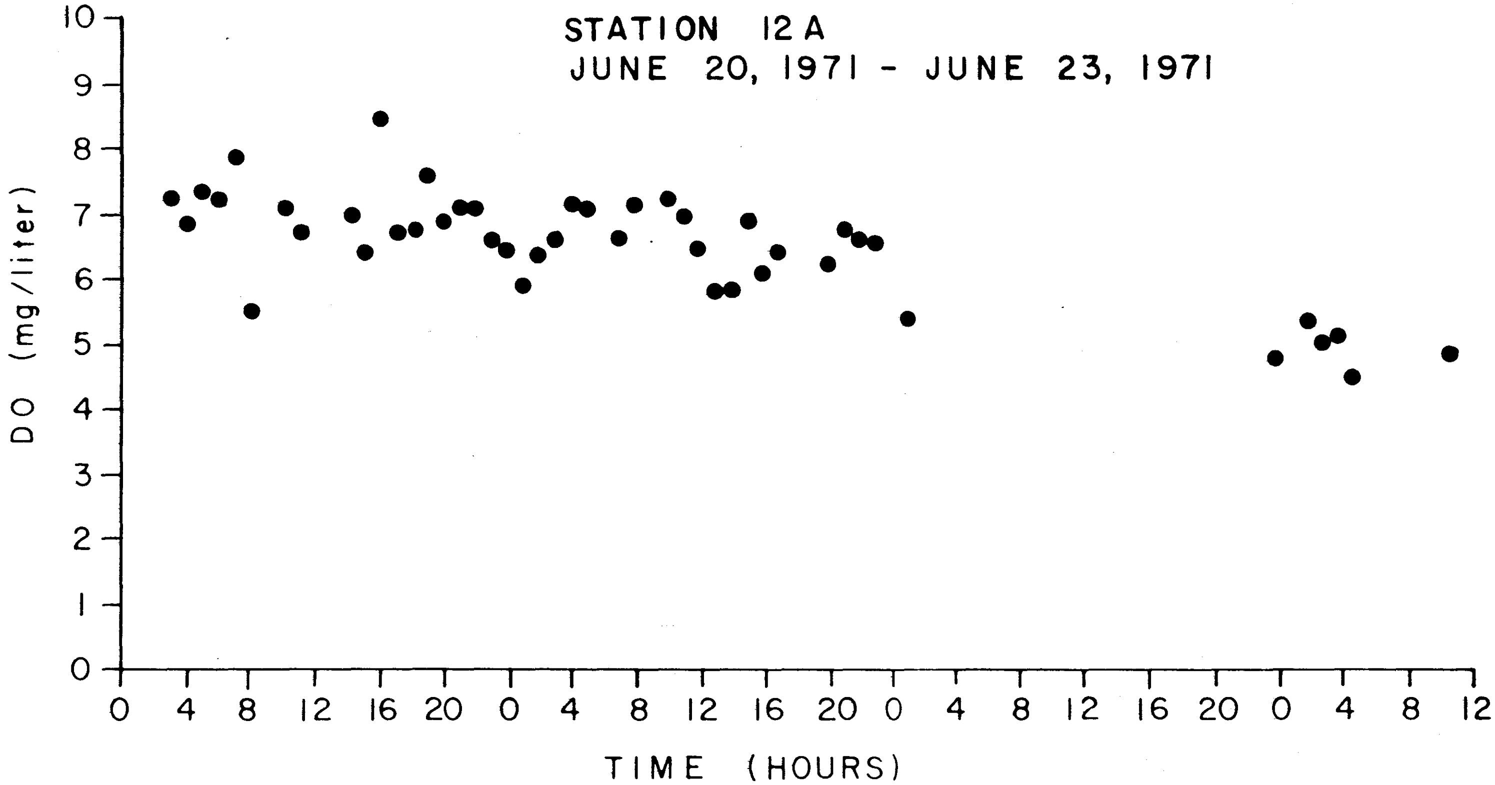

STATION 10 C
JUNE 26, 1971 - JUNE 29, 1971
DO (mg/liter)
TIME (HOURS)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12

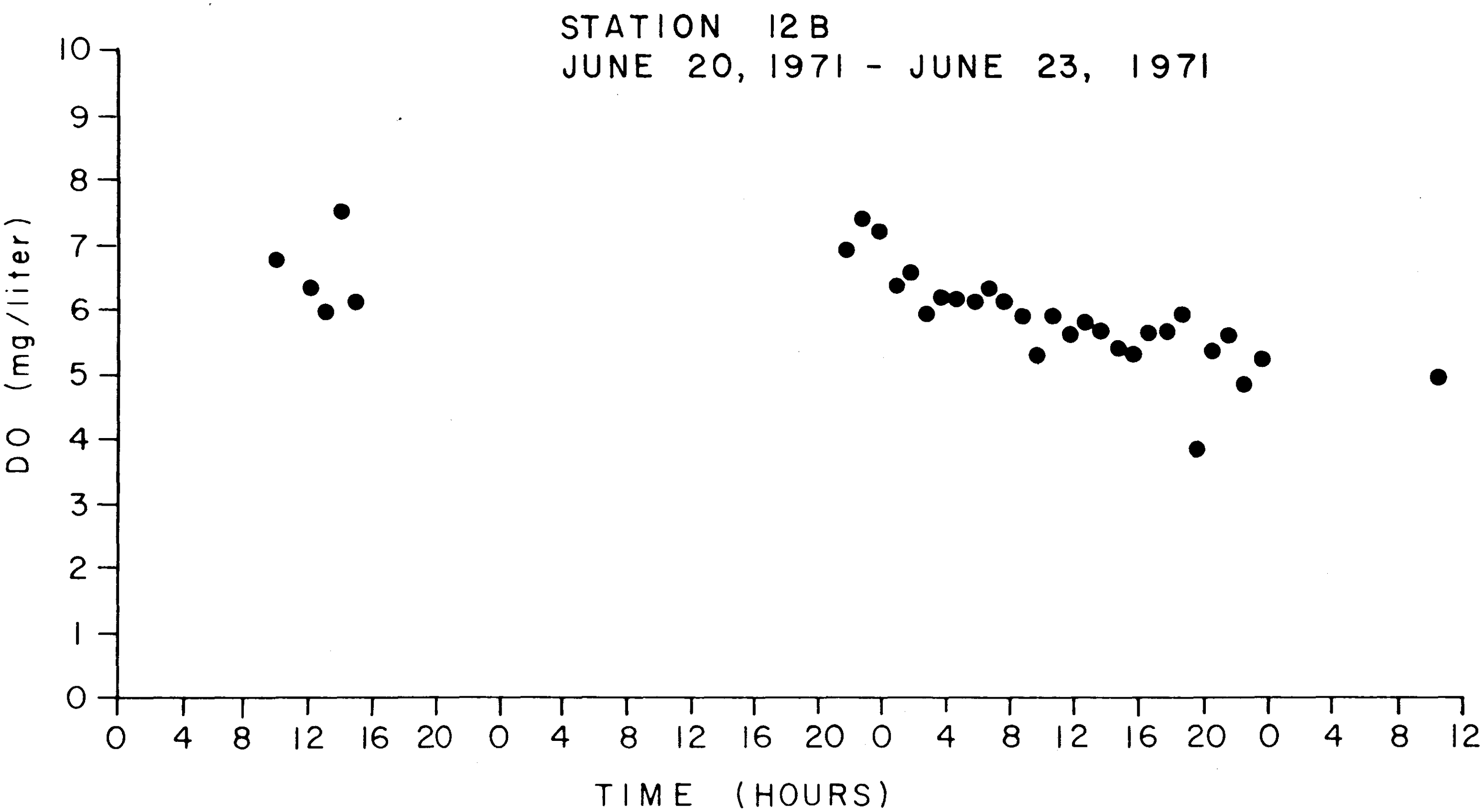

STATION 11A
JUNE 25, 1971 – JUNE 28, 1971
DO (mg/liter)
TIME (HOURS)
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
0 1 2 3 4 5 6 7 8 9 10

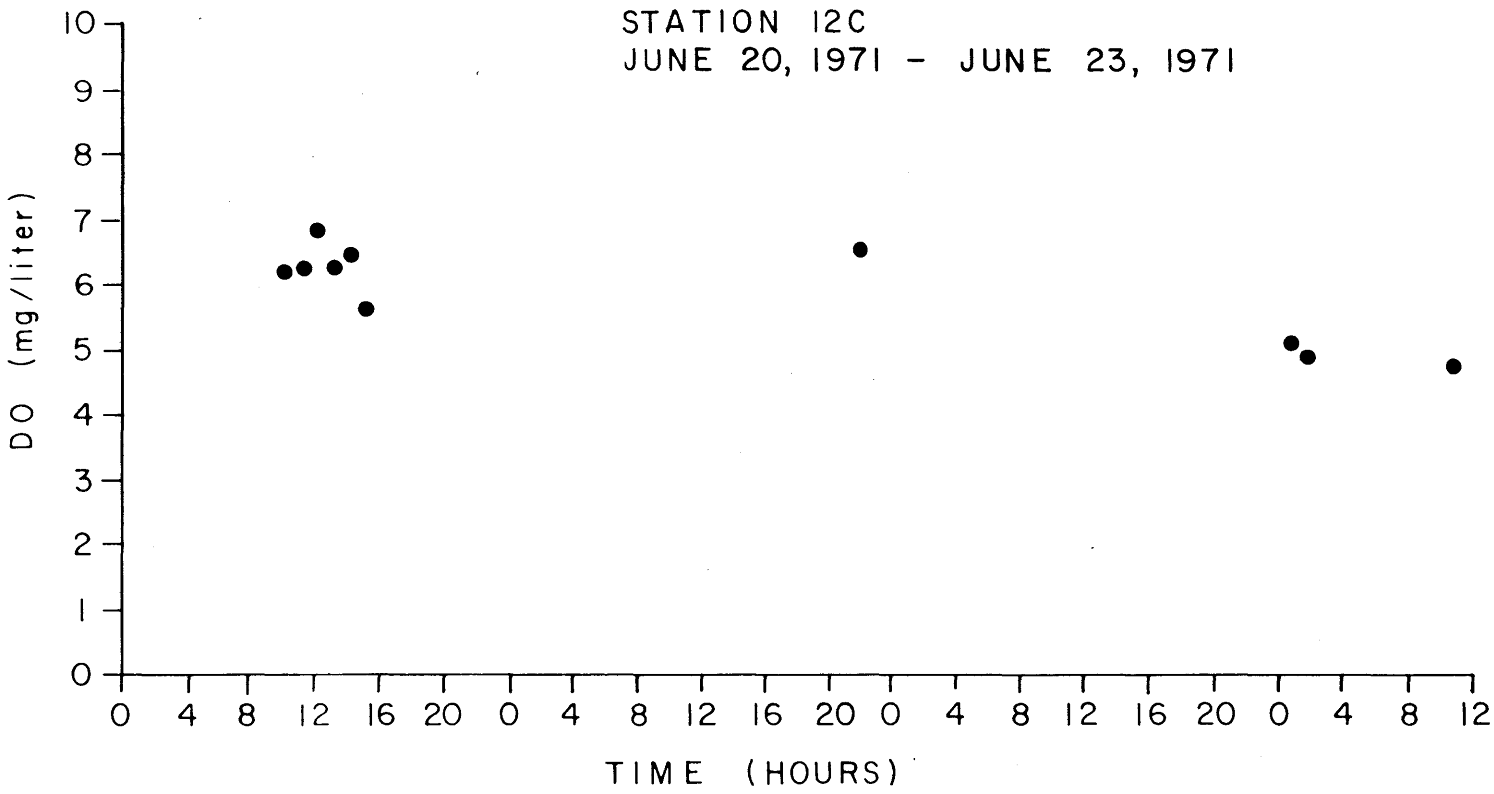

STATION 11B
JUNE 20, 1971 - JUNE 23, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

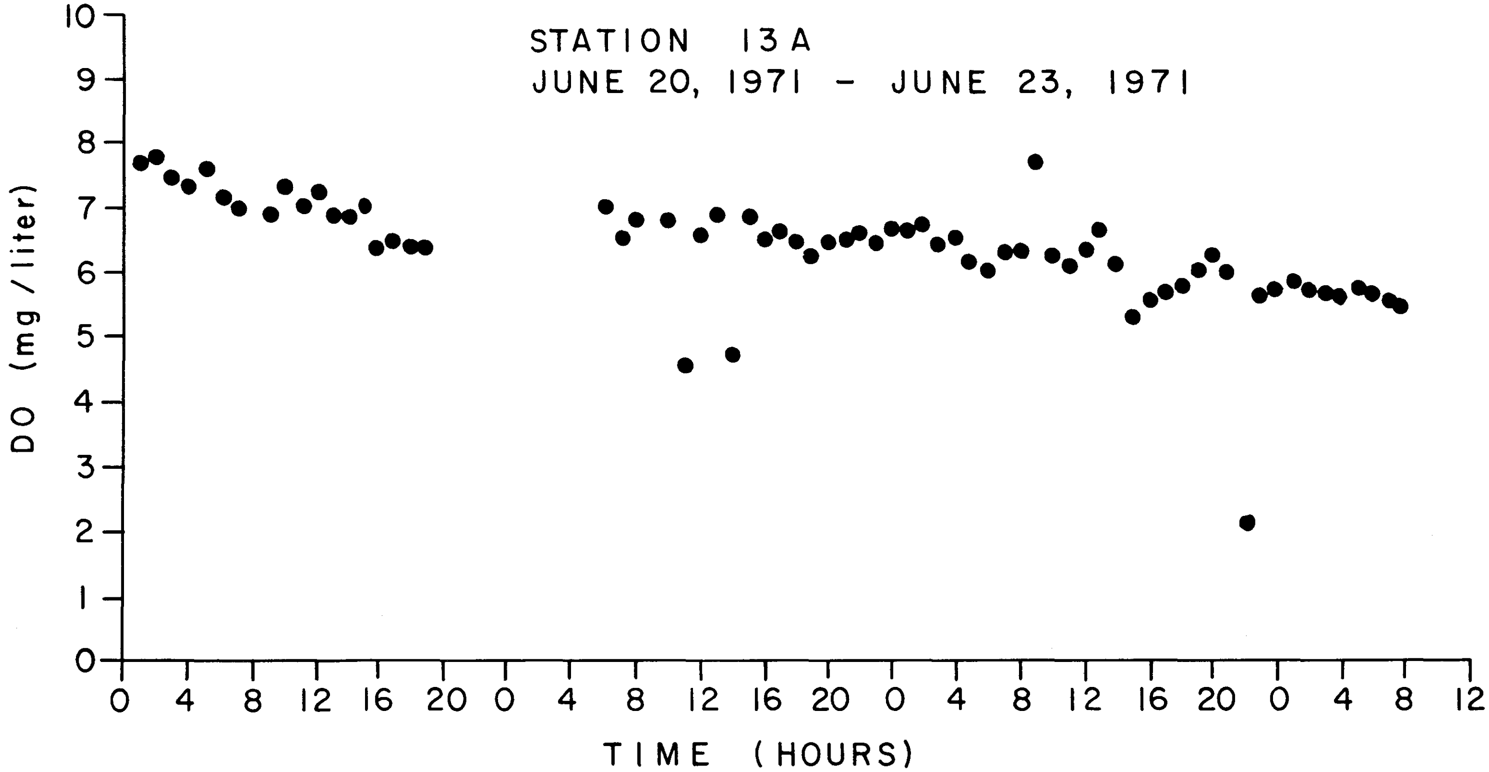


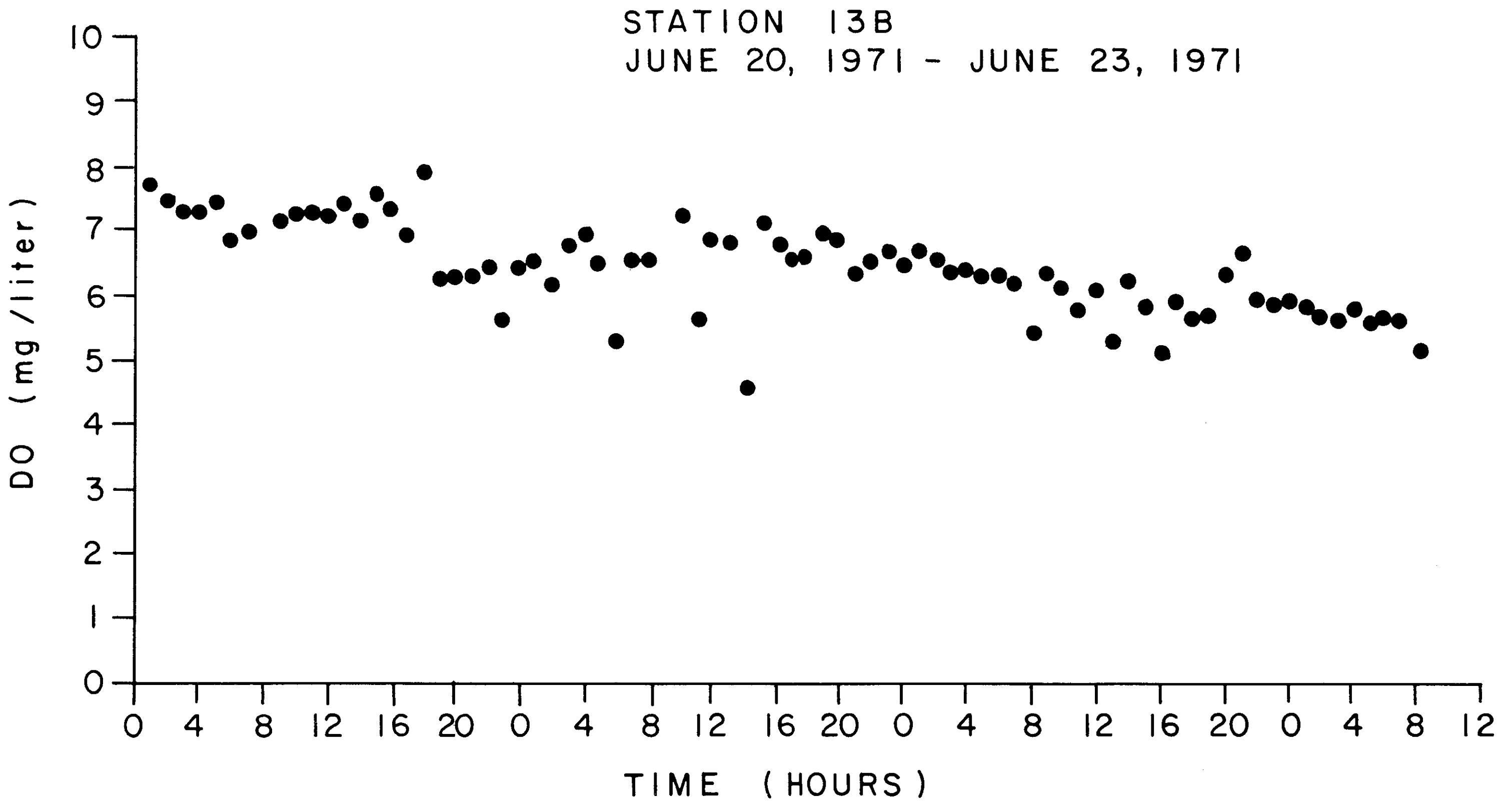
STATION IIC
JUNE 25, 1971 - JUNE 28, 1971
DO (mg/liter)
10
9
8
7
6
5
4
3
2
1
0
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)


STATION 12 A
JUNE 20, 1971 - JUNE 23, 1971
DO (mg/liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)

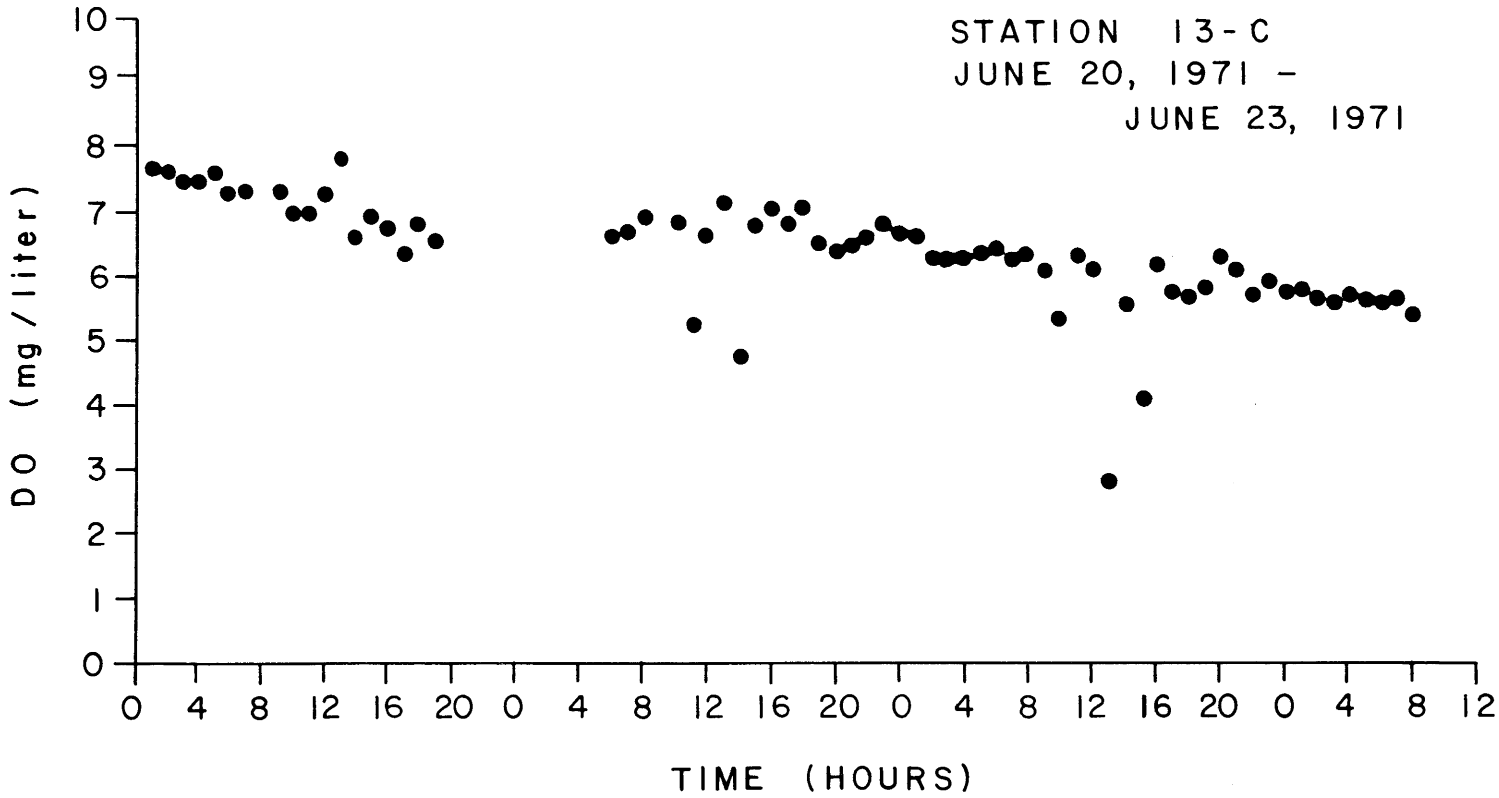

STATION 12B
JUNE 20, 1971 - JUNE 23, 1971
DO (mg/liter)
TIME (HOURS)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12


STATION 12C
JUNE 20, 1971 - JUNE 23, 1971
DO (mg/liter)
10
9
8
7
6
5
4
3
2
1
0
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)


STATION 13A
JUNE 20, 1971 - JUNE 23, 1971
DO (mg / liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)



STATION 13B
JUNE 20, 1971 - JUNE 23, 1971
DO (mg/liter)
10
9
8
7
6
5
4
3
2
1
0
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)


STATION 13-C
JUNE 20, 1971 -
JUNE 23, 1971
DO (mg / liter)
0
1
2
3
4
5
6
7
8
9
10
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12
TIME (HOURS)