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Technical Report 76-C4

INVESTIGATION OF FLUSHING TIME IN THE LAFAYETTE RIVER, NORFOLK, VIRGINIA

By

Carvel H. Blair

John H. Cox

and

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Final Technical Report

Prepared for the
National Oceanic and Atmospheric Administration
U.S. Department of Commerce as a
Sea Grant Project

Under
VIMS Subcontract, June 1, 1976 - December 31, 1976
Roger D. Anderson, Technical Director
Virginia Institute of Marine Science
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INVESTIGATION OF FLUSHING TIME IN THE
LAFAYETTE RIVER, NORFOLK, VIRGINIA

By

Carvel H. Blair,[1] John H. Cox,[2] and Chin Y. Kuo[3]

ABSTRACT

Two consecutive dye tracer experiments were conducted in the Lafayette River during the period July 14 to August 29, 1976 in order to determine the flushing time of the estuary. Slug releases of Rhodamine WT fluorescent dye in the north branch (km 8) and at the mouth of the main branch (km 1.5) produced concentration fields which were periodically monitored. Additional parameters measured during these experiments included rainfall, salinity, and tidal height. Dye mass and center of dye mass in the estuary were determined. After tracer release at km 8 in dry summer conditions maximum dye concentration dropped 50 percent in about one day; about 1.5 days were required to flush 50 percent of the dye mass out of the north branch, while 9.5 days were required to flush a similar amount out of the mouth of the Lafayette River. When release occurred at km 1.5, about four days were required for maximum concentration to drop by 50 percent, while 5.5 days were required to flush 50 percent of the dye mass from the estuary.

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I. INTRODUCTION

A. Objective

The goals of this research are (1) to determine the flushing time (as defined herein) of the Lafayette River, Norfolk, Virginia, by determining the temporal and spatial variation of concentrations of Rhodamine WT introduced as a slug tracer, and (2) to determine, simultaneously, the fields of estuarine parameters affecting flushing time. The results are presented in a format permitting convenient use by subsequent investigators in verifying and calibrating estuarine dispersion models as well as empirical flushing time models.

B. Previous Investigations

A significant body of knowledge has evolved concerning the hydrography, hydraulics, and mass transfer characteristics of the Lafayette estuary. The contents of all known reports and publications are summarized in table 1. To some degree each of these works bears on the subject of flushing time, and one (White, 1972) includes approximate calculations of its magnitude. No previous experimental data exists, however, whereby one can determine this parameter directly.

II. DESCRIPTION OF THE LAFAYETTE ESTUARY

Figures 1 and 2 depict the location and shape of the Lafayette River estuary. Station numbers are synonymous with kilometers upstream from the mouth. Table 2, adapted from Blair 1976, lists its main characteristics. The estuary is seen to be typical of the short tributaries of Chesapeake Bay in Virginia's coastal plain. Dendriform in shape, the main branch enters the Elizabeth River near Craney Island two miles south of Hampton Roads. A number of shallow tidal creeks, many of them only the vestiges remaining after extensive upstream filling, enter both sides of the main branch. At station 7 the main branch separates into the south and north branches. The latter again forks at station 8.5 where Wayne or Rinda Creek enters from the west. All three branches end at distances of 11 to 12 kilometers above the mouth. A dredged channel extends across the bar at the mouth off Tanner's Point (also called Sandy Point); project depth is eight feet. Knitting Mill Creek is also dredged with project depth set at six feet. The natural channel has a maximum depth of 20 feet below mean low water; this occurs beneath both the Hampton Boulevard and Granby Street Bridges and doubtless results from bridge scour. Except for a 10-foot hole at South Marsh Island, the upper branches nowhere exceed six feet in depth and are generally even shallower. Most of the lower reaches are bulk-headed. The upper reaches support 335 acres of marsh vegetation comprised of *Spartina alterniflora, Spartina cynosuroides, Baccharis halimifolia,* and *Iva frutescens.* The mean tidal range is 2.6 feet; the average depth below mean low water is 4.0 feet. Thus tidal volume is of the same order of magnitude as tidal estuary volume. The watershed is small, and hence the volume of freshwater flow is low. The ratio of river to tidal flow causes the estuary to be, in periods of normal rainfall, in the well-mixed category. The longitudinal salinity gradient is low over most of the length of the estuary, and the vertical profile nearly isohaline. A two-layered circulation thus exists (Pritchard 1967 and White 1972). The urban character of the watershed causes rapid runoff, however, and periods of heavy rainfall as experienced during tropical storms can increase the ratio of freshwater flow to tidal flow so that the estuary moves towards Pritchards' partially mixed classification. At such times an anomalous situation sometimes exists. The lower reaches are of low salinity because of high runoff into the Elizabeth and James Rivers; the middle reaches are of higher salinity, and the upper reaches of low salinity due to local runoff. Typically, however, the estuary's salinity profile resembles the mean depicted in figure 3.

III. EXPERIMENTAL PROCEDURE

The flushing time of an estuary is not constant, being dependent on variables such as freshwater inflow, tidal range and wind set-up. Furthermore, the flushing time of one pollutant may differ from that of another, the location of release and the density of the particular material influencing its fate.

Because of the important influence of location, it was determined to make two separate tracer releases at different points in the estuary. The north branch, which is considerably narrower and shallower than the main branch of the Lafayette River, can be treated either as a separate system, or as a part of the whole Lafayette estuary; thus, a release in the north branch allows analysis of the response of two systems: the north branch being one, the Lafayette River, the other. Furthermore, a release in the north branch would tend to simulate a pollutant source located in a tributary.

A release at the mouth of the Lafayette, on the other hand, would tend to indicate the physical response of the estuary to a pollutant source located in the Elizabeth River. It was thus determined to make the first slug release at km 8 in the north branch, to be periodically monitored until most of the dye was flushed out, at which time a second, larger release would be made at the mouth, km 1.5.

On 14 July 1976 the river was surveyed for fluorescent background with a Turner Model 111 Fluorometer with No. 110-880 high volume continuous-flow attachments. The power supply was a 220-watt EICO model 1080 solid-state inverter connected to a 108-ampere-hour storage battery (fig. 4). Water was pumped through the fluorometer by a Simer 12-Volt, 15-amp, d.c. motor-driven pump. A Y-valve allowed sampling either (a) near the surface (about 0.5 to 1 foot depth) by a wide-mouthed probe clamped to the boat transom or (b) at depths through a weighted 40-foot hose. Salinity was surveyed at the same time by an Endeco Type 102 Refractive Salinometer supplemented by a Beckman inductive salinometer with 50-foot cable.

Later on 14 July, at slack before flood current began, a 54.4-pound (24.6 kg) batch of 20 percent Rhodamine WT dye solution was released at station 8.0. Dye was poured on the surface from a drum to form a narrow band extending from one bank to the other. The band, initially clearly visible, began to widen and to move upstream. The existence of large eddies became apparent as arms of red dye projected from the main band.

At the next low tide, approximately 12 hours later, the river was again surveyed for salinity and for fluorescence. The latter was measured at the surface on the centerline of the channel. In addition, centerline readings were made at greater depths, and surface readings were taken on both sides of the river. Another survey was made at the following high tide. Thereafter surveys were made at longer intervals (table 6). Instrumentation was unchanged from the 14 July survey except that the inductive salinometer was not used on subsequent surveys.

Tidal height was measured continuously in Larchmont Creek (see fig. 1) by a C&GS-type float-operated portable tide gage. Rainfall was measured at Crab Creek (see fig. 1) by a Weather Measure Corporation P501 recording rain gage connected to a P521 event recorder. Additional rainfall data was obtained from the Old Dominion University Weather Station at the location shown in figure 2 for rain gage No. 2. Wind velocity and direction were measured on the survey boat and continuously at the Old Dominion University Weather Station.

Surveys were continued at intervals until 12 August. At this time 16 concentration fields had been measured. Calculations showed that approximately 2 percent of the original mass of dye remained in the north branch and approximately 20 percent remained in the entire estuary (above station 1.5). Although it would have been desirable to continue this phase of the experiment until flushing was complete, it was also desirable to make another release during the time available. Therefore it was decided to begin a second phase with a batch release at the estuary mouth. From 1837 until 1848 on 12 August an additional 180.87 (49.38 kg) pounds of 20 percent solution were pumped into the river at station 1.5. On this occasion the dye was transferred from a drum by means of a Teel 200 gph model 1P866 pump, driven by a hand-held electric drill. The drill was powered by a 500-watt inverter connected to a 108-ampere-hour storage battery. This method of release was tidier and better controlled than the earlier manual dump. As before, dye advection was uneven. The fastest travel was noted over the flats on the left bank (looking downstream) above station 1.5 (confirming qualitatively the distribution of current velocity shown in figure 7).

Dye and salinity surveys were resumed on 13 August following the procedures developed during phase one. The sampling arrangement was improved as shown in the modified portion of figure 4. The 40-foot hose was connected to the pump inlet and the Y-valve shifted to the outlet side, with hoses running from the Y to the probe and to the probe and to the fluorometer. When intake from the probe was desired, both valves were opened. The pump impeller blocked the hose connection. By running at a speed of 10 to 12 knots, the boat produced sufficient ram pressure to force water through the system. As a result, battery drain and noise as well as wear on the pump motor, which was not designed for continuous operation, were reduced. For deep samples or for stationary surface samples the probe valves were shut and the pump run as before.

Sampling was continued periodically until 26 August when manpower limitations put an end to field work (table 6). Data were reduced as explained in chapter IV.

IV. COMPUTATIONAL PROCEDURE

This chapter explains the methods used to reduce data gathered during the experiment (data are summarized in tables 4, 5, and 6). Unless otherwise specified, the mouth of the estuary is taken as the narrows at Tanners Point (station 1.5). When rectangular coordinates are employed, x indicates distance upstream along the channel axis; y indicates transverse location; z indicates depth below the surface.

A. Dye Concentration

In the laboratory, calibration curves were prepared for each fluorometer scale (1x, 3x, 10x, 30x) following the procedure termed Method II in section 5.7.3 of Turner Associates (1974). For the continuous flow attachment, the battery and inverter were used for power supply. For the batch sample attachment, 120-volt, 60-cycle VEPCO power was used. These curves permit one to determine the concentration of Rhodamine WT dye (expressed in $\mu g/\ell$, which is equivalent to parts per billion) corresponding to any reading on the fluorescence dial (expressed as "fluorescent units" or "f.u."). Thus

$$c' = \phi\ (f) \tag{4.1}$$

where

c' = dye concentration (in $\mu g/\ell$) ;

f = reading of fluorescence meter (in f.u.).

The relationship ϕ proved to be linear or nearly so.

The initial field survey revealed that water in the Lafayette River is slightly fluorescent even in the absence of Rhodamine dye. This fluorescence is termed "background." Its magnitude in f.u. was found to increase from a negligible value at the estuary mouth to a maximum in the headwaters. A linear approximation fit the data adequately, and the following was used:

$$c_b = 0.0193x \tag{4.2}$$

and

c_b = background fluorescent concentration in $\mu g/\ell$,

x = distance in kilometers from station 0.

The true concentration c of Rhodamine WT at a given point x in the estuary is then given by

$$c = c' - c_b \ . \tag{4.3}$$

For subsequent calculations it was necessary to interpolate or extrapolate missing data; however, unmeasured concentrations in the shallow upper reaches were considered never to exceed the nearest adjacent measured value.

B. Dye Mass

Cross-sectional areas of the estuary at low and high water were available from research supporting Blair (1976). From these, the cross-sectional area at each 0.5 kilometer station was determined (table 3) for both mean low water and mean high water. Over the lunar month, varying tide-producing forces cause the actual levels of high and low waters to differ from their long-term means. Correction for actual level (fig. 5) was made by assuming a linear variation of cross-sectional area with water level. For a low water survey the cross-sectional area is used to calculate dye mass:

$$A_L = A_{MLW} + \frac{(h + 0.7)}{2.6} \ (A_{MHW} - A_{MLW}) \ . \tag{4.3a}$$

For high water the corresponding equation is

$$A_L = A_{MHW} + \frac{(h - 1.9)}{2.6} \ (A_{MHW} - A_{MLW}) \tag{4.3b}$$

where

A_L , A_H = cross-sectional area at time of survey, subscript L denoting low water and H , high water;

A_{MLW} = mean low water cross-sectional area (table 3);

A_{MHW} = mean high water cross-sectional area (table 3);

and

h = measured water level relative to 1929 sea level at time of survey (fig. 5).

When the time of survey, taken as the time of the station 7 measurement, varied from the measured time of high or low tide, a further correction was made by the "Twelfths Rule." This approximates the tidal change in water level by 1/12 the measured tidal range for a one-hour difference, and by an additional 2/12 change for the second hour (Watts, 1975).

On this basis, the volume V_2 of the ith half-kilometer reach is

$$V_{L_i} = 46.5\ A_{L_i}\ ; \tag{4.4a}$$

$$V_{H_i} = 46.5\ A_{H_i}\ . \tag{4.4b}$$

Since each survey spanned about one hour, the water level and its corresponding cross-sectional area were not actually constant; because of the low rate of change near HW and LW , however, no correction was applied for variations in water level during a survey.

Dye mass m_i within each half-kilometer reach was calculated as

$$m_i = c_i\ V_i \tag{4.5}$$

where

c_i = dye concentration at the surface at station i ;

and

V_i = volume of ith reach as calculated from equations (4.4a) and (4.4b).

If several values of C_i for varying transverse locations were available, their mean was used. As discussed in chapter VI, vertical variation in dye concentration was considered negligible.

For each survey the dye masses of the half-kilometer reaches were summed from the 1.5 km reach to the headwaters to give mass remaining in the entire estuary. In addition, mass remaining in the north branch, including Wayne Creek, was calculated by summing the dye mass from the N 7.5 kilometer reach to the headwaters. For $t_o = 0$, that is, at the time of the slug release, M is the known mass of dye released. For $t_o > 0$, M is

$$M = \sum_i m_i \ . \tag{4.6}$$

Since some dye from phase one remained in the estuary at the time of phase two release on 12 August, the mass at that time was taken to be $(9.876 + M')$kg where M' was the mass computed from the prerelease survey of 12 August.

C. Maximum Dye Concentration

For each survey there was, at some location in the estuary, a maximum measured dye concentration $c_{max}(x, y, z, t)$. This was assumed to be the maximum existing in the estuary even though the extreme upper reaches were not surveyed and readings were not, in general, taken between stations. Any error was considered negligible. An indicator of flushing is the movement, if any, of the location of c_{max}; that is, the change of x. This can be expressed as $V(c_{max})$, the rate at which the location of c_{max} travels upstream or approximately $\{x(c_{max-2}) - x(c_{max-1})\}/(t_2 - t_1)$.

D. Half-Life of Dye Tracer

The dye mass calculated for each survey provides a time record of the amount of tracer remaining in the estuary; the half-life of dye mass in the estuary, a measure of flushing time, is based on this time record. However, dye mass varies with tide, since dye leaving on ebb flow may re-enter on flood, making it necessary to use a faired time record of dye mass in order to calculate half-life values. For this experiment

$$T_{50}\ (t_0) = t_0\ (M) - t\ (0.5M) \tag{4.6}$$

where

T_{50} = half-life (mass) of dye;

t_0 (M) = time at which total dye mass in estuary (or designated branch) is M ,

and

t (0.5M) = time at which total dye mass in estuary (or designated branch) is $0.5M$.

An indicator of dispersion or spreading of the tracer is the half-life of the maximum dye concentration. Having noted the maximum or peak concentration for each survey it is possible to compute the time required for the maximum value to be reduced by half

$$\tau_{50} = t_0(c_{max}) - t(0.5\ c_{max}) \tag{4.8}$$

where

τ_{50} = half-life (concentration),

t_0 (c_{max}) = time at which maximum dye concentration in estuary (or designated branch) is c_{max} ,

and

t (0.5 c_{max}) = time at which maximum dye concentration in estuary (or designated branch) is $0.5\ c_{max}$.

E. Center of Dye Mass

Other indicators of flushing time are the location of the center of dye mass $\bar{x}$ and the velocity $v(\bar{x})$ with which the center travels. These are defined as

$$\bar{x} = \frac{\sum x_i m_i}{\sum m_i} \tag{4.9}$$

where

m_i = mass of dye within reach centered at station x_i (computed by equation 4.5);

$$v(\bar{x}) = \frac{\bar{x}(t_2) - \bar{x}(t_1)}{t_2 - t_1} \tag{4.10}$$

where

$\bar{x}(t)$ = center of dye mass at time t.

F. Normalization of Salinity and Distances

In order to facilitate comparison of salinity distribution in the Lafayette River with that in other estuaries, normalized salinity $\hat{s}$, upstream distance $\hat{x}$, and depth $\hat{y}$ are defined as follows:

$$\hat{s} = s(x)/s(x = 1.5) \tag{4.11}$$

$s(x)$ = laterally averaged surface salinity in ppt at x kilometers above station 0;

$$\hat{x} = \frac{x - 1.5}{L} \tag{4.12}$$

$$\hat{y} = y/d$$

y = depth from surface, measured downward

d = water depth at time of observation

L = length of the estuary = 11 kilometers for the Lafayette River.

Thus the longitudinal profile ($\hat{s}$ vs. $\hat{x}$) has, by definition, a unit intercept (that is, $\hat{s} = 1$ where $x = 1.5$, $\hat{x} = 0$). Similarly the vertical profile ($\hat{s}$ vs. $\hat{y}$) has unit intercept at the surface.

G. Rainfall

Records of rainfall vs. time from Crab Creek spanned the period 14 July to 29 August, while that from the O.D.U. Weather Station spanned the period 4 July to 29 August. The latter provided total precipitation per storm; the former provided duration and intensity of storms as well. For Crab Creek, therefore, mean intensity for each major storm (in inches/hour) was calculated as the ratio of total precipitation during storm to duration of rainfall. The mean daily precipitation for July and for August was computed by dividing the 1941 to 1970 average monthly total for each month as reported by the National Weather Service by 31.

H. Surface Current Velocities

Surface currents, while not measured during this experiment nor needed for these calculations, may be pertinent in other investigations. Their value at any time and location, however, can be closely approximated from the data in figures 6 and 7 as follows:

Ebb current

$$|u' (x, y, t)| = |u_{max} (x, y)| \sin \left[\left\{ \frac{t - t(h_H)}{t(h_L) - t(h_H)} \right\} \pi \right] \quad (4.13)$$

Flood current

$$|u' (x, y, t)| = |u_{max} (x, y)| \sin \left[\left\{ \frac{t - t (h_L)}{t (h_H) - t (h_L)} \right\} \pi \right] \quad (4.14)$$

where

$u' (x, y, t)$ = surface current velocity at location (x, y), time t, for mean tidal range,

$u_{max} (x, y)$ = mean surface current at strength of ebb (fig. 6) or strength of ebb (fig. 7) as appropriate,

$t (h_H)$ = time of high water immediately preceeding time t (for ebb current calculation) or immediately following t (for flood current calculation),

and

$t (h_L)$ = time of low water immediately preceeding time t (for flood current calculation) or immediately following t (for ebb current calculation).

$$|u (\Delta h, t)| = \left[\frac{\Delta h}{2.6} \right] u' (t) \quad (4.15)$$

where

$$\Delta h = h_H - h_L , \quad (4.16)$$

$u (\Delta h, t)$ = surface current velocity for tidal ranges Δh,

Δh = range of tide spanning time t,

h_H = tidal height of high water immediately before or after time t,

h_L = tidal height of low water immediately before or after time t .

and

$$u' = u' \ (x, y, t) \text{ as computed by equation (4.13) or (4.14).}$$

The tidal wave in the Lafayette River can be treated as a standing wave with negligible error (Blair, 1976). Direction of currents should be taken as parallel to main channel.

I. Wind Velocity

Surface wind velocity (direction from which blowing and speed in statute miles per hour) was recorded at O.D.U. Weather Station on a two-track paper roll which moved at 3 in/hr. The average direction and average velocity were estimated by eye for each 12-hour (36-inch) section of the record. Direction was rounded off to the nearest octant, that is, N, NE, E, SE, S, SW, W, NW. Frequency distribution of direction over the experimental period was calculated, and mean velocity for each octant computed. Spot checks of wind at the research boat, made several times during each survey, showed wind velocity on the river to be in good agreement with that recorded at the weather station.

V. RESULTS

A. Salinity Profiles

Figure 8 depicts the longitudinal salinity distribution in the estuary under various conditions (complete surface salinity data are in table 5). Salinities and distances have been normalized as explained in section IV F. Except for a few days immediately following the heavy rain of hurricane Belle on 9 August, the lower reaches showed a typically flat, nearly isohaline longitudinal gradient. During most of the experiment the upper reaches also were nearly isohaline, as might be expected from the dry weather. Figure 9 shows rainfall measured during each storm by gages at Crab Creek (solid bars) and O.D.U. Weather Station (dashed bars). On 49 of the 58 days from 1 July to 27 August, rainfall was significantly less than the long-term mean. Figure 10 shows normalized vertical salinity profiles. Except for a short period immediately after Belle, the vertical trace was typically isohaline.

B. Discharge

Neither the "rational method" (Linsley and Franzini, 1972) nor simple salt-balance procedures will yield a satisfactory estimate of discharge in the Lafayette. No hydrologic model of the watershed is available; consequently, discharge was not calculated. An approach used in an earlier investigation (Blair, 1976) took advantage of a tidal hydraulic model of the estuary at O.D.U. Since the model includes the effects of dispersion of salt, it is possible to manipulate freshwater discharge until the model salinity field matches that observed in the prototype. This method yielded a value for Q of 5.1 ft^3/sec for the dry conditions existing in summer 1975, a reasonable magnitude in comparison with White's (1972) annual mean discharge of 31.6 ft^3/sec as reported in table 2. As a first approximation, a figure of 5 ft^3/sec for the present study is probably reasonable. The corresponding estuary number is 916. Thus the estuary during the 1975 and 1976 dye releases resembles Bowden's (1967) and Pritchard's (1967) Class IV. This is a category of nearly vertical homogeneity.

C. Tide Levels

Measured heights of high and low water at Larchmont Creek are plotted on figure 5. The large scale permits accurate measurement of heights for use in possible refinements of area calculations. Mean half-tide level for each day (i.e., one-fourth the sum of the two high water levels and two low water levels occurring on that day) is presented in figure 11. Variation in half-tide level is an indication of the daily variation in mean volume of the entire estuary.

D. Tide Range

Figure 12 is a graph faired by eye through points representing the semidiurnal tidal ranges. The points fall in a band centered on the curve and extending about 0.3 feet on either side. The phase of the moon is also presented since it strongly affects the times of spring and neap tides. Tidal range is an indication of size of the tidal prism. Because of the shallow (4 ft) mean depth of the estuary, the curve is also an indication of the amount of tidal flushing.

E. Wind

Figures 13 and 14 show semidaily averages of wind velocity during the experiment. The highest 12-hour average occurred on 9 August during hurricane Belle, when the wind blew at 15 mph from the NE. (Peak velocity was about double the average.) A comparison of figure 13 and figure 11 shows the usual correlation between wind and sea level in Chesapeake Bay. Strong northeasterlies (i.e., from NE) tend to raise the water level; strong southwesterlies tend to lower it.

F. Maximum Dye Concentration

At the time of first release at low water slack on 14 July at Station 8.0, maximum concentration was, of course, at that location. Because the current was just starting to flood, the dye moved upstream for the next six hours. After the first half of that tidal cycle the tide turned, and dye began to return downstream on the ebb. As figure 15 (upper, solid curve) shows, however, the location of the point of maximum concentration moved upstream at a rate of about two km/day until 15 July. Thereafter it oscillated between Station 10 at the high tides and a point about one km downstream at the low tides. (The actual location may have been even farther upstream because sampling was in general not possible above Station 10 at high water and station 9 at low water.) After about 16 days the point of maximum concentration began to migrate downstream. It was beginning to reach the main branch after about 27 days at a velocity of about 0.2 km/day. The absolute value of the maximum concentration dropped during this period, as shown in figure 16, by nearly two orders of magnitude.

Phase two dye release, on 12 August, shifted the location of c_{max} far downstream. As before, however, its location then moved upstream, at a rate of about 0.8 km/day. It then began a slow downstream descent from station 8 at a velocity of about 0.1 km/day. Absolute value dropped during the 15-day period following phase two release by an order of magnitude (fig. 16).

G. Dye Mass

Because of the inevitable approximations and the spatial and temporal discontinuity of data, calculation of dye mass as explained in section IV B is not completely accurate. Figure 17, for example, shows more dye mass in the estuary (by 10 to 20%) during the first three surveys than was actually released. This error was probably due to initial nonuniform distribution of dye mass. It is likely that concentrations were at first lower in the many tributary creeks than in the river proper, where fluorometer measurements were taken. Since the latter readings were assumed for calculation purposes to exist throughout the entire water volume at that station, an overestimation of dye mass probably results. The error would be expected to become negligible as concentration became more uniform. Later spot checks in the small creeks did, in fact, show little variation from the river proper.

Figure 17 shows distinct fluctuations between mass at high and low tides. This too is to be expected, since some dye leaving the estuary mouth on ebb tide is carried back from the Elizabeth River on the flood.

Behavior in the above respects during phase two was similar to that in phase one.

Figures 18 and 19 show the variation of dye mass in the north branch when it is analyzed as a system; the vertical scales of these figures are logarithmic and linear respectively. Initial loss of dye is more rapid than in the Lafayette as a whole (fig. 17) since dye leaving the north branch must travel an additional 6.5 km before leaving the Lafayette. The surplus dye error noted for the Lafayette as a whole does not appear when the north branch is analyzed presumably because mixing is more rapid and measurements are more representative in the smaller volume of the north branch.

Evidence of upstream travel of dye from the phase two release appeared within 24 hours. Dye mass in the north branch began to increase on the afternoon (low water) survey on 13 August. (Figure 15 shows that dye also entered the south branch; on 23 August, maximum concentration occurred at station 7.5.) The mass in the north branch, as seen in figures 18 and 19, rose until 18 August, then resumed its decline as in phase one.

H. Center of Dye Mass

The axial location of $\overline{x}$, the center of dye mass in the entire estuary above station 1.5, is shown in the lower curve of figure 15. During phase one, the center of dye mass traveled, except for tidal oscillations, steadily downstream. It did not show an initial upstream movement as did the location of c_{max} . The net traveling rate downstream, that is $v(\overline{x})$, was about 0.1 km/day. During phase two, $\overline{x}$ moved upstream during the first 11 days and then reversed direction to travel towards the mouth.

Figure 20 shows that the center of mass in the north branch during phase one moved in a fashion similar to that of the center of total mass for phase two (fig. 15), that is, initial travel upstream followed by movement downstream. In both cases the releases were made close to the mouth (of the north branch for phase one, of the main branch for phase two). Such behavior may be typical.

I. Half-life

As explained in section IV D, half-life can be calculated either on a basis of loss of 50 percent of dye mass (T_{50}) or on a basis of a decay by

50 percent of maximum concentration (τ_{50}). If $t_0 = 0$, the loss or decay is with respect to the situation at the time of initial release. If $t_0 > 0$, the base for dye mass or for maximum concentration is that existing after some loss/decay has already occurred. Figure 21 shows T_{50} and τ_{50} for the entire estuary. In addition, T_{50} for the north branch, phase one, is plotted. (Where gaps exist in the graphs, the parameters are either undefined or not significant for the data in this experiment.) For phase one, half-lives of both types are seen to increase with time. Qualitatively speaking, an initial rapid drop in mass and in concentration is followed by successively slower drops. For phase two, both half-lives are approximately constant and equal, about 4.5 days. T_{50} decreases slowly while τ_{50} increases slowly. By comparison, τ_{50} for phase one increased from about 1 to about 14 days, while T_{50} for phase one increased from 9 to 16 days. T_{50} for phase one, north branch, increased from about 1.5 to 13 days.

J. Vertical Distribution of Dye

Figures 22a to 22c show, for stations 4, 6.5, and 8.2, the variation in dye distribution with depth for a number of different surveys. Initially (survey 1) distribution shows a distinct vertical gradient. Thereafter the gradients decreased; and, in general, the surface concentration was a good approximation of the vertical average. On several occasions, however, marked discontinuities appeared (for example, station 10 on survey 23, 20 August). Their significance is discussed in chapter VI.

VI. DISCUSSION AND CONCLUSIONS

Initially one is tempted to seek simple correlations among the parameters discussed above. Upon reflection, however, one concludes that the dispersion process in a natural estuary is too complex for intuitive analysis. A sounder application of the data and results presented herein is testing and calibrating appropriate mathematical and physical models. In particular, simplistic explanations of the results are hampered by the boundary condition for dye concentration at the estuary mouth. Concentration there is not constant; i.e., $dc(\hat{x} = 0)/dt \neq 0$. Some of the dye that leaves on the ebb tide escapes the estuary forever in the net downstream flow of the Elizabeth River; some is diffused forever down the concentration gradient into the Elizabeth; the rest is carried back into the Lafayette on the flood. Thus the dye concentration at the mouth varies with time. The two-layered flow, moreover, brings dye upstream in the lower depths while carrying it seaward near the surface. Figures 22a to 22c show varying vertical gradients of concentration which strongly suggest a corresponding velocity shear, a phenomenon which also complicates intuitive analysis.

A study of the experimental results, nevertheless, permits one to reach the following conclusions without putting forward a theoretical explanation of the causes of those results:

A. After release of a conservative solute at station 8 in dry summer conditions, maximum dye concentration dropped 50 percent in about one day (τ_{50} $(t = 0) \approx 1$ day).

B. Under the same conditions, about 9.5 days were required to flush 50 percent of the dye mass out of the estuary (T_{50} $(t = 0) \approx 9.5$ days).

C. When the release occurred at the mouth of the main branch (station 1.5), about 4 days were required for maximum concentration to decay 50 percent, while about 5.5 days were required to flush 50 percent of the dye mass (τ_{50} $(t = 0) \approx 4$ days, T_{50} $(t = 0) \approx 5.5$ days).

D. When the release occurred near the mouth of the north branch, at station 8, about 1 day was required for maximum concentration to drop 50 percent; about 1.5 days were required to flush the north branch dye by

50 percent (τ_{50} (t = 0) $\simeq$ 1 day, T_{50} (t = 0) $\simeq$ 1.5 days). The faster flushing, as compared to the entire estuary, as noted in A, B, and C above, is due to the smaller volume of the north branch as compared to that of the entire estuary.

E. In both upstream (phase one) and downstream (phase two) releases, the concentration half-life τ_{50} (t) increased as t_0 became greater. That is to say, each 50 percent reduction in maximum concentration required a longer time than did the preceeding 50 percent reduction. Qualitatively phrased, this result implies that a very long time is required to reduce concentration to a very low level. Thus, in setting water quality standards, one should consider the consequence of specifying conservative safety factors: a significant increase in the time required to reach the "safe" pollutant level.

F. A solute released in an estuary having a longitudinal salinity gradient will be transported upstream from the release point. One of the causes of this transport is the density-driven layered flow. The characteristics of this mass transport are best analyzed in an appropriate mixing model.

Table 1. Previous investigations of Lafayette River.

Blair, 1972. Correlation of current velocity and sediment size with distance upstream. Both found to decrease with distance from mouth.

Golub, 1972. Diurnal variations of physical and biological parameters at several points.

Montgomery, 1972. Measurement of time and space fields of concentration of phosphate, nitrate, oxygen, salt, and of temperature. Attempt to relate to tide and to output of Lambert's Point sewage outfall.

White, 1972. Study of salinity, temperature, and tides. Measurement of net nontidal velocity. Attempt to determine flushing time.

Blair, 1973. Survey of wetlands including species distribution of *Spartina* and other marsh plants.

Melchor, 1973. Correlation of faunal distribution with salinity and water quality in Lafayette and Piankatauk estuaries.

Harrell, 1973. Correlation of sediment size-distribution with axial and lateral position (finest sediment is found upstream and mid-channel).

Sisson, 1976. Adaptation and verification of two-dimensional, mathematical model of tidal elevation and vertically-averaged current velocity.

Farling, 1976. Adaptation and verification of one-dimensional network model of dispersion of conservative dye tracer.

Blair, 1976. Hydrographic and tidal hydraulic surveys. Construction and verification of physical hydraulic model. Dye tracer tests.

Table 2. Characteristics of the Lafayette River estuary.

Parameter	English	Metric
Channel length	5.9 nm	11 km
Maximum width	2625 ft	800 m
Maximum depth below MLW	19.5 ft	5.9 m
Mean depth below MLW	4.0 ft	1.2 m
Mean tidal range Δh	2.6 ft	0.8 m
Maximum velocity	1 ft/sec	30.5 cm/sec
Froude number = $U_{max} (gh_{max})^{1/2}$	0.040	
Re = $U_{mean} h_{mean} / \nu$	255,000	
Manning's coefficient n	0.025	
Tidal period T	12.4 hr	
Water volume at MLW	3.15×10^8 ft^3	8.89×10^6 m^3
Water surface area (mean) A	7.85×10^7 ft^2	7.29×10^6 m^2
Tidal prism P = $A\Delta h$	2.04×10^8 ft^3	5.78×10^6 m^3
Q_{mean} (White 1972)	31.6 ft^3/sec	0.89 m^3/sec
Estuary number = P/QT	145	

Table 3. Cross-sectional areas of Lafayette River.

Station No. (kilometers from station 0)	Mean cross-sectional area of reach centered at given station in square feet	
	Mean Low Water	Mean High Water
Main Branch		
1.5	8,000	15,900
2.0	9,900	17,000
2.5	8,700	15,600
3.0	10,500	16,200
3.5	9,500	14,400
4.0	8,300	12,600
4.5	8,100	12,700
5.0	6,300	10,450
5.5	7,000	10,300
6.0	5,300	9,100
6.5	5,200	7,500
7.0	4,071	7,351
South Branch		
7.5	2,200	4,700
8.0	1,200	2,700
8.5	900	2,150
9.0	400	1,800
9.5	20	400
10.0	0	100
10.5	0	0
North Branch		
7.5	2,200	5,400
8.0	2,100	3,900
8.5	700	1,800
9.0	150	800
9.5	20	500
10.0	0	100
10.5	0	0
Wayne Creek		
8.5	750	2,100
9.0	400	1,300
9.5	300	1,300
10.0	300	1,000
10.5	80	650
11.0	50	550
11.5	10	450
12.0	0	150
12.5	0	0

Table 4. Mean surface dye concentrations (mg/l).

Station \ Run	First Release 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1			0.02		0.10		0.05	0.10	0.01	0.15	0.19	- 0.07	0.09	0.10	0.05	0.16	
.5							0.03	0.03	0.09	0.12	0.15	0.05	0.15	0.05	0.09	0.18	
1			0.02		0.02		0.01	0.05	0.19	0.10	0.13	0.06	0.17	0.02	0.10	0.17	
1.5			0.05	0.00*	0.01		0.03	0.05	0.25	0.08	0.12	0.07	0.19	0.00	0.12	0.17	0.12
2			0.08	0.00*	0.00		0.08	0.05	0.27	0.07	0.21	0.07	0.19	0.00	0.10	0.18	0.09
2.5			0.15	0.00*	0.09		0.09	0.06	0.29	0.14	0.38	0.14	0.25	0.04	0.17	0.22	0.16
3	0.06		0.22	0.00*	0.19	0.00	0.14	0.11	0.46	0.18	0.38	0.15	0.25	0.04	0.20	0.25	0.17
3.5	0.02		0.27	0.00*	0.24	0.02	0.20	0.18	0.56	0.13	0.54	0.06	0.30	0.04	0.20	0.27	0.26
4	0.04		0.32	0.01	0.29	0.04	0.20	0.11	0.58	0.21	0.51	0.08	0.33	0.04	0.20	0.24	0.23
4.5	0.09	- 0.05	0.66	0.06	0.58	0.20	0.25	0.20	0.72	0.16	0.47	0.12	0.25	0.06	0.26	0.34	0.22
5	0.56	- 0.05	0.99	0.11	0.64	0.17	0.33	0.38	0.75	0.26	0.84	0.13	0.39	0.15	0.30	0.27	0.32
5.5	0.79	0.00	1.33	0.07	0.89*	0.53	0.53	0.62	0.82	0.33	1.21	0.24	0.44	0.18	0.38	0.38	0.34
6	2.74	0.44	2.11	0.44	1.14	0.58	0.72	0.49	0.94	0.45	1.35	0.27	0.48	0.21	0.45	0.59	0.33
6.5	2.39	0.35	2.47	0.35	1.54	0.65	1.07	0.49	1.09	0.67	1.41	0.42	0.50	0.28	0.48	0.54	0.41
7	4.01	0.93	2.50	0.79	2.09	0.45	1.02	0.42	1.20	0.64	0.78	0.37	0.54	0.20	0.56	0.55	0.50
N7.5	8.77	3.11	5.31	3.30	3.01	1.02	1.49	0.56	1.33	0.68	0.73	0.47	0.61	0.22	0.43	0.62	0.50
N8	15.04	2.80	6.51	1.76	3.74	0.63	1.77	0.72	1.39	0.91	0.63	0.56	0.65	0.34	0.57	0.50	0.45
N8.5	15.10	5.77	6.95	3.41	3.93	1.18	1.93	1.00	1.63	1.03	0.76	0.55	0.53	0.35	0.66*	0.47	0.40*
N9	12.51	8.14	6.94*	4.41	4.97*	1.49	2.17	1.12*	1.63*	1.02	0.75*	0.59	0.52*	0.56	0.65*	0.45*	0.35*
N9.5	---	11.36	6.93*	5.03	4.96*	1.48	2.48	1.25*	1.62*	1.21	0.74*	0.65	0.51*	0.49	0.64*	0.42*	---
W8.5	17.64	2.86	7.68	2.31	3.93	1.07	1.79	1.00	1.81	0.92	1.05	0.61	0.63	0.30	0.50	0.52	0.57
W9	13.51	7.77	7.89	3.00	4.66	1.29	2.07	0.94	1.93	0.92	1.05	0.45	0.61	0.43	0.49	0.44	0.56*
W9.5	7.37*	7.67	6.59	4.94	5.14	1.71	2.56	1.35*	1.92*	1.09	1.04*	0.60	0.62	0.41	0.59	0.43*	0.55*
W10	2.24*	10.06	6.18*	6.21	5.13*	2.13	2.86	1.42*	1.91*	1.29	1.03*	0.71	0.62*	0.49	0.58*	0.42*	0.54*
W10.5	0.00*	7.65*	4.94*	6.45*	5.12*	2.12*	2.85*	1.41*	1.90*	1.28*	1.02*	0.70*	0.61*	0.48*	0.57*	0.41*	---
W11	---	7.73*	3.71*	6.44*	5.11*	2.11*	2.84*	1.40*	1.89*	1.28*	1.02*	0.69*	0.60*	0.47*	0.56*	0.40*	---
W11.5																	
W12																	
S7.5	2.61	1.25	1.22	1.16	2.55	0.65	1.30	0.66	0.96	0.66	0.73	0.46	0.43	0.43	0.40	0.45	0.25
S8	- 0.03	1.45	0.66	1.53	1.44	0.83	1.34	0.68	0.93	0.77	0.71	0.56	0.43	0.49	0.42	0.36	0.30
S8.5		1.57	0.55	1.48	1.19	0.74	1.17	0.69	0.50	0.68	0.70*	0.56	0.50	0.62	0.47	0.26*	0.39
S9		0.77	0.00	0.89	1.09*	0.58	1.02	0.55*	0.07*	0.71	0.68*	0.63	0.49*	0.51	0.46*	0.16*	0.38*
S9.5	---	0.00*	0.00*	0.57	1.08*	0.38	0.65	0.42*	0.06*	0.62	0.66*	0.61	0.48*	0.50	0.45*	0.07*	---

(continued)

Table 4. Concluded.

Run / Station	Second Release							
	18	19	20	21	22	23	24	25
0	0.12	0.28	0.05	0.14	0.16	0.62	0.07	0.67
.5	3.54	0.10	0.27	0.14	0.26	0.61	0.10	0.73
1	2.73	0.03	0.84	0.18	0.23	0.83	0.10	0.31
1.5	2.91	1.20	0.96	0.47	0.18	0.84	0.11	0.29
2	2.83	0.44	1.12	0.35	0.33	0.80	0.08	0.31
2.5	2.73	0.81	1.21	0.47	0.24	0.80	0.12	0.33
3	2.40	1.55	1.22	0.70	0.26	0.83	0.13	0.36
3.5	1.50	1.99	1.20	0.72	0.82	0.99	0.21	0.32
4	0.94	2.46	1.14	0.83	0.66	0.94	0.26	0.27
4.5	0.47	3.26	1.09	1.15	0.70	1.08	0.27	0.33
5	0.28	2.79	0.99	1.10	0.76	0.98	0.31	0.28
5.5	0.24	2.61	0.95	1.20	1.00	1.18	0.39	0.29
6	0.19	1.48	0.79	1.30	1.11	1.16	0.44	0.33
6.5	0.28	1.38	0.66	1.19	1.17	1.23	0.52	0.34
7	0.32	0.96	0.62	1.14	1.12	1.22	0.75	0.35
N7.5	0.36	0.51	0.42	0.95	1.10	1.26	0.80	0.38
N8	0.32	0.31	0.36	0.78	1.14	1.30	0.88	0.33
N8.5	0.48	0.69	0.49	0.67	1.04	1.27	0.84	0.39
N9	0.47*	0.21	0.48*	0.68	0.99	1.15	0.73	0.38*
N9.5	0.46*	0.21	0.47*	0.59	0.91	1.04*	0.72	0.37*
W8.5	0.36	0.41	0.49	0.90	1.04	1.21	0.84	0.45
W9	0.38	0.58	0.46	0.75	1.04	0.96	0.73	0.40
W9.5	0.37*	0.34	0.43*	0.65	0.95	1.05	0.87	0.33*
W10	0.36*	0.31	0.40	0.54	0.83	0.96*	0.66	0.27*
W10.5	0.35*	0.27*	0.37*	0.44*	0.79*	0.83*	0.51*	0.21*
W11	0.33*	0.24*	0.34*	0.34*	0.71*	0.72*	0.36*	0.15*
W11.5								
W12								
S7.5	0.29	0.25	0.34	0.93	1.14	0.95	0.92	0.38
S8	0.31	0.23	0.59	0.83	1.01	1.08	0.83	0.35
S8.5	0.23	0.25	0.54	0.84	0.79	0.91	0.69	0.25*
S9	0.15*	0.39	0.49*	0.75	0.89	0.89*	0.73	0.14*
S9.5	0.07*	0.38	0.44*	0.50	0.75	0.61*	0.51	0.04*

* Interpolated or extrapolated values.

--- Negligible water volume in reach due to tide.

N.B.: negative concentrations were assumed to be zero in calculation of dye mass.

Table 5. Mean surface salinity values ($^{o}/oo$).

Station \ Run	First Release																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0					19.7		18.8		20.3	20.6	21.0	20.8	20.4	20.7	21.0	19.1	
.5								19.6								18.9	
1					20.4		19.6	19.9	20.3	20.3	20.9	21.1	20.0	21.0	19.9	18.7	
1.5																18.9	19.5
2					20.4		20.2	20.7	20.2	20.2	19.4	21.0	19.8	20.9	19.5	18.6	19.2
2.5																18.5	18.8
3	19.5		19.7		20.0		20.7	20.7	20.3	20.3	20.6	21.1	19.6		18.2	18.1	18.7
3.5																17.5	18.0
4	19.4		19.2	21.6	19.6	20.3	20.4	20.7	20.0	20.2	20.0	20.9	19.5	20.7	19.1	17.5	18.0
4.5		21.4					20.1				20.0			20.6		16.4	18.5
5	19.1		19.2	20.3	19.5	20.5	20.7	20.9	19.7	20.1	19.8	20.7	19.3		18.8	18.1	17.8
5.5	19.0	20.8														18.1	17.5
6	18.8	20.3	18.7	20.2	18.8		20.0	20.1	19.7	19.8	20.0	20.6	19.2		18.8	17.2	17.0
6.5	18.8													18.6		16.3	16.4
7	18.6	20.3	18.5	19.8	18.9		19.9	19.4	19.4	19.0	19.6	20.3	18.5	18.9	18.5	15.2	16.2
N7.5	18.4															12.2	16.3
N8	18.3	20.1	18.2	19.7	19.0	20.4	19.6	19.8	19.5	19.5	19.5	20.0		17.3	17.3	10.2	16.4
N8.5	17.8		17.9						18.8		19.8		15.4			4.5	14.4
N9		20.0		19.1	18.9		19.4	19.4		19.1		19.9		16.6			
N9.5				18.5		18.3	18.9	19.0				19.6					
W8.5	17.8												13.6			8.5	
W9	17.8	19.4		19.2		19.7	19.5	19.6	18.9	19.2	19.2	20.0	16.4	16.9	15.4	6.1	
W9.5			17.4		18.2												
W10		19.0					19.0	19.3		18.9		19.8		14.9			
W10.5																	
W11																	
W11.5																	
W12																	
S7.5	18.9												18.8	17.9		15.0	16.0
S8	18.6	19.9	18.0	19.1	17.8	19.5	19.8	19.5	19.7	19.2	19.3	19.8	18.8	17.3	18.0	13.8	14.7
S8.5													18.7	16.8			13.8
S9		19.7	16.4	19.1	16.9		19.0	19.1		19.0		19.7		16.3			
S9.5		19.5		18.4		18.3	18.4	18.9		18.4		19.7		15.7			

(continued)

Table 5. Concluded.

Station \ Run	Second Release							
	18	19	20	21	22	23	24	25
0	19.6		20.2	19.9	21.3	21.1	20.3	21.3
.5	19.1							
1	18.8		19.3		21.1	20.7	20.3	20.9
1.5	18.9							
2	18.8		18.9	20.3	21.0	20.9	20.7	21.1
2.5								
3	18.7		18.9	19.9	20.9	20.5	20.6	20.9
3.5								
4	18.2		18.8	19.5	20.6	19.9	20.2	20.8
4.5								
5	17.7		18.2		20.1	19.4	20.0	20.3
5.5								
6	17.0		18.0	19.4	19.0	19.2	19.8	20.4
6.5	16.9					19.0		
N7	16.4		17.2	18.4	18.6	18.7	19.4	19.9
N7.5								
N8	15.7		16.5	17.6	18.0	18.5	19.0	19.7
N8.5	14.3		16.0					19.6
N9				16.6	17.4	17.4	18.4	
N9.5					16.8			
W8.5	14.8		16.0					19.5
W9	13.8		15.5		17.6	17.4	18.7	19.0
W9.5						16.8		
W10				15.9	16.1		17.9	
W10.5								
W11								
W11.5								
W12								
S7.5								
S8	16.1		17.1		18.0	18.3	18.8	19.9
S8.5	15.8		16.4	17.2		18.2		19.8
S9					17.4		18.4	-
S9.5					16.9			

Table 6. Survey runs during flushing experiment, Lafayette River, 1976.

Run Number	Date of Survey	Time of Survey (Station 7, EDT)	Tide	Notes
1	15 July	0741	Low	14 July, Release at Station 8, North Branch, Low Water Slack, Time: 1836
2	15 July	1315	High	
3	16 July	0830	Low	
4	16 July	1416	High	
5	17 July	0947	Low	
6	18 July	1548	High	
7	19 July	1652	High	
8	20 July	1726	High	
9	22 July	1200	Low	
10	24 July	0902	High	
11	26 July	1612	Low	
12	28 July	1132	High	
13	30 July	0643	Low	First Survey After Heavy Thunderstorm
14	2 August	1544	High	
15	6 August	1344	Low	
16	10 August	1717	Low	9 August Hurricane Belle
17	12 August	1711	Near Low	12 August, Release at Station 1.5, Low Water Slack, Time: 1837
18	13 August	0702	Low	
19	13 August	1311	High	
20	16 August	0747	Low	
21	16 August	1549	High	
22	18 August	1634	High	
23	20 August	1208	Low	
24	23 August	0854	High	
25	26 August	1716	Low	

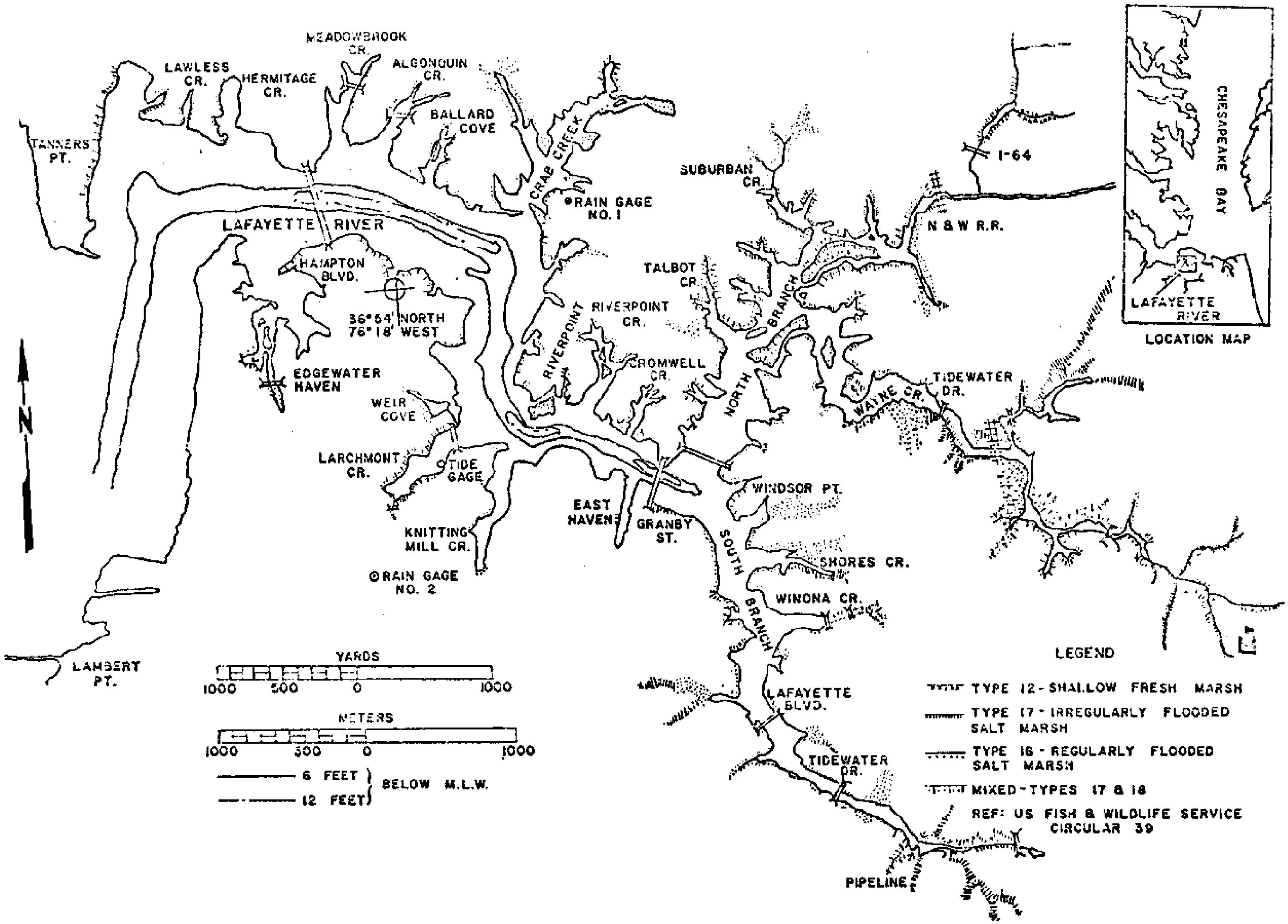


Figure 1. Lafayette River, Blair 1973.

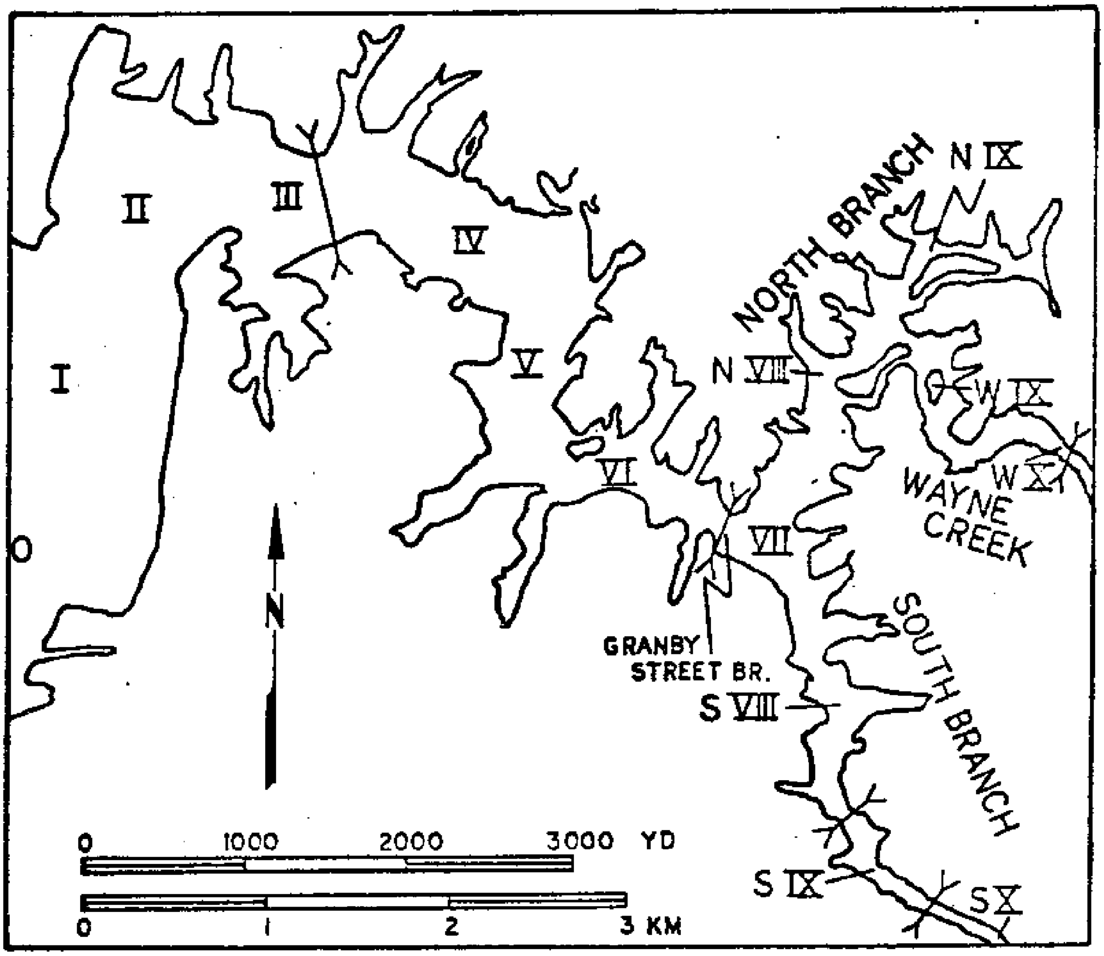


Figure 2. Station locations, Lafayette River. Roman numerals correspond to distance in kilometers upstream from station 0. Prefixes N, S, and W denote respectively north branch, south branch, and Wayne Creek. Suffixes, when used, have the following significance: B - midchannel; A - right side looking downstream; C - left side looking downstream.

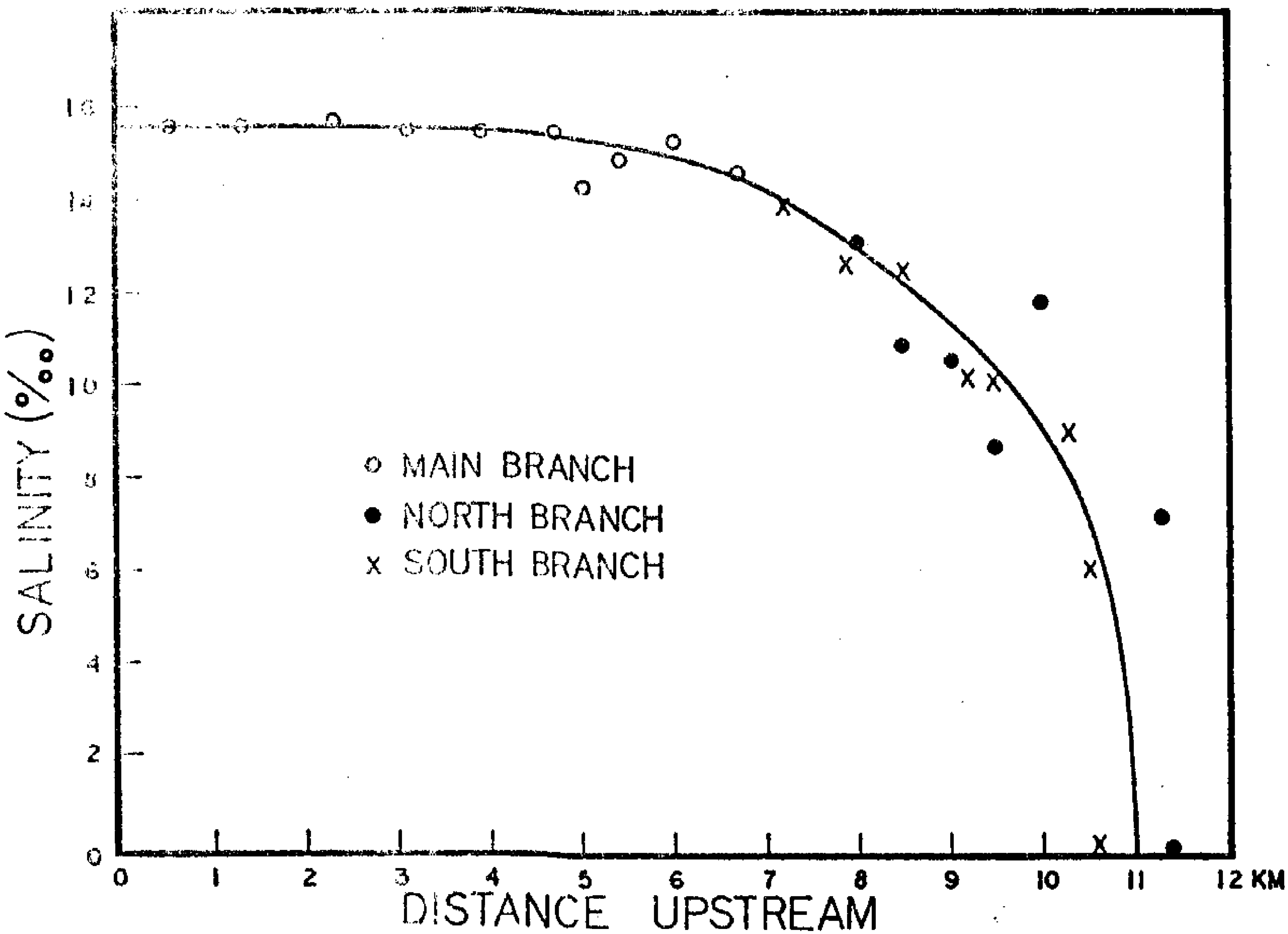


Figure 3. Longitudinal variation in mean salinity (1971-1975), Blair 1976.

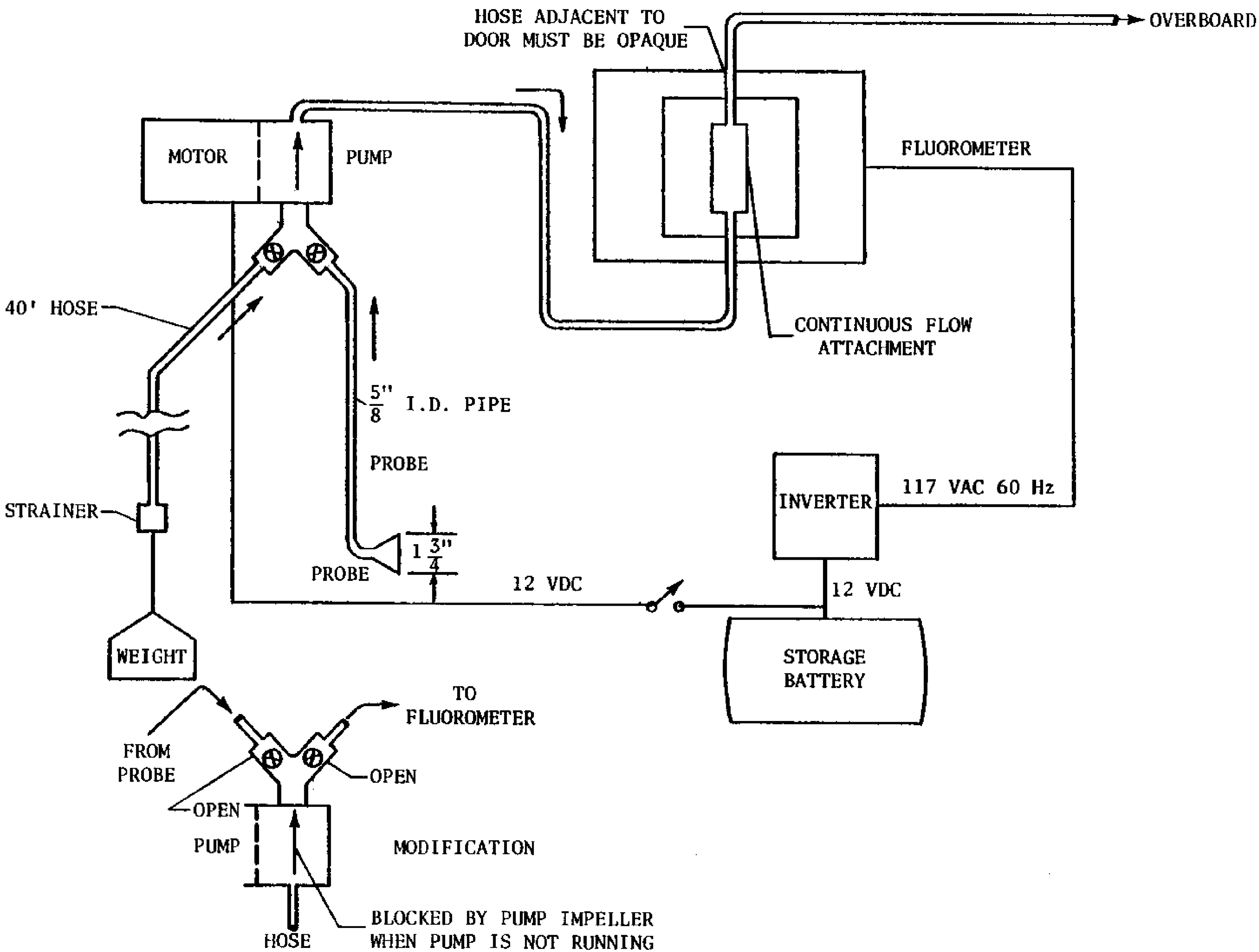


Figure 4. Continuous sampler arrangement.

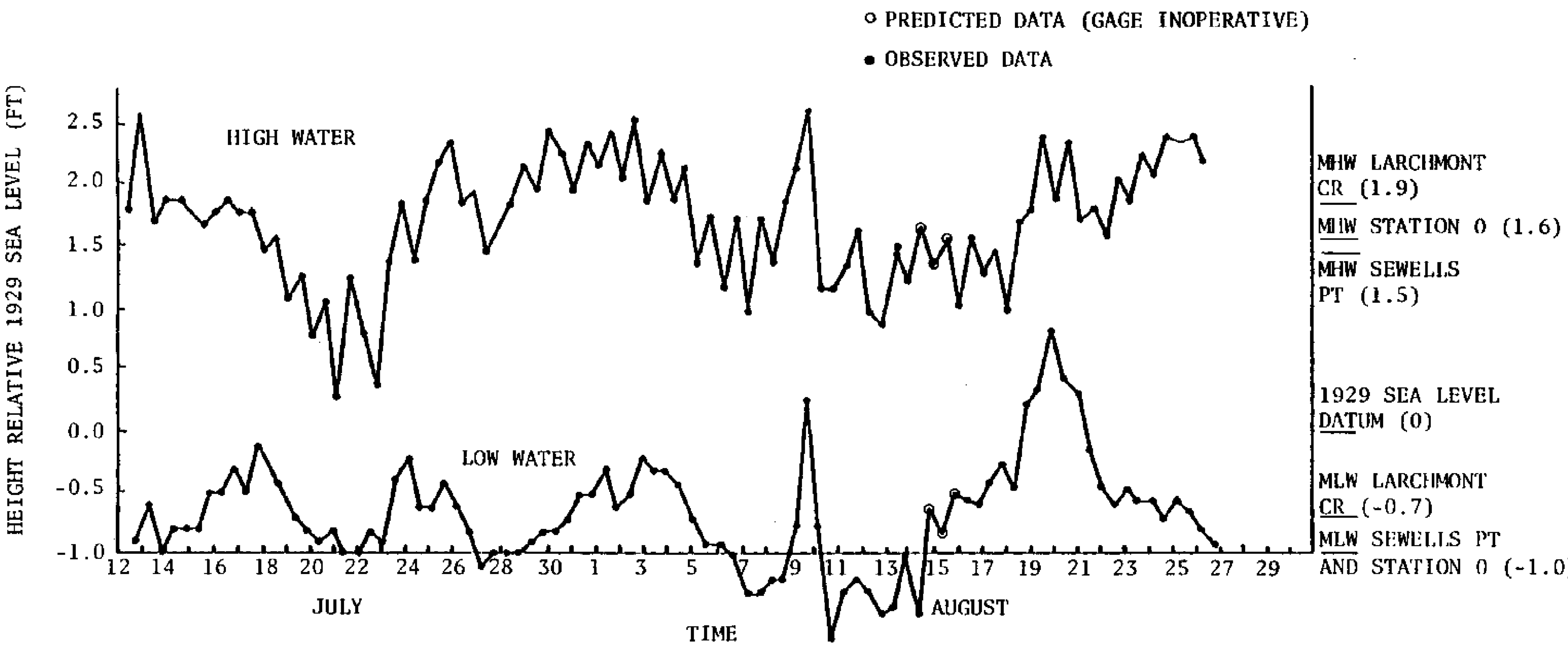


Figure 5. Tidal heights.

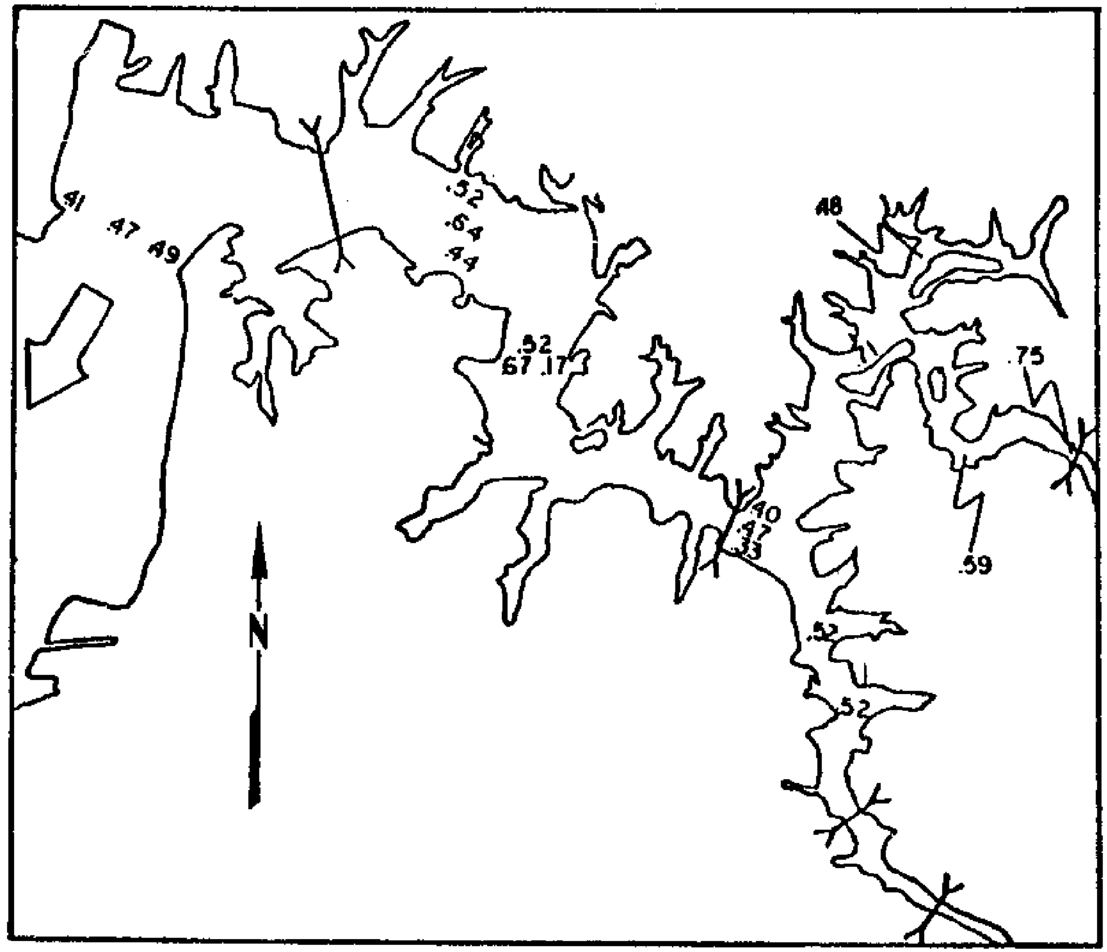


Figure 6. Mean surface current velocity at strength of ebb (Blair 1976).

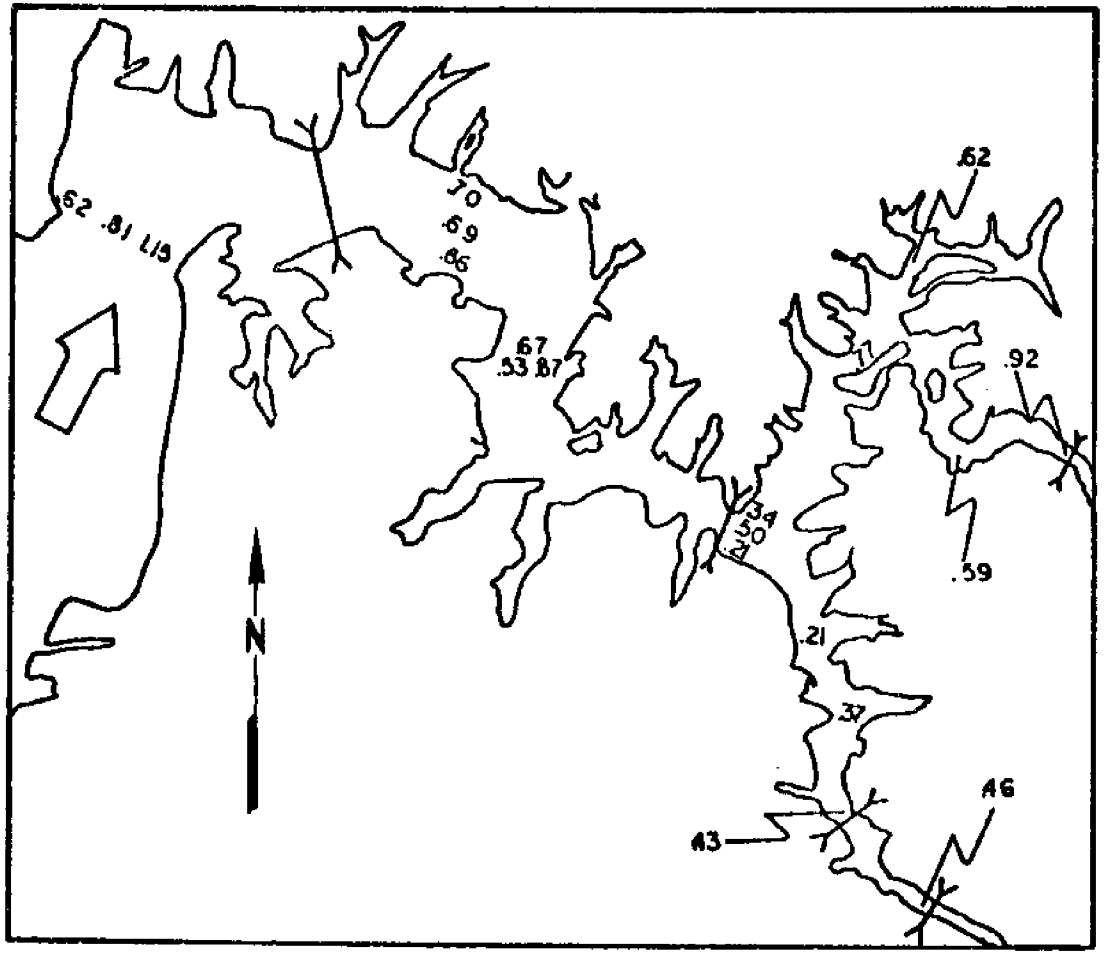


Figure 7. Mean surface current velocity at strength of flood (Blair 1976).

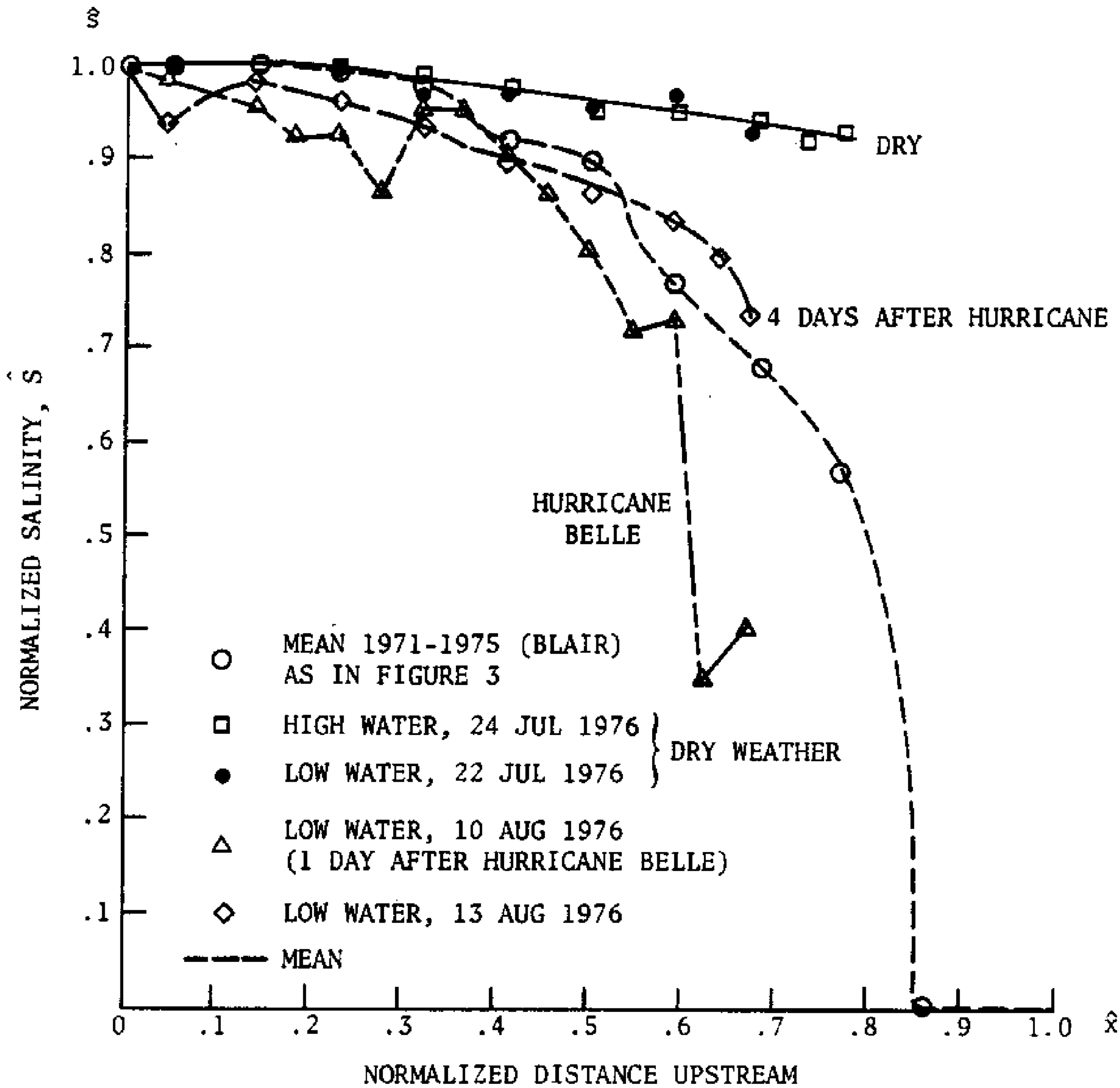


Figure 8. Normalized longitudinal surface salinity profiles.

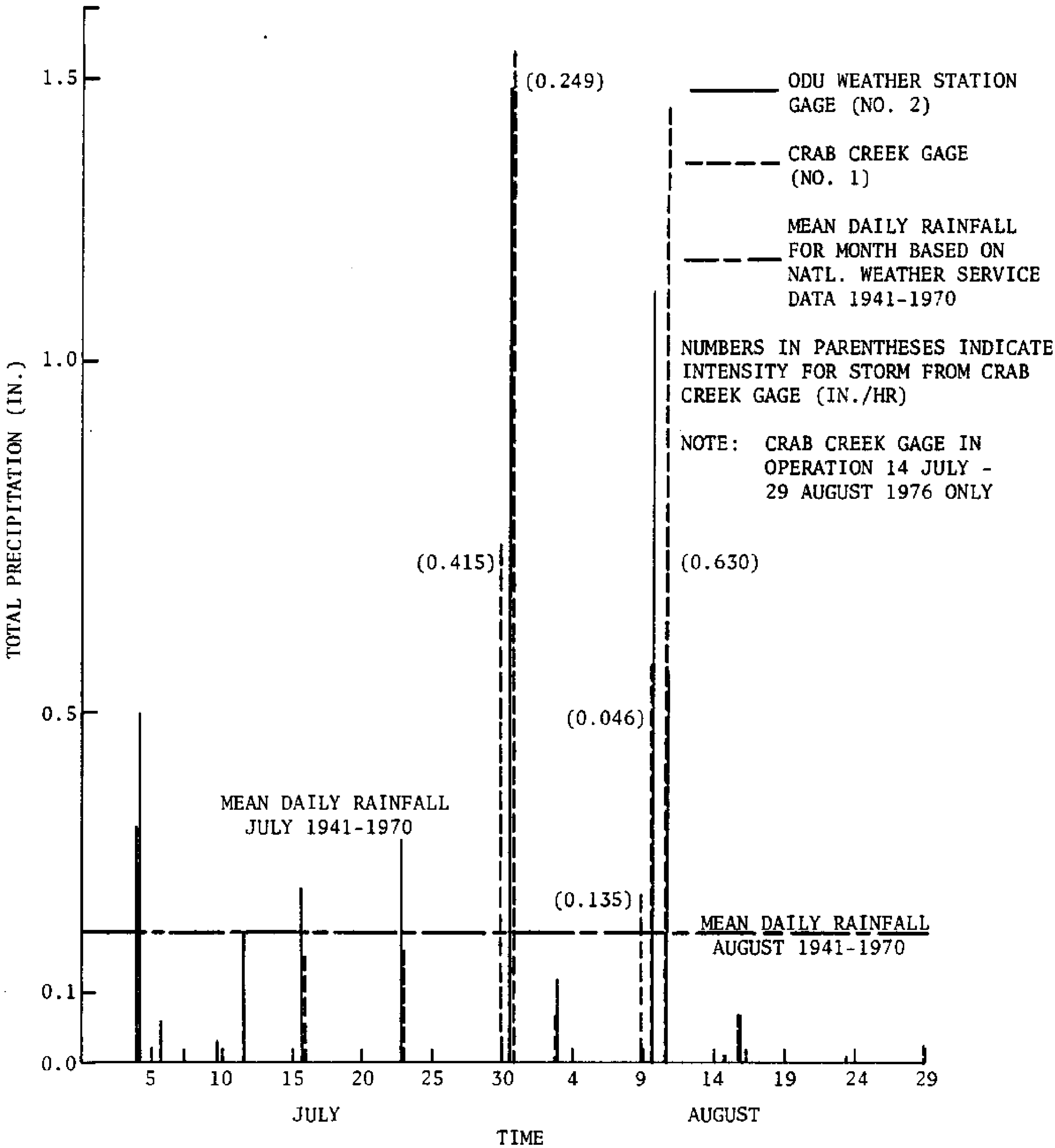


Figure 9. Total precipitation per storm (in.).

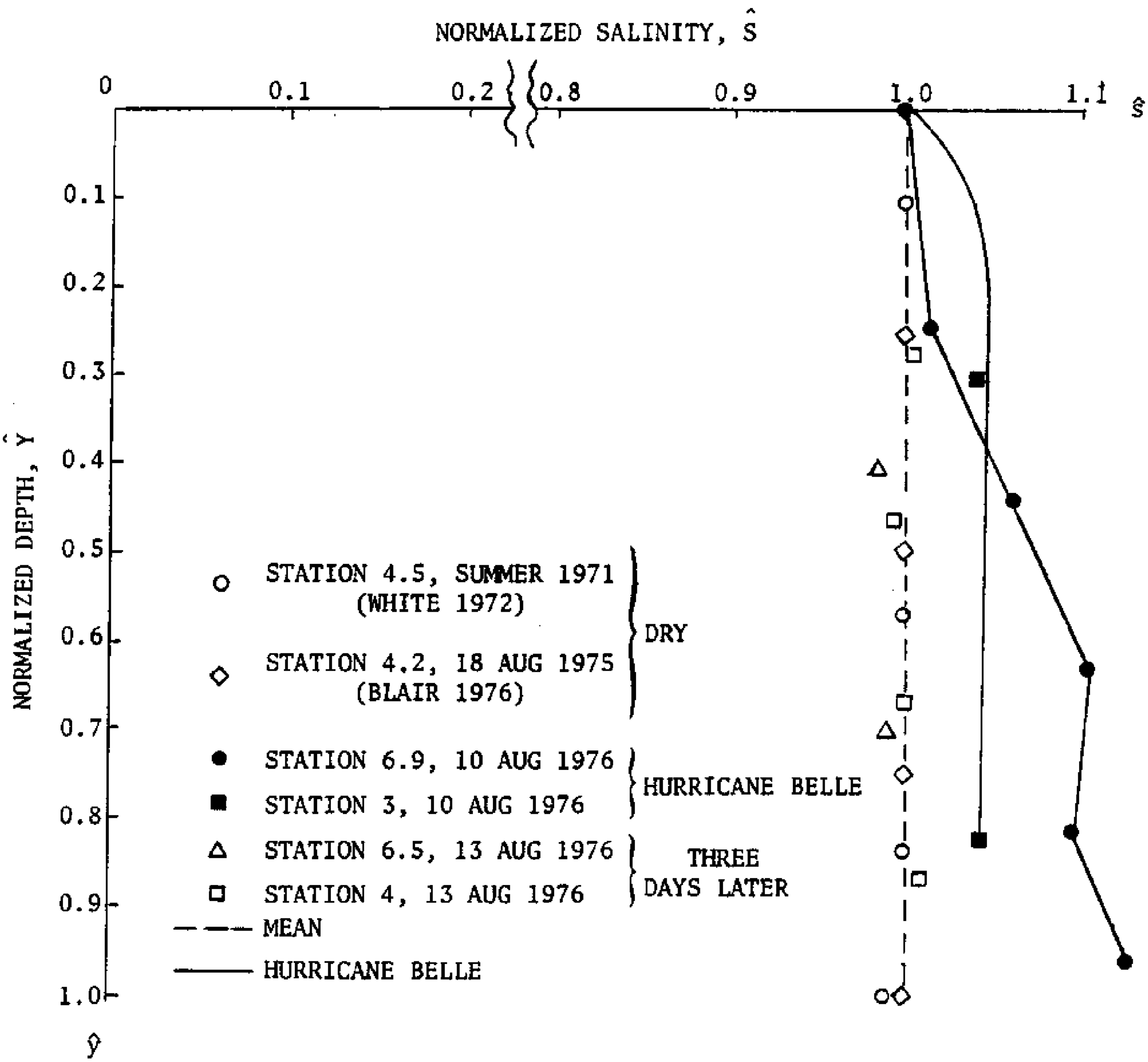


Figure 10. Normalized vertical salinity profiles.

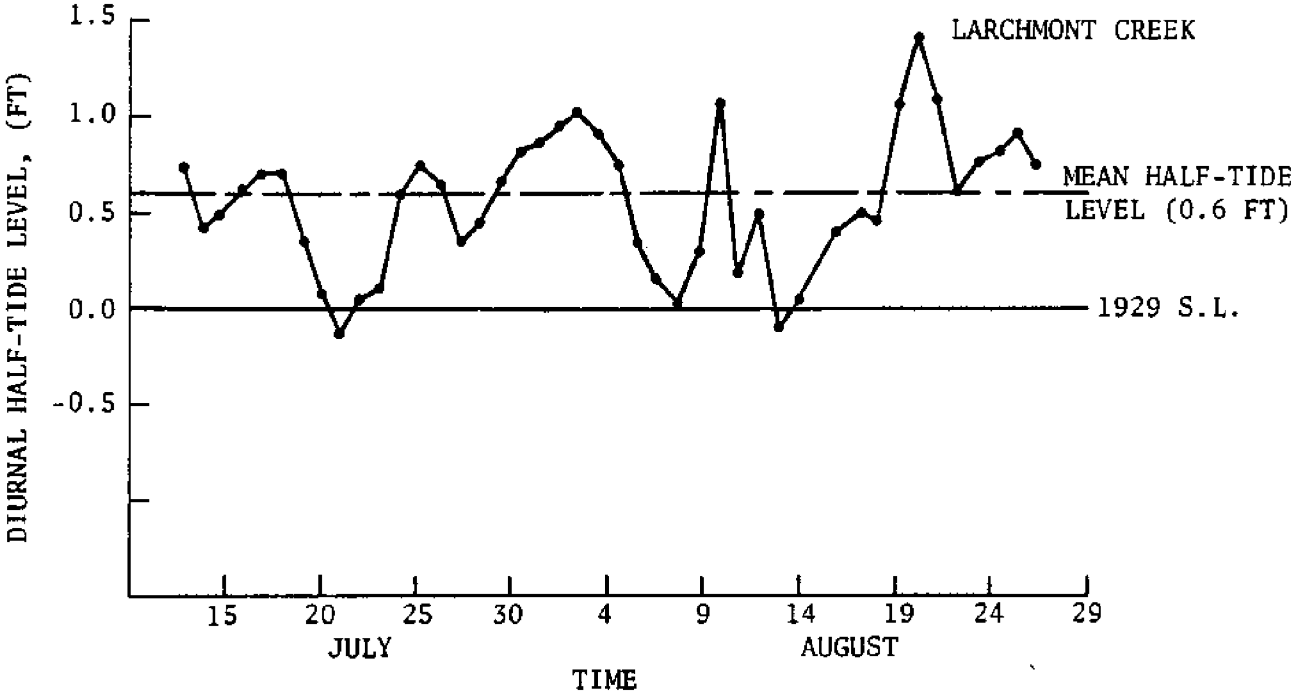


Figure 11. Temporal variation in half-tide level.

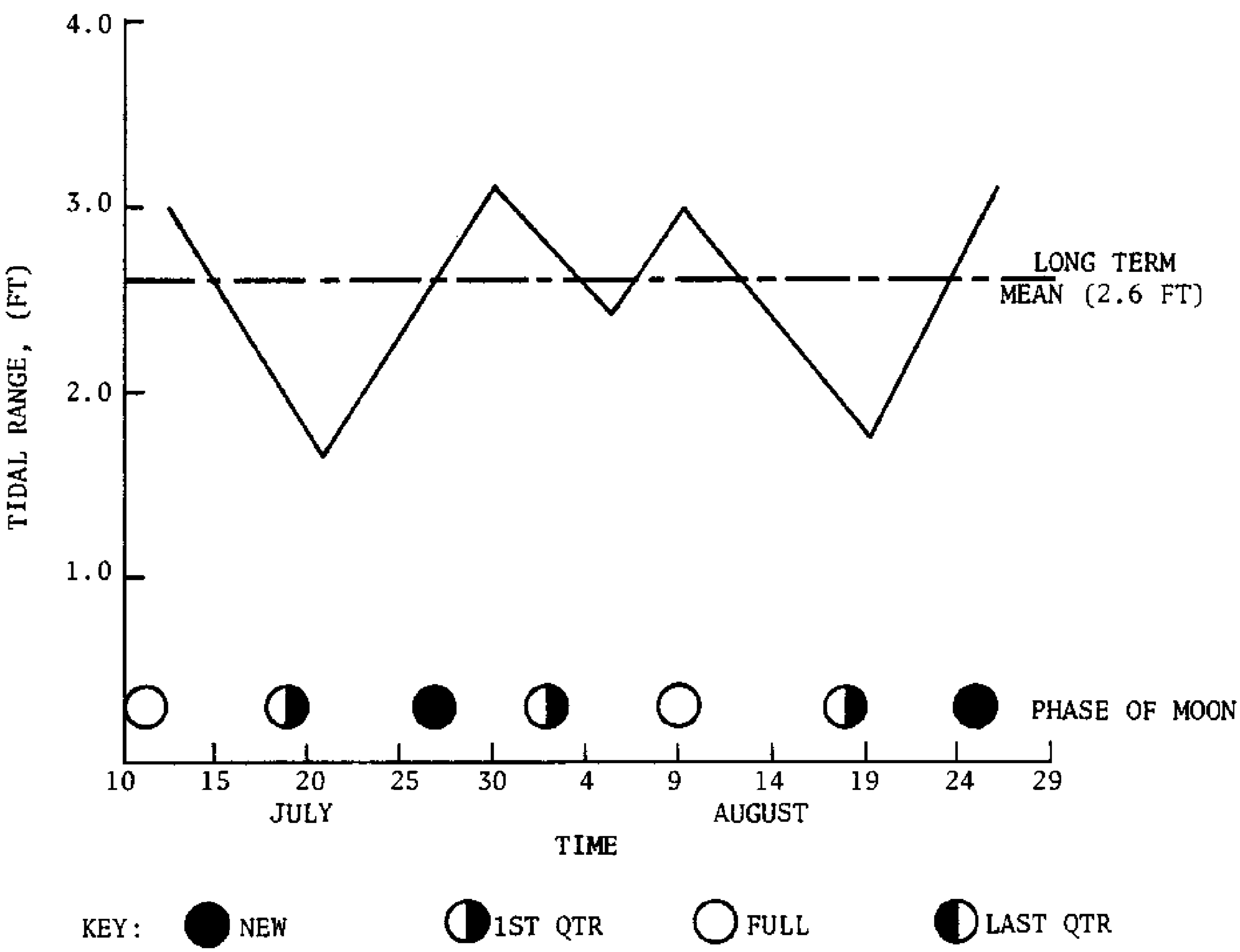


Figure 12. Temporal variation in tidal range.

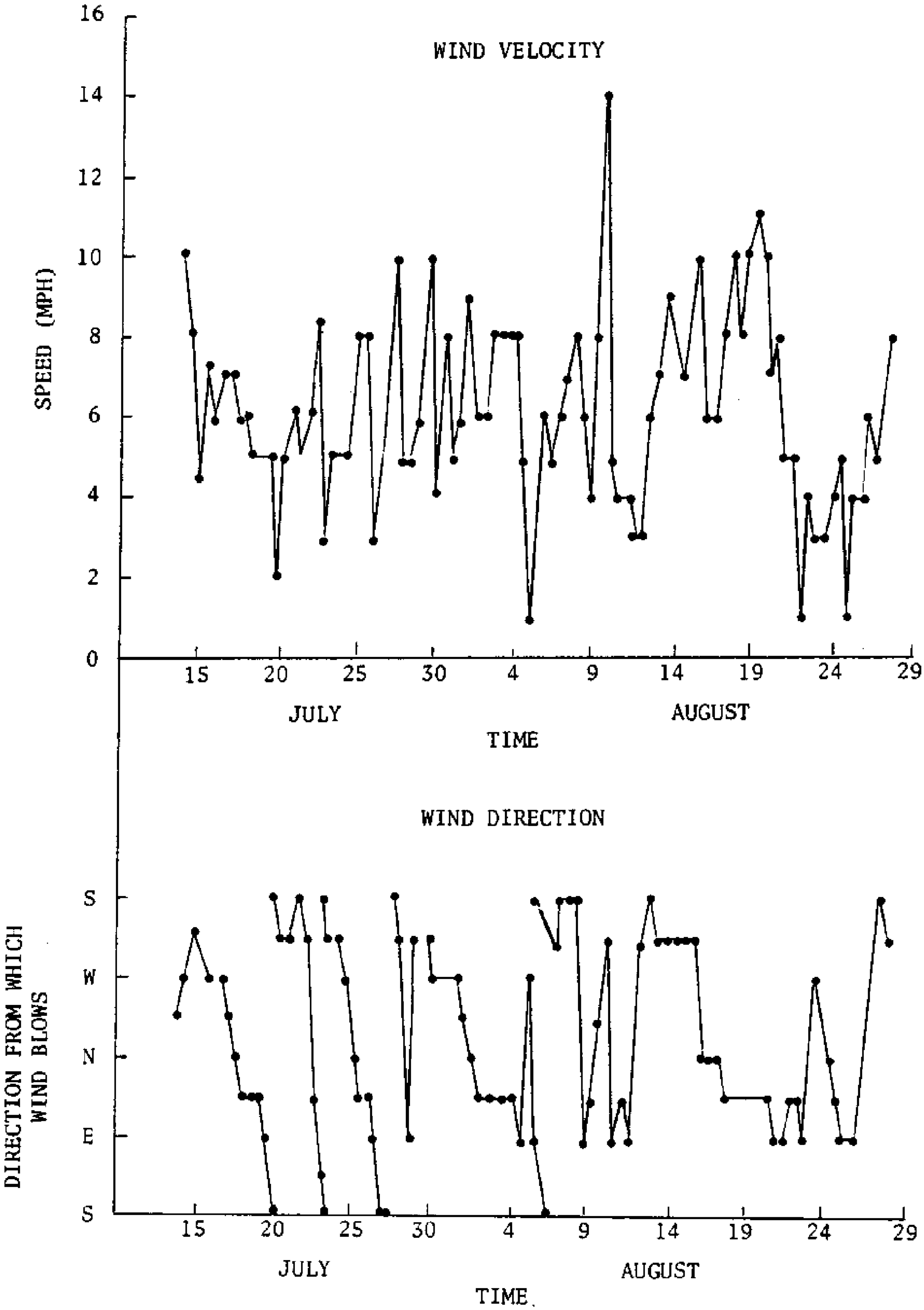
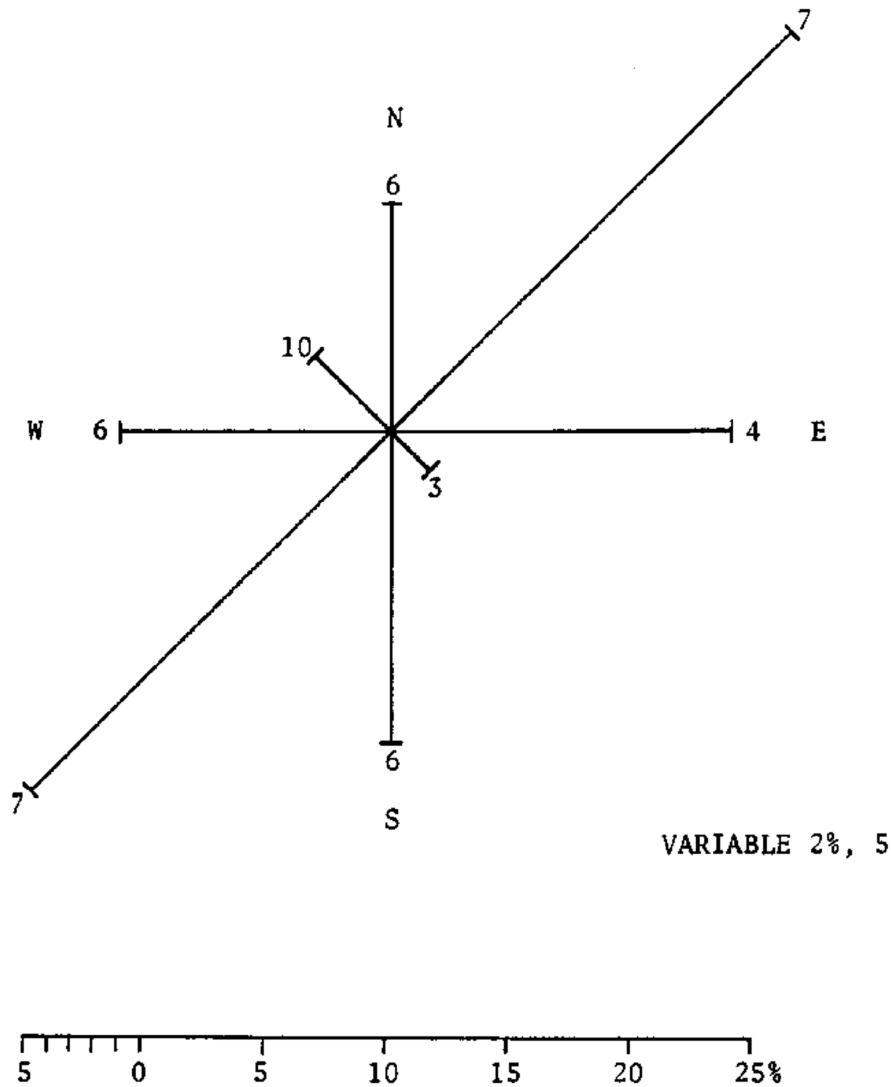


Figure 13. Wind velocity and direction.



LENGTH OF LINE INDICATES PERCENTAGE OF TIME DURING WHICH WIND BLEW FROM DIRECTION INDICATED. NUMERAL AT END OF LINE INDICATES MEAN VELOCITY IN M.P.H. OF WINDS BLOWING FROM THAT OCTANT.

Figure 14. Wind rose.

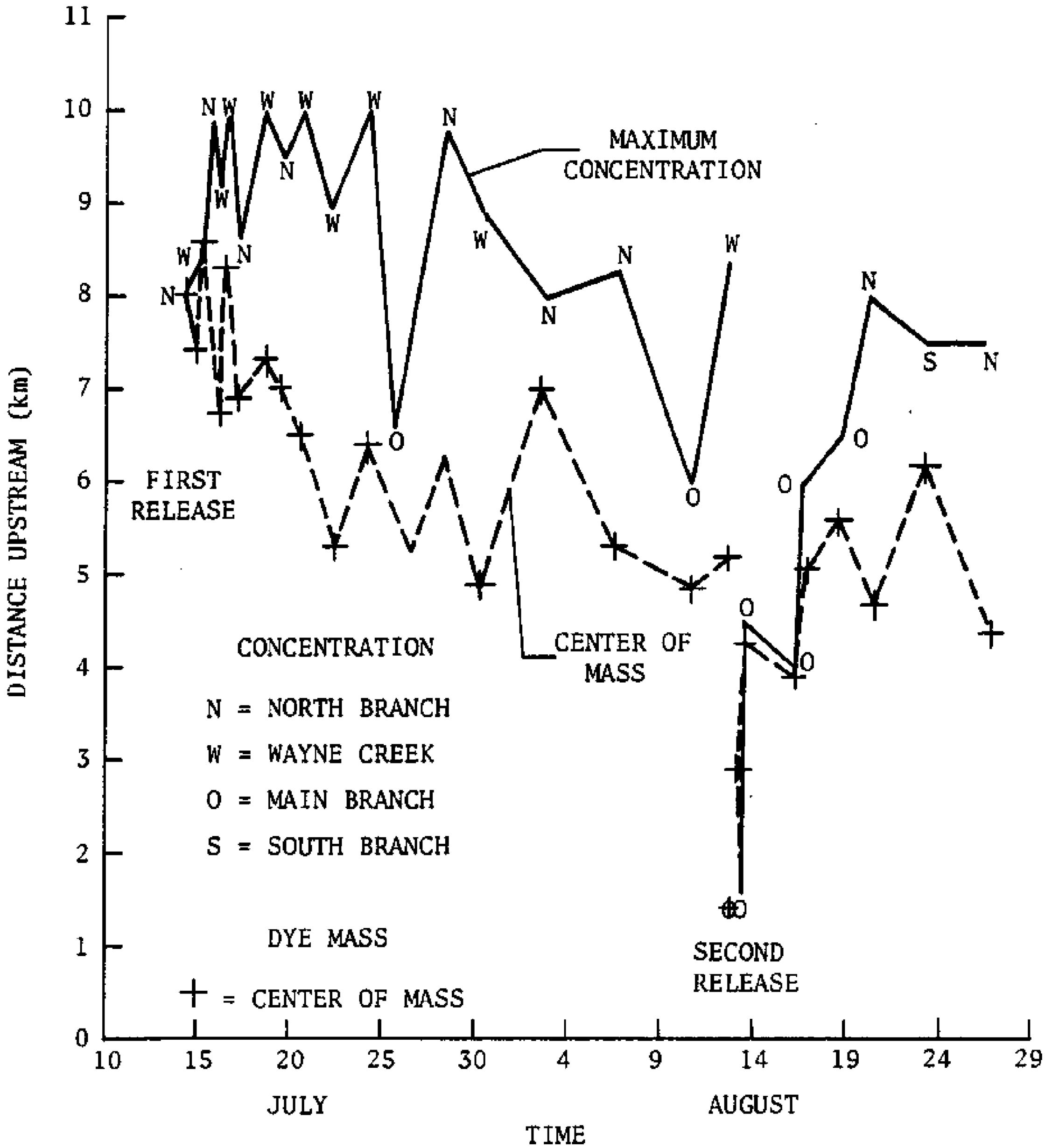


Figure 15. Location of maximum concentration and center of dye mass.

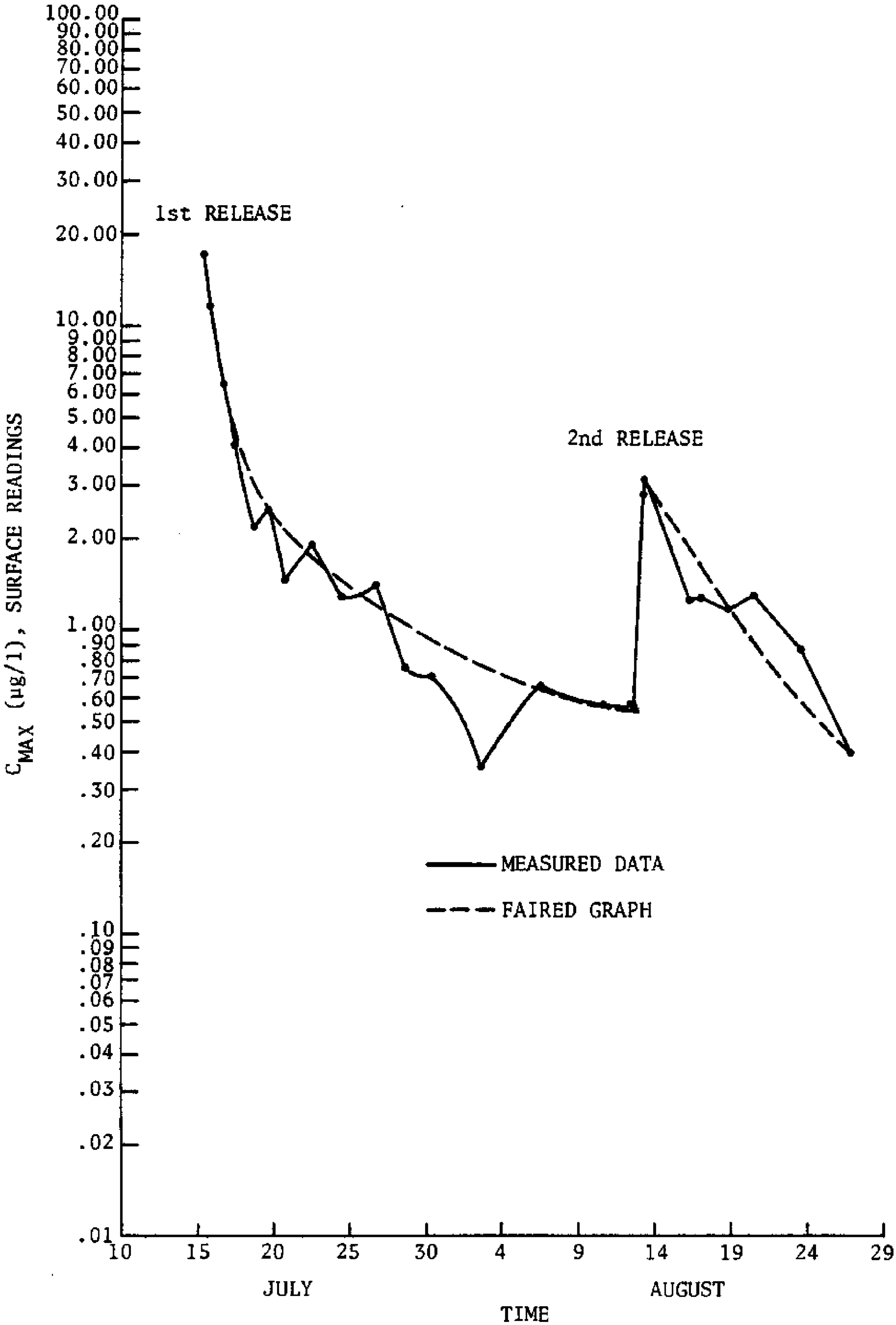


Figure 16. Variation of maximum concentration with time.

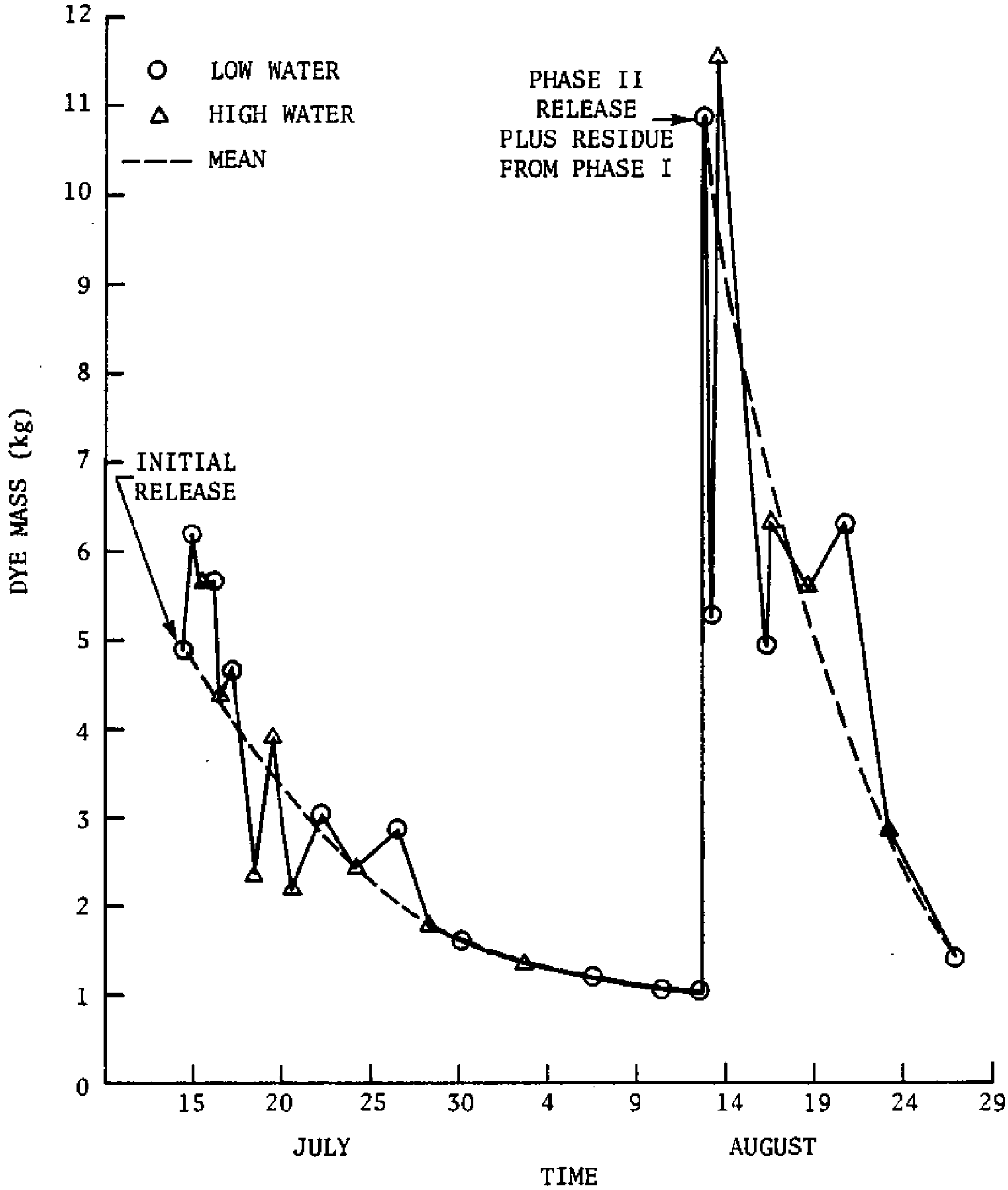


Figure 17. Variation of dye mass with time, entire estuary.

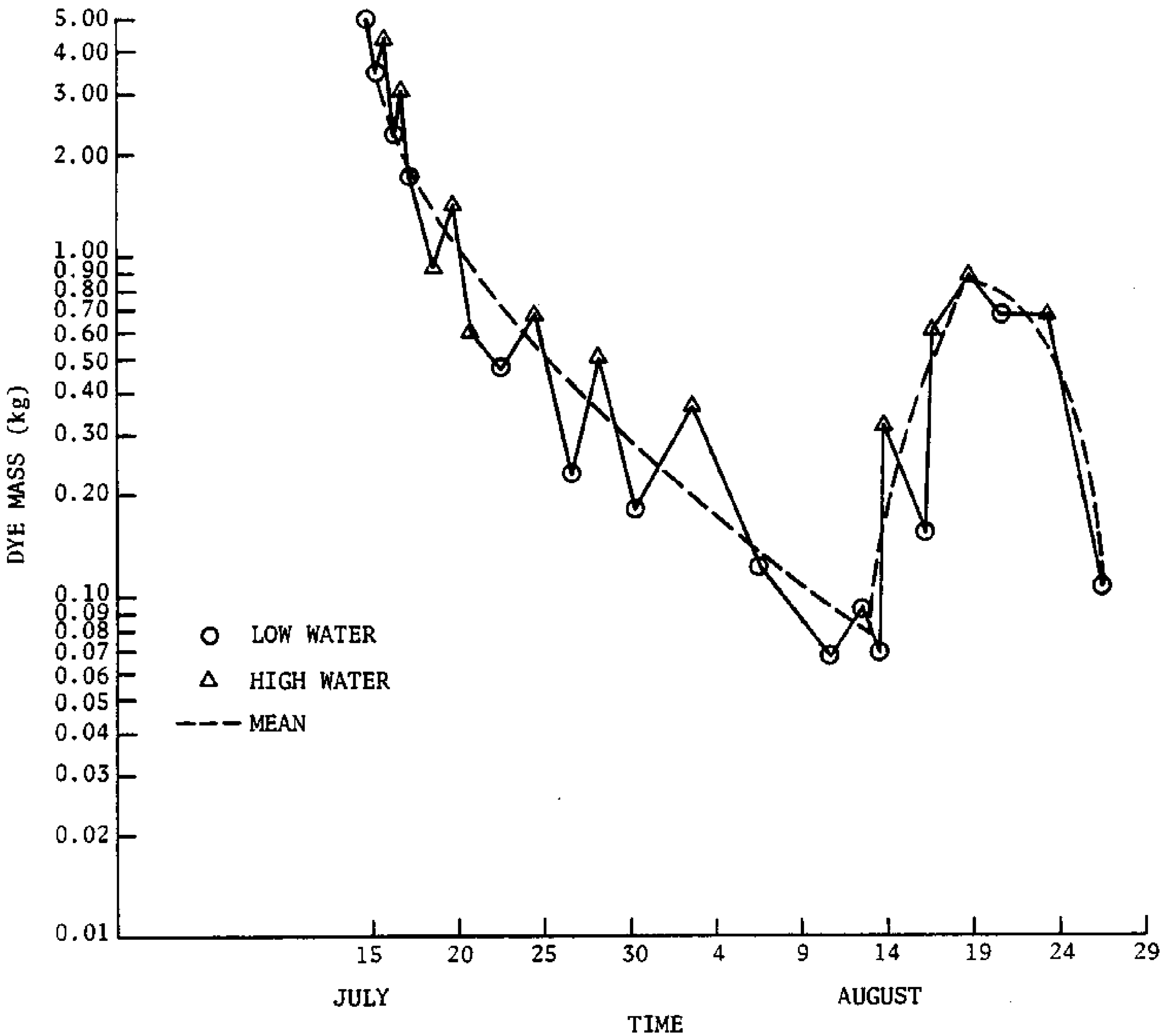


Figure 18. Variation of dye mass with time, north branch (including Wayne Creek).

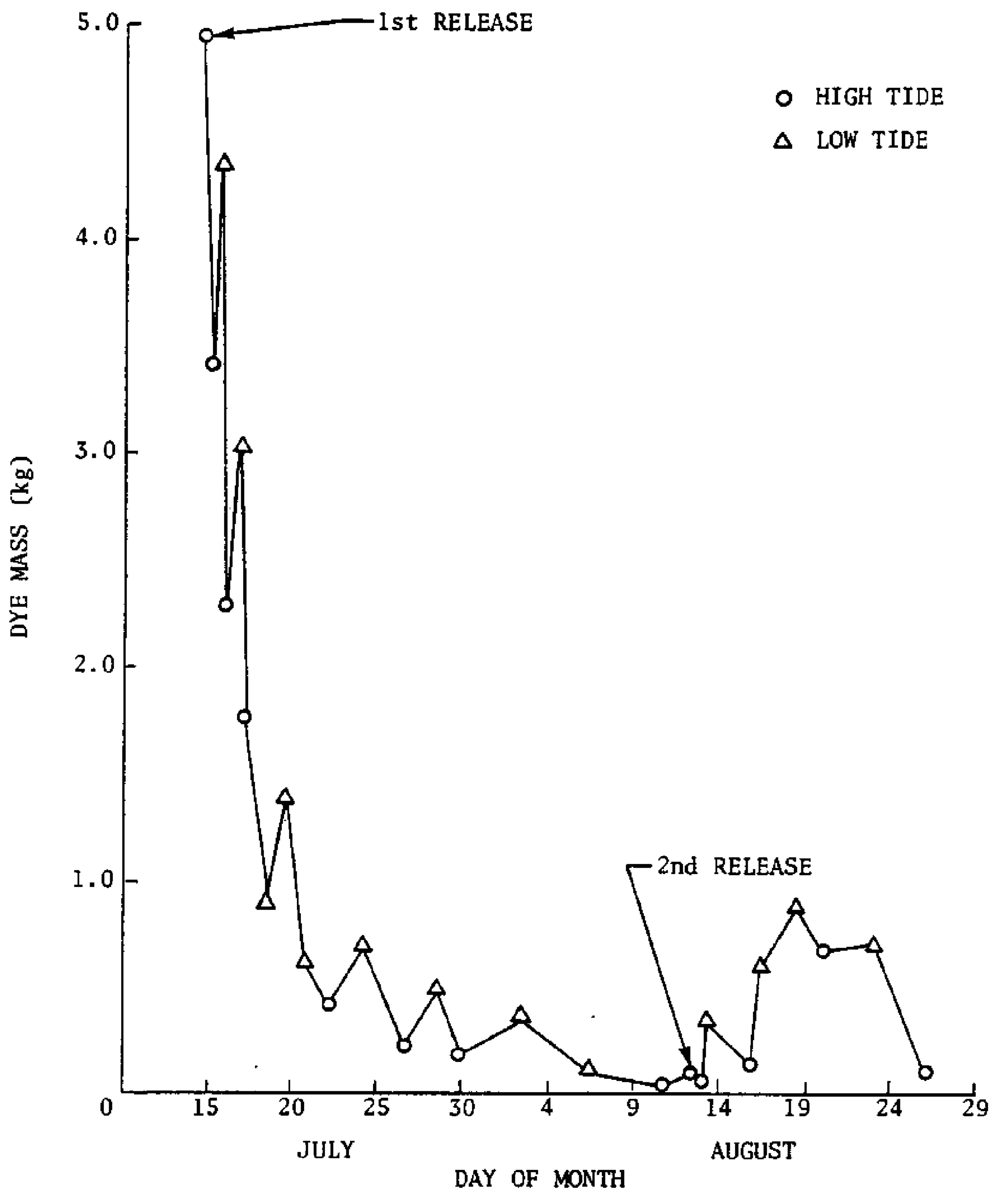


Figure 19. Linear plot of variation of dye mass with time, north branch (including Wayne Creek).

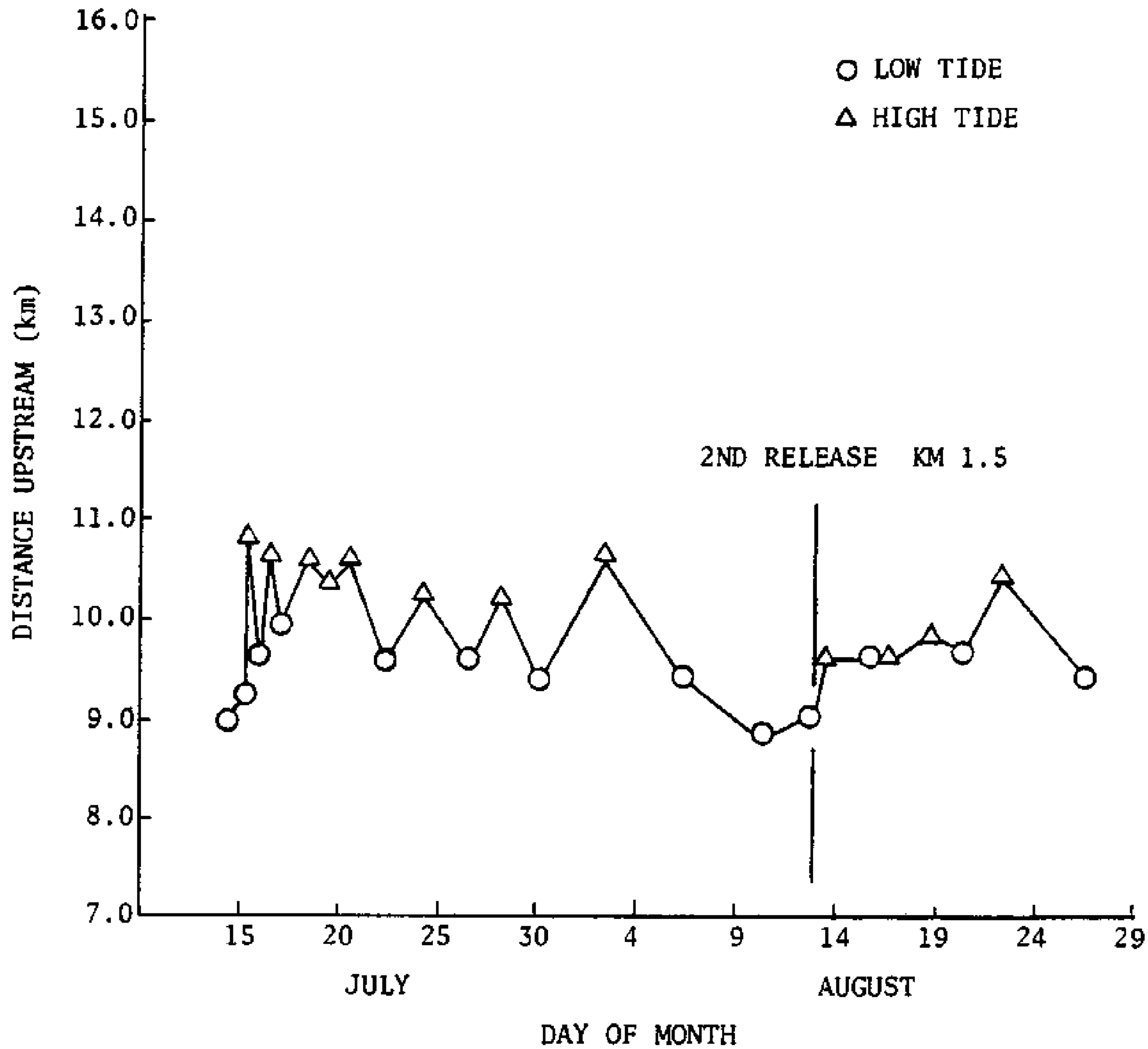


Figure 20. Location of center of dye mass, north branch (including Wayne Creek).

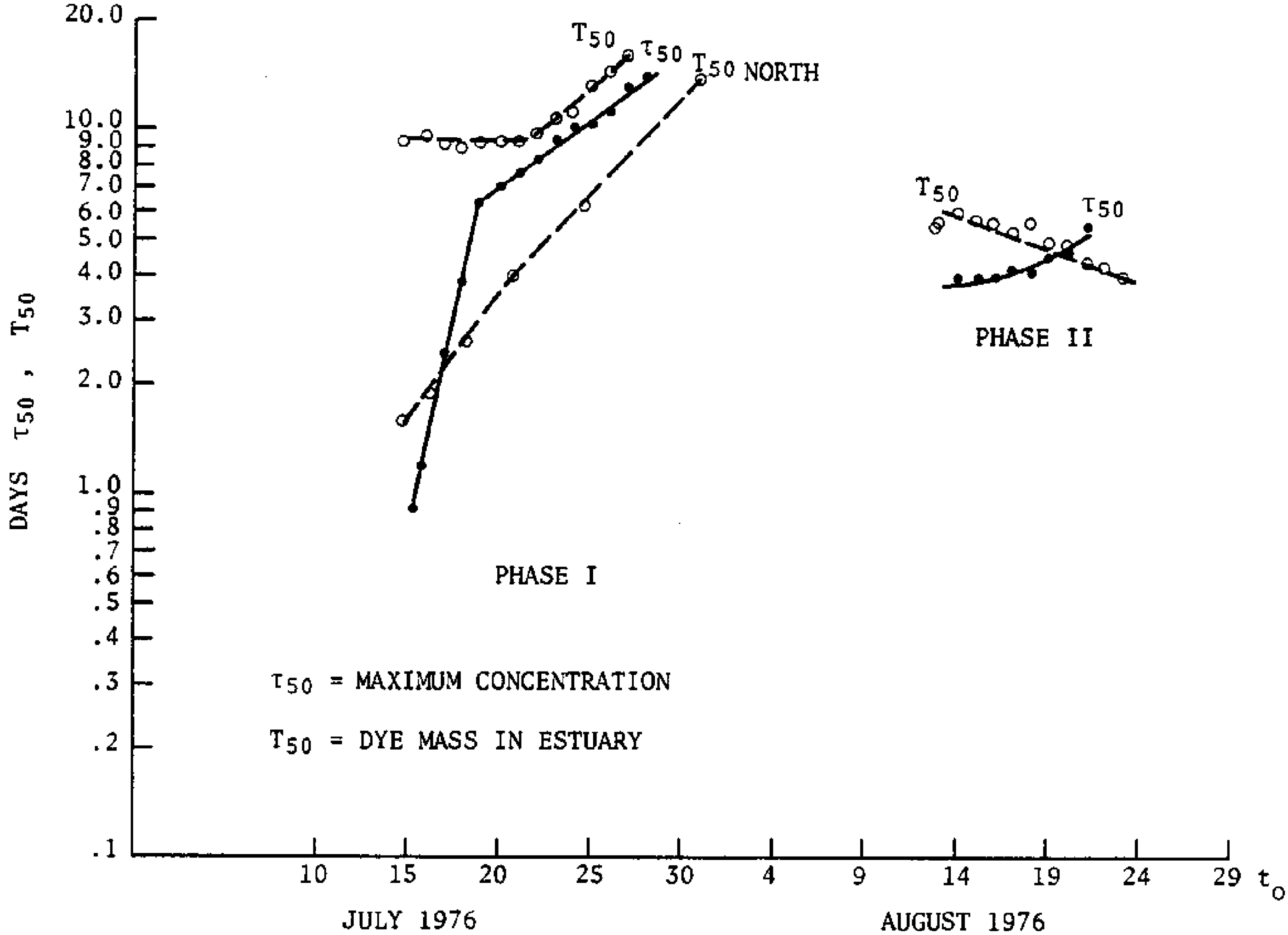


Figure 21. Half-life vs Start time.

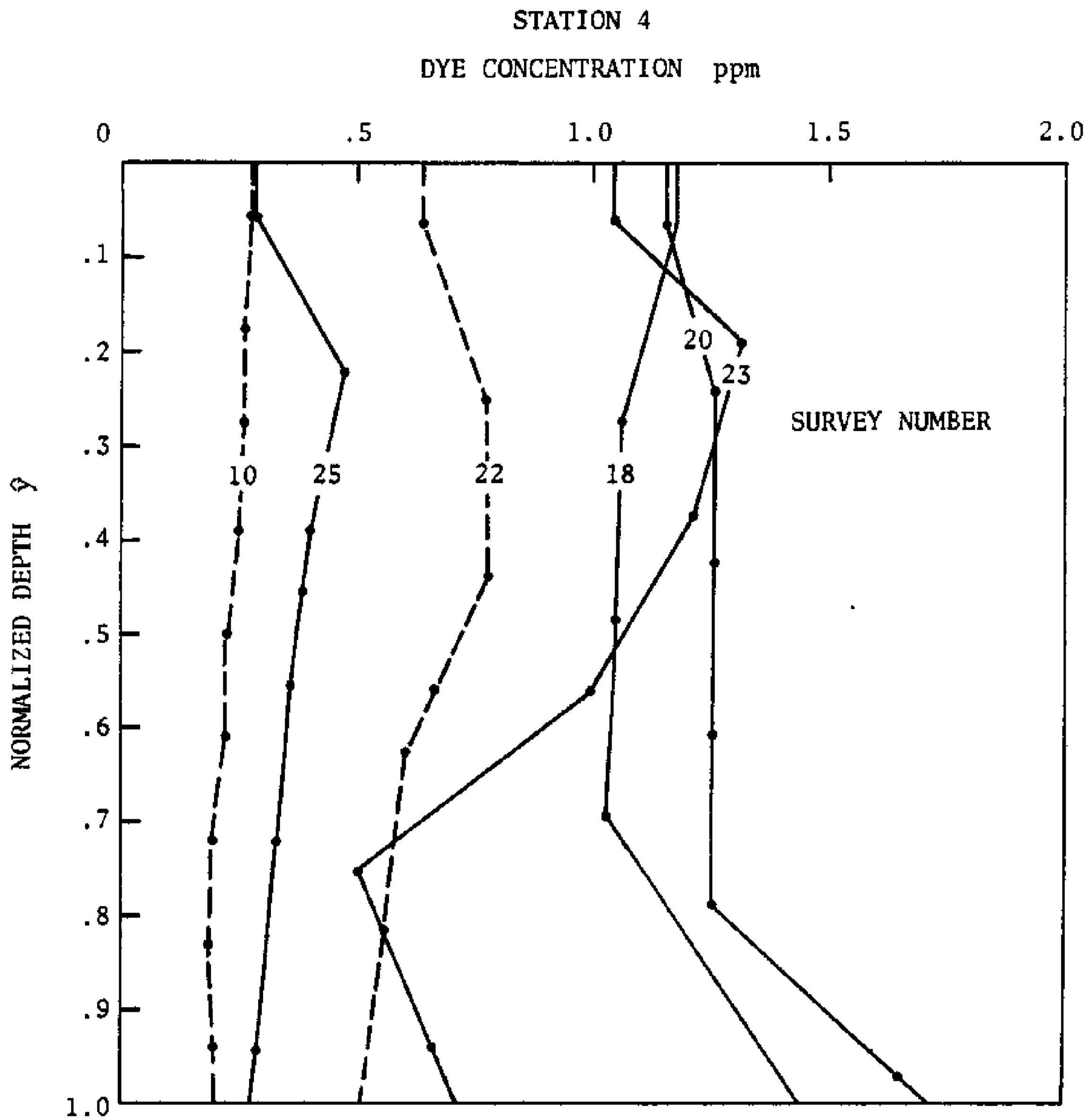


Figure 22a. Vertical dye concentration profiles (station 4).

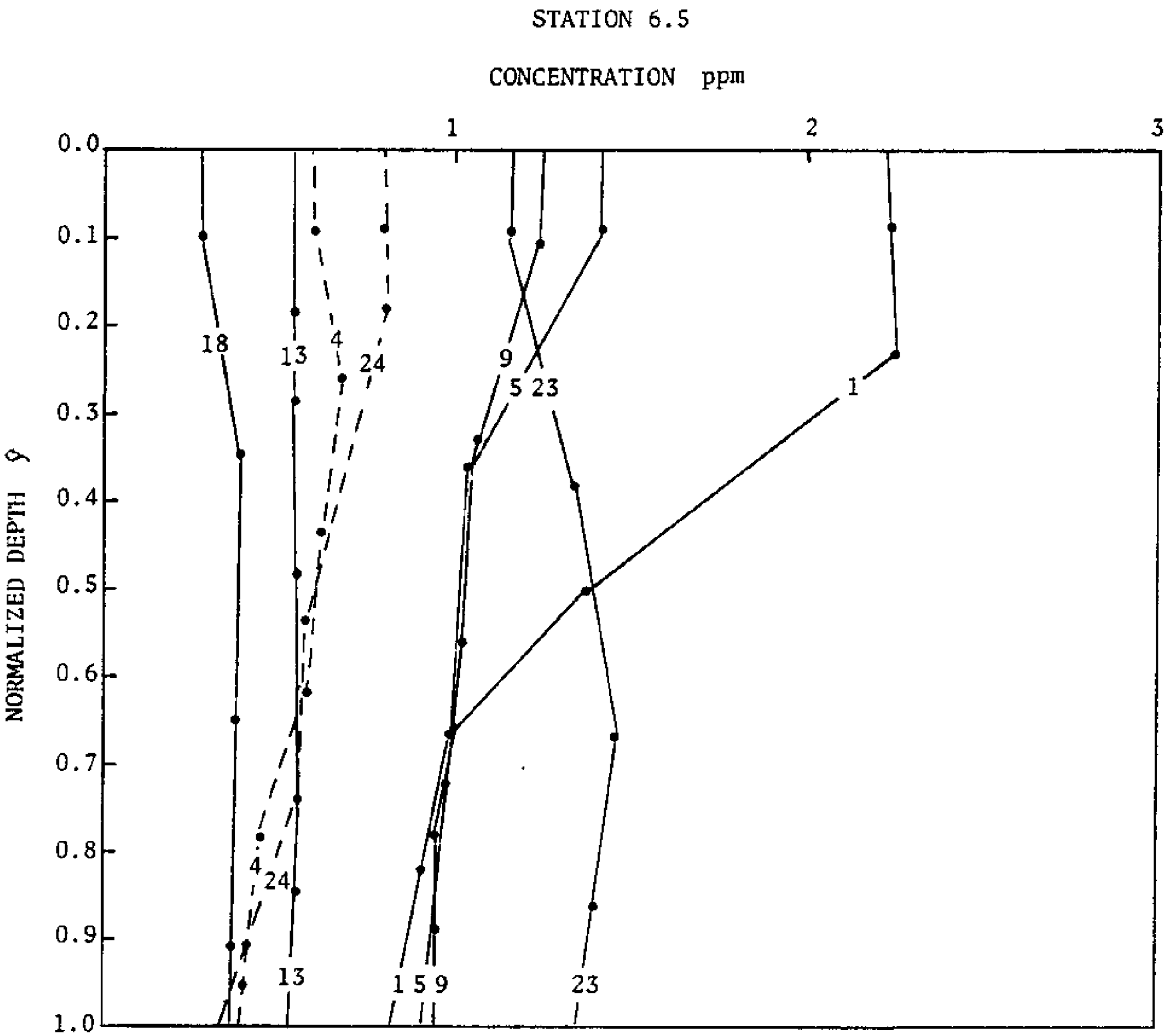


Figure 22b. Vertical dye concentration profiles (station 6.5).

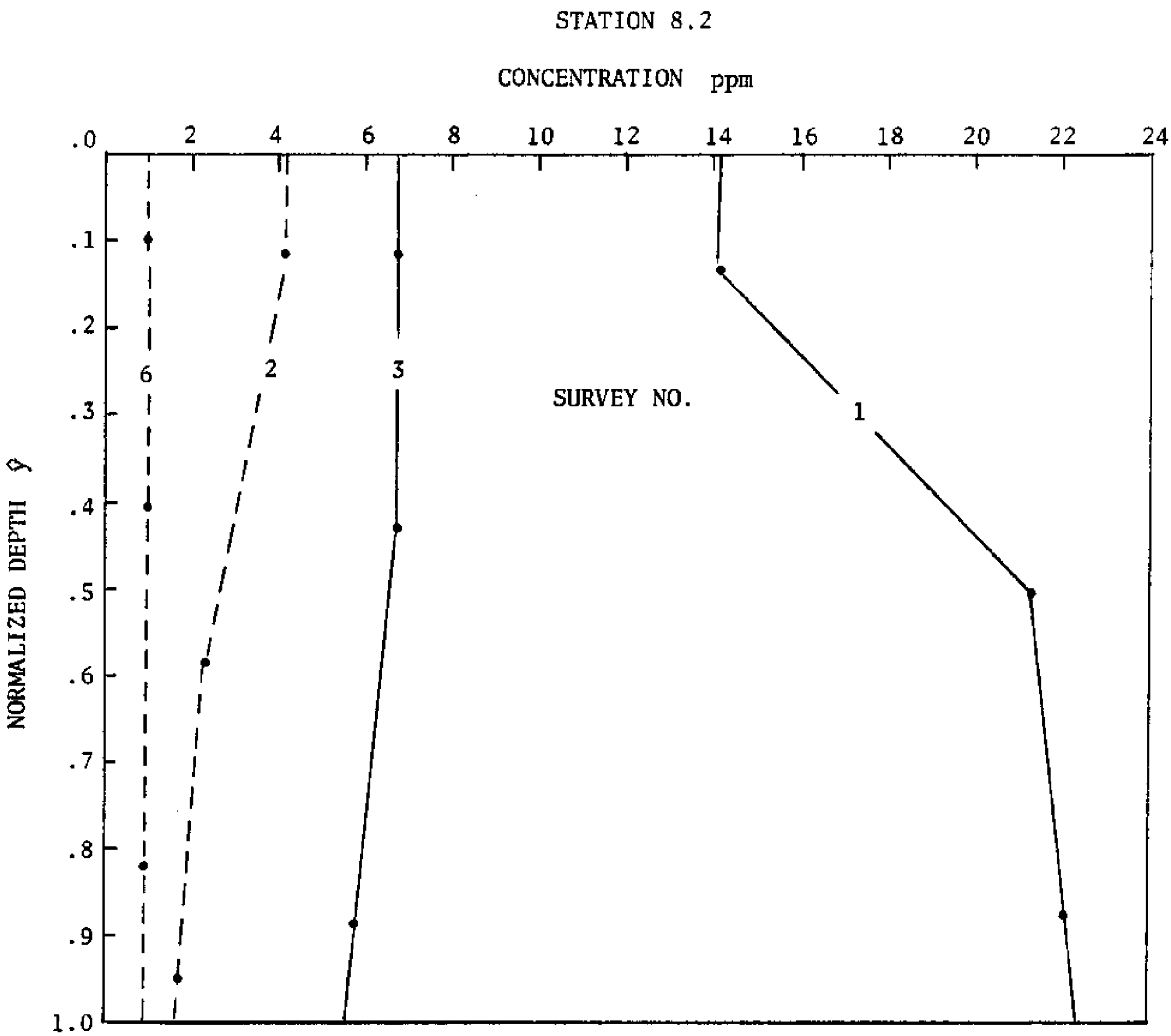


Figure 22c. Vertical dye concentration profiles (station 8.2).

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