INITIAL ASSESSMENT OF TIME OF TRAVEL AND MIXING THROUGH GULF ISLAND POND AND THE LOWER ANDROSCOGGIN RIVER, MAINE

By Gene W. Parker and Gardner S. Hunt

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4020

Prepared in cooperation with the
MAINE DEPARTMENT OF ENVIRONMENTAL PROTECTION

Augusta, Maine

1983

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information,
write to:

U. S. Geological Survey
26 Ganneston Drive
Augusta, Maine 04330

Copies of this report
can be purchased from:

Open-File Services Section
Western Distribution Branch
U. S. Geological Survey
Box 25425, Federal Center
Lakewood, Colorado 80225
Telephone: (303) 234-5888

CONTENTS

ILLUSTRATIONS

TABLES

CONTENTS.--cont.

Factors for converting International System (SI) to inch-pound units

To convert from	to	multiply by
	Length	
Meter (m)	Foot (ft)	3.281
Kilometer (km)	Mile (mi)	0.6214
	Area	
Square kilometer (km^2)	Square mile (mi^2)	0.3861
	Flow	
Liter per second (L/s)	Cubic foot per second (ft^3/s)	0.03532
Cubic meter per second (m^3/s)	Cubic foot per second (ft^3/s)	35.32
	Velocity	
Meter per second (m/s)	Foot per second (ft/s)	3.281
Kilometer per hour (km/h)	Mile per hour (m/h)	0.6214
	Temperature	
Degree Celsius (°C)	Degree Fahrenheit (°F)	(1.8) + 32
	Mass	
Gram (g)	Pound (lb)	0.002205
Kilogram (kg)		2.205

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level."

ABBREVIATIONS USED IN REPORT

C_i - observed dye concentration at T_i

CVT - concentration versus time

D - mean channel depth

E - Transverse mixing coefficient.

F - Froude number

H - depth at plunge line

h - hour

Lm - length of river necessary for complete lateral mixing

M_i - dye mass flow at T_i

M_{inj} - mass of pure dye injected

M_{obs} - total dye mass observed

MVT - mass versus time

PR - percent recovery

Q - average discharge

Q_i - discharge at T_i

S - skewness of a distribution

T - time of centroid of a dye cloud

T_i - i-th hour after injection

V - Variance of a distribution

v - mean velocity

W - mean channel width

α - 1/2 base angle of average channel cross-section

$\Delta\rho$ - difference of water densities

Δt_i - i-th time interval $\frac{(T_{i+1}-T_{i-1})}{2}$

µg/L - micrograms per liter

ρ - density of water

INITIAL ASSESSMENT OF TIME OF TRAVEL AND MIXING THROUGH GULF ISLAND POND AND THE LOWER ANDROSCOGGIN RIVER, MAINE

By: Gene W. Parker[1] and Gardner S. Hunt[2]

ABSTRACT

Flow-stratification patterns were observed in Gulf Island Pond during time-of-travel studies in May and August 1980. The stratification patterns in this 70 million cubic-meter impoundment were due to temperature differences between inflowing water and reservoir water. Separation was observed at temperature differences of 0.5°C in May 1980 and 1.0°C in August 1980. The pathway taken by inflowing water through the reservoir was governed by the temperature-related density forces acting between the two water masses. Data collected during August 1980 to define differences in dye concentrations with depth at two fixed profile points in Gulf Island Pond showed average water velocity to be seven times faster near the bottom than near the surface.

A concept of mass flow was used to analyze data collected at sites downstream from Gulf Island Dam where flow varied rapidly with time. This report presents the mathematical derivation of centroid traveltime, skewness, and percentage recovery of dye mass as determined from mass versus time curves.

---

[1] Hydrologist, U.S. Geological Survey
[2] Director, Division of Laboratory and Field Services, Maine Department of Environmental Protection

INTRODUCTION

The U.S. Geological Survey entered into an agreement with the Maine Department of Environmental Protection in October 1977 to evaluate and describe the traveltime and dispersion characteristics of selected streams with known or potential water-quality problems. The information will be used to calibrate and verify models that simulate waste loads to the rivers.

During the open-water period of 1980, a time-of-travel study was started on the Androscoggin River from Rumford to Brunswick, Maine (fig. 1). Fluorescent dye was used to measure traveltime and dispersion of soluble materials. Dye was injected at the upstream end of a series of study reaches, and concentrations were monitored at downstream locations as the dye cloud passed.

The 1980 time-of-travel data through Gulf Island Pond revealed unexpected stratification patterns. Also, the rapidly changing flow common below Gulf Island Dam required a mass flow-versus-time approach for analysis.

Purpose and Scope

The purpose of this interim report is to describe the unconventional methods required to analyze time-of-travel data in this reservoir and the regulated section of the Lower Androscoggin River. A family of time versus concentration curves is presented for each study run. The movement of the dye cloud through Gulf Island Pond while the dye cloud was present are depicted in the Appendix (figs. A1-7, B1-11). Temperature profiles of Gulf Island Pond while the dye cloud was present are depicted in the Appendix (figs. C1-4). The relationship between time versus concentration curves, hydrographs and dye mass flow versus time are graphically presented in the Appendix (figs. D1-10).

Acknowledgments

Special recognition is extended to Gary Westerman and James Jones of the Maine Department of Environmental Protection, who collected the fluorometry data, often under difficult field conditions.

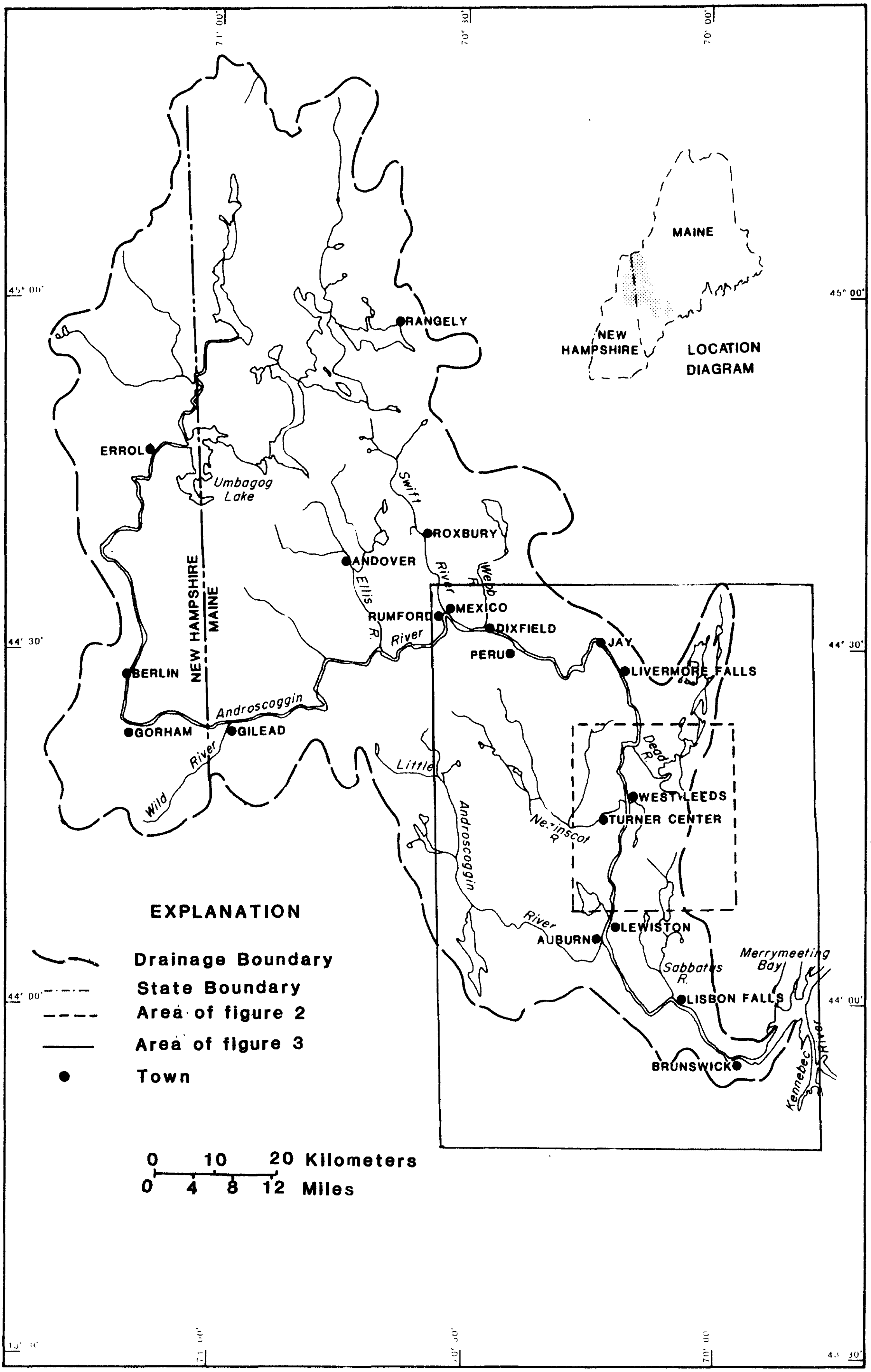


Figure 1.--Map showing drainage basin of the Androscoggin River.

Description of Study Reach

The Androscoggin River begins at the outlet of Umbagog Lake on the Maine-New Hampshire border and flows 259 km through New Hampshire and Maine to the tidal waters of Merrymeeting Bay at Brunswick, Maine (New England-New York Inter-Agency Committee, 1954). Total drainage area is 9,127 km² (Fontaine, 1979). The drop in elevation is 379 m over the 259-km length. Along its course through Maine, the river receives waste discharges from three industrial and six municipal waste-treatment plants.

The flow of the Androscoggin River is greatly influenced by regulation of numerous dams, both on the river itself and on its tributaries. Over 90 percent of the present storage is in the chain of lakes that make up the headwaters of the basin above Errol, N.H. Downstream from Errol, the largest single source of regulation is Gulf Island Dam near Lewiston, Maine, built in 1928. The reservoir, Gulf Island Pond, accounts for 3.5 percent of the usable storage of the basin (New England-New York Inter-Agency Committee, 1954). It has a capacity of 31 million m³ in the top 3 m below elevation of 79.9 m above mean sea level. Physical characteristics of Gulf Island Pond are given in table 1; a map of the pond is shown in figure 2.

Table 1.--Physical Characteristics of Gulf Island Pond

Normal pond-surface elevation: 79.9 m*	Drainage area: 7,415 km²
Length: 23.3 km	Mean width: 476 m
Capacity: 70,400,000 m³	Maximum depth: 22.9 m
Surface area: 11.1 km²	Mean depth: 6.3 m

* National Geodetic Vertical Datum of 1929

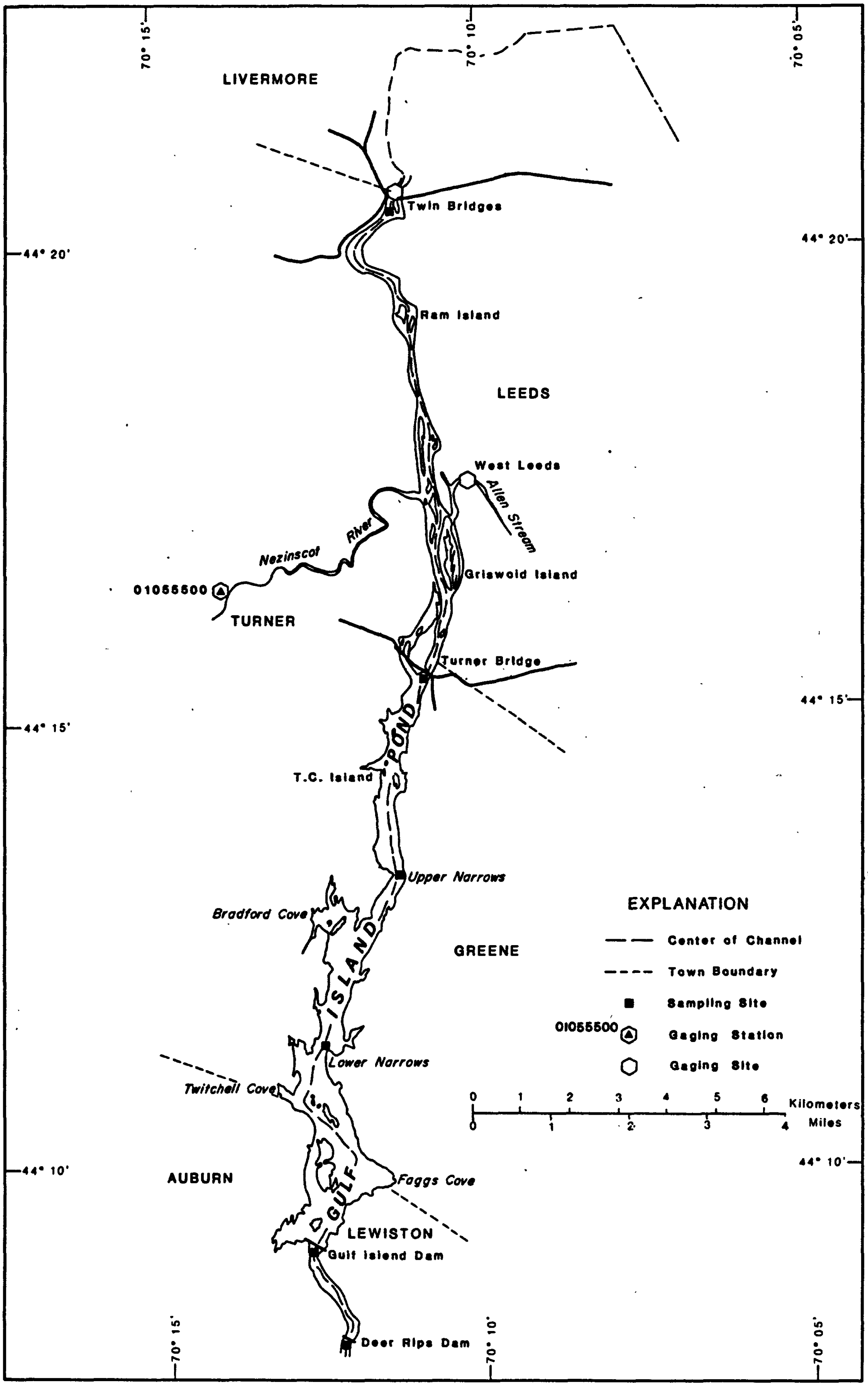


Figure 2.--Map showing Gulf Island Pond study area.

Flow is regulated at Errol to maintain a constant discharge of 44 m^3/s at Berlin, N.H. All other impoundments on the mainstem of the Androscoggin River have run-of-the-river operations except Gulf Island Pond. The pond is used primarily for power generation. Consistent flow generally is passed except on weekends when flows are restricted to rebuild storage in the reservoir. During low flows in the Androscoggin River basin, flow is restricted during the night to rebuild storage levels. The effects of regulation are evident in the entire reach below Gulf Island Dam to Brunswick and head-of-tide.

The U.S. Geological Survey operates 11 gaging stations in the Androscoggin River basin and a two parameter water-quality monitor at the Brunswick, Maine gaging station. Data on these sites are published annually by the Survey.

The overall study reach of the Androscoggin River extends from Rumford to Brunswick, Maine. Three subreaches were chosen for hydrologic and logistic reasons: (A) Rumford to Livermore Falls, (B) Livermore Falls to Gulf Island Dam near Lewiston, and (C) Gulf Island Dam to Brunswick (fig. 3). This report describes only subreaches B and C, where stratification in Gulf Island Pond and rapidly varying flow from Gulf Island Dam required the use of unconventional study techniques.

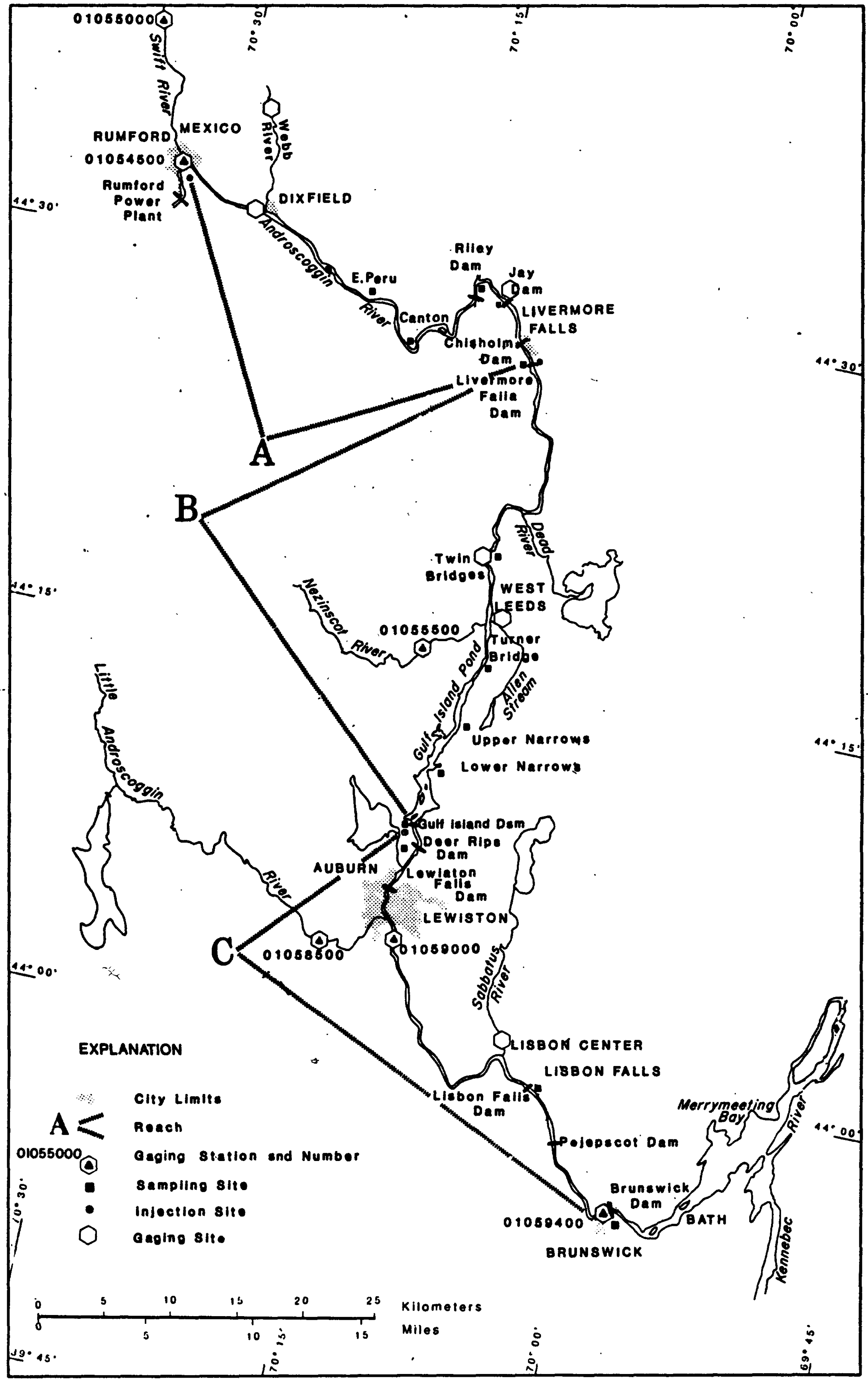


Figure 3.--Map showing location of study area.

FIELD OPERATIONS AND PRESENTATION OF DATA

Planning the Dye Study

Target discharges of 190, 120, and 50 m^3/s (25-, 50- and 90-percentile flow durations) were selected to define dispersion and time-of-travel over a range of discharge from mean 7-day, 10-year low flow to a high average annual flow. The U.S. Geological Survey gage on the Androscoggin River near Auburn, Maine (station 01059000), was used as the reference gage for the study. Fixed sites where time-concentrations curves were to be defined were selected at Twin Bridges, Turner Bridge, Upper Narrows, Lower Narrows, Gulf Island Dam, and Deer Rips Dam (fig. 2). A curve was also defined at Lisbon Falls (fig. 3). Site suitability for sample collection was confirmed by field reconnaissance. Because the movement of the dye cloud was expected to be slow, it was decided to supplement fixed-site monitoring in Gulf Island Pond with longitudinal and lateral mobile monitoring for additional definition of the dye-cloud shape and location. The hydroelectric dam at Livermore Falls, 20 km upstream from Twin Bridges, was selected as the site for injection of the dye tracer to ensure thorough mixing before the dye cloud entered Gulf Island Pond.

Rhodamine WT[1] dye at 20-percent solution was used as the tracer because of its miscibility in water, conservancy, and detectability at very low concentrations. The amount of dye required to obtain a 5-µg/L peak dye concentration at the lower end of a study reach was estimated from techniques outlined by Kilpatrick (1970).

[1] Use of the brand name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Discharge Measurement

Time of travel is a function of discharge and channel characteristics. Daily mean discharge was estimated at each fixed sampling site while the dye cloud was present. The Auburn gaging station (01059000) was used as the principal reference or index gage for the reach downstream from the Turner Bridge. The Rumford gaging station (01054500) was used as the index gage for flows upstream from Turner Bridge. Discharges were determined at the following sites:

Androscoggin River

Rumford gage (01054500)
Twin Bridges
Auburn gage (01059000)

Tributaries

Swift River near Roxbury gage (01055000)

Nezinscot River at Turner Center gage (01055500)

Allen Stream at West Leeds

Little Androscoggin River near Auburn gage (01058500)

Sabattus River at Lisbon Center

Individual discharge measurements were made at the Androscoggin River at Jay, upstream from the Livermore Falls dam, at the time of dye injection but a simple stage-discharge rating is not possible at this site.

Hourly discharges at Gulf Island Dam were provided by Central Maine Power Company. Discharge at each of the ungaged sampling sites (fig. 3) was estimated from nearby gaging sites on the Androscoggin River, adjusted for the intervening drainage area. Adjustments were based on runoff per square kilometer computed from discharges at nearby gaged tributaries. Drainage-area and river-distance data for selected gaged and ungaged sites on the Androscoggin River and major tributaries are listed in table 2.

Table 2.--Drainage area and river distance of selected sites in the study area (Locations are shown in fig. 3)

Site Name	Drainage area (km^2)	River distance* (km)
Androscoggin River at Rumford (gage)	5359	130.8
Swift River at Roxbury (gage)	251	130.5**
Androscoggin River at Jay (dam)	6444	3.2
Androscoggin River at Livermore Falls (dam)	6465	88.5
Androscoggin River at Twin Bridges	6835	68.6
Nezinscot River at Turner Center (gage)	438	61.5**
Allen Stream at West Leeds	38.3	59.1**
Androscoggin River at Turner Bridge	7358	57.6
Androscoggin River at Gulf Island Dam	7415	44.9
Androscoggin River at Deer Rips Dam	7420	42.8
Little Androscoggin River near Auburn (gage)	850	36.8**
Androscoggin River near Auburn (gage)	8451	34.3
Sabattus River near Lisbon Center	188	16.6**
Androscoggin River at Lisbon Falls (dam)	8759	13.7

* River distance above tide effect (0.1 km below most downstream dam at Brunswick, Maine).

** River distance at point where tributary enters.

Dye Injection and Initial Mixing

Two dye tracer studies were completed in the 1980 open-water period, one in May and the other in August. The dye was dumped as a slug into active penstocks of the Livermore Falls dam to provide initial mixing. During the May study about 50 percent of the flow passed through the turbines. It was estimated that over 90 percent of the flow passed through the turbines during the August study. The amounts of 20-percent rhodamine WT dye injected were 500 kg in May and 454 kg in August.

In the May study, data were not available to determine whether the dye was completely mixed before the cloud reached Twin Bridges. One of two automatic samplers at the Twin Bridges site did not operate. Therefore, the length of river required for complete mixing was estimated using the equation for a single-point side injection (Hubbard and others 1979, Eq.5.10a):

$$L_m = 0.4 \frac{v W^2}{E} \qquad (1)$$

where L_m = approximate length of river for complete lateral mixing.

v = mean velocity.

W = mean width of stream.

E = transverse mixing coefficient.

In the May study, L_m was estimated to be 19 km. Because the distance to Twin Bridges is 20 km, mixing was considered to be complete at this site. This estimate represents a worst-case situation. The injection was made near the center of the flow being passed through the turbines, which would create quicker mixing than the single-point side injection estimate. In the August study, comparison of data collected in the cross-section at Twin Bridges indicated complete mixing. (See later sections for discussion of mixing.)

Sample Collection and Analysis

Fixed Sites

Water samples collected at seven sites in the reach were analyzed for dye concentration. These sites were Twin Bridges, Turner Bridge, Upper Narrows, Lower Narrows, Gulf Island Dam, Deer Rips Dam, and Lisbon Falls (fig. 3).

During the May 1980 dye run, the following equipment was used at the sites indicated:

Twin Bridges.--An automatic pumping sampler was suspended from the center of the east channel bridge and another from the west channel bridge. Samples were collected at a depth of 1 m. Unfortunately, the west channel pumping sampler stopped operating before the dye cloud arrived. Discharge measurements indicated that 95 percent of the flow passed through this channel.

Turner Bridge.--Two floating automatic syringe samplers were evenly spaced across the channel 60 m upstream from the bridge and collected samples at a depth of 0.1 m.

Upper Narrows and Lower Narrows.--Two floating automatic syringe samplers were evenly spaced across the channel at each site and collected samples at a depth of 0.1 m.

Gulf Island Dam.--An automatic pumping sampler, secured to the left bank, collected samples from the outfall of the dam.

Deer Rips Dam.--An automatic pumping sampler, secured to the left bank, collected samples from the outfall of the dam.

Lisbon Falls.--An automatic pumping sampler, secured to the right bank, collected samples 10 m from shore at a depth of 0.5 m.

During the August 1980 dye run the equipment setup was the same as for the May dye run except for the following:

Twin Bridges: Two automatic pumping samplers were suspended from the west channel bridge, evenly spaced across the span. Samples were collected at the 1 m depth. Discharge measurements indicated 99 percent of the flow passed through this channel.

Turner Bridge: An automatic pumping sampler was suspended from the center of both bridge spans to collect samples at a depth of 1 m.

The data collected by the floating syringe samplers at Upper and Lower Narrows were of little value because nonuniform flow occured.

Water samples were analyzed in the field for dye concentration by a fluorometer equipped with either a flow-through or 40-mL discrete cuvette and powered by a constant voltage source. The fluorometer was calibrated at the beginning of each work day with standards according to methods of Wilson (1968). Calibration was checked at the end of each work day; on no occasion was there significant change. Because of the large volumes of dye used for each injection, several lots were used. Standards were prepared from single dye lots and used until depleted. New standards were then prepared from another dye lot. Comparisons of the standards made from the various dye lots showed no significant variations.

Mobile Sampling

The movement of the dye cloud through Gulf Island Pond was monitored by sampling water at various depths and horizontal locations and analyzing for fluorescence. Water was pumped from specific depths through a fluorometer equipped with a flow-through cuvette and concentration was recorded on a strip chart. Site location on the pond was identified by triangulation and depth soundings. A bathymetric map of the pond, provided by the Maine Department of Inland Fisheries and Wildlife, was used for navigation during work on Gulf Island Pond and in development of cross-sectional profiles at Upper Narrows and Lower Narrows. Water-temperature distributions within Gulf Island Pond were measured once during the May study and three times during the August study. Vertical profiles were obtained for temperature, dissolved oxygen, specific conductance, and pH by a four-parameter water-quality monitor. These profiles were obtained during sampling for vertical profiles of dye concentration. Water-temperature data at the Twin Bridges site were collected with each discharge measurement.

Presentation of Data

The plots in figures A1-7, B1-11, and C1-4 present mobile monitoring data of May dye distribution, August dye distribution and temperature distribution, respectively, obtained near the center of the channel. These data, collected during a single day, usually in less than 4 hours, are depicted as having occurred at 1200 hours that day. The location of any given data point could vary by 1 km owing to water velocity in the pond, uncertainty of location, and the difference of sampling times from 1200 hours. The depths indicated in the appendix illustrations do not indicate the observed extremes but do show the trend of the streambed altitude. Figures D1-10 show discharge hydrographs and time-concentration curves at several fixed sampling sites.

DATA ANALYSIS

Time-Concentration Curves at Fixed Sites

Dye concentration measured at Twin Bridges, Turner Bridge, Gulf Island Dam, Deer Rips Dam, and Lisbon Falls was plotted against time after injection for both the May and August dye studies. A smooth curve was drawn through all data points, taking into consideration possible background fluorescence determined from samples collected before the arrival of the dye cloud and occasional outliers. Figures 4 and 5 show plots for May and August, respectively, of dye concentration versus time after injection for all sites. From the curves, the elapsed time after injection to each of three important features of the dye cloud was determined. The features are:

<u>Leading edge</u> - arrival of dye at the sampling point
<u>Peak</u> - maximum dye concentration at the sampling point
<u>Trailing edge</u> - point on the recession of the CVT curve at which concentration is 10 percent of the peak.

From the curve, three important dye cloud characteristics are calculated. These are:

<u>Area</u> - representative of the dye cloud mass.
<u>Centroid</u> - moments of the center of the area (center of mass).
<u>Skewness</u> - measure of the nonsymmetry of the curve.

Under steady flow conditions, a CVT (concentration versus time) curve would describe the passage of a dye cloud past a fixed location and would enable the time to the dye cloud centroid to be readily determined. However, the discharge in the reach below Gulf Island Dam is unsteady and changes of 60 m^3/s within an hour are common. Use of CVT data to determine dye-cloud characteristics requires constant discharge; therefore, the unsteady discharges observed precluded the use of CVT curves and necessitated the use of the fundamental dye-mass flow concept. MVT (dye-mass flow versus time after injection) curves were therefore created to accurately determine dye cloud characteristics.

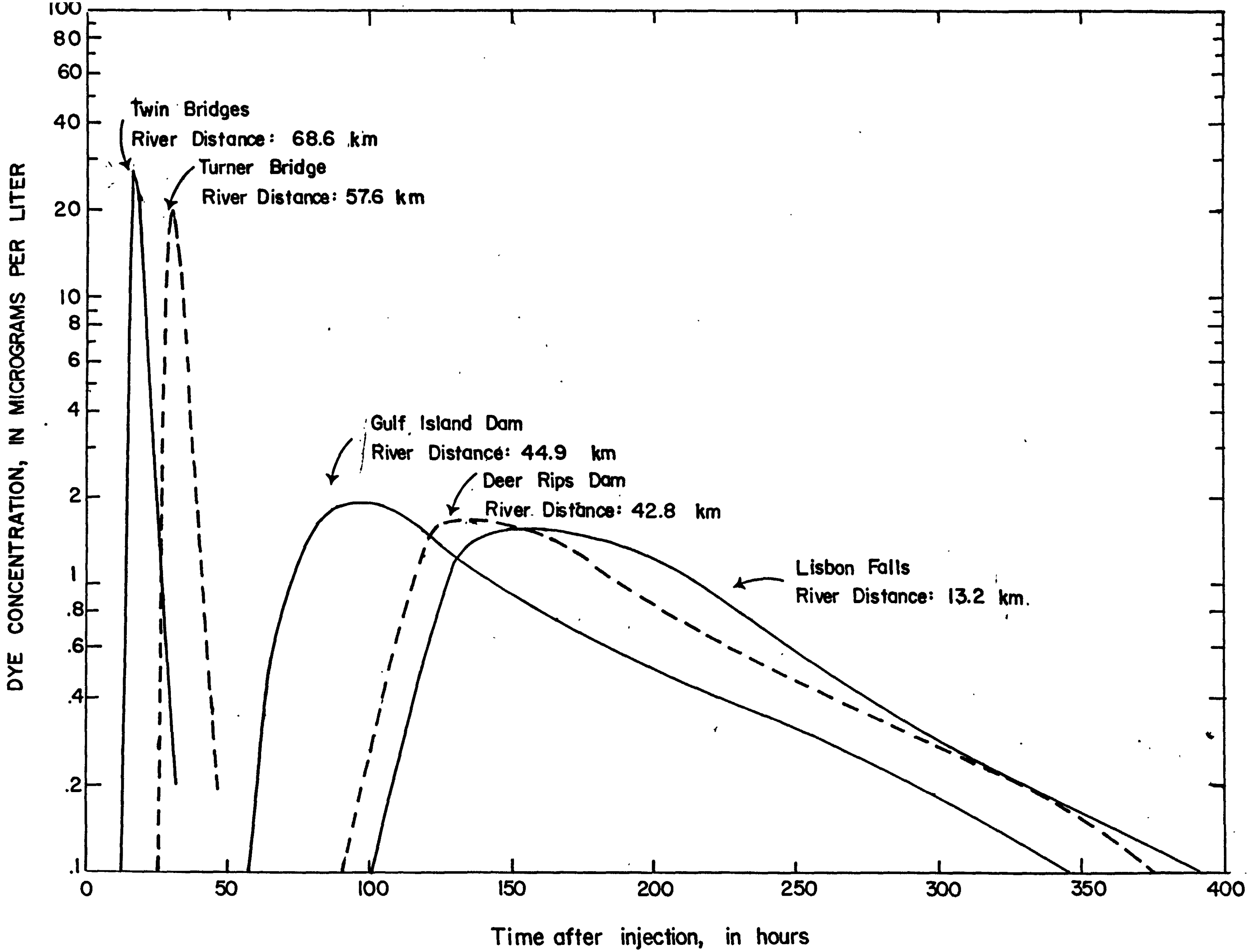


Figure 4.--Time concentration curves for May 1980 study

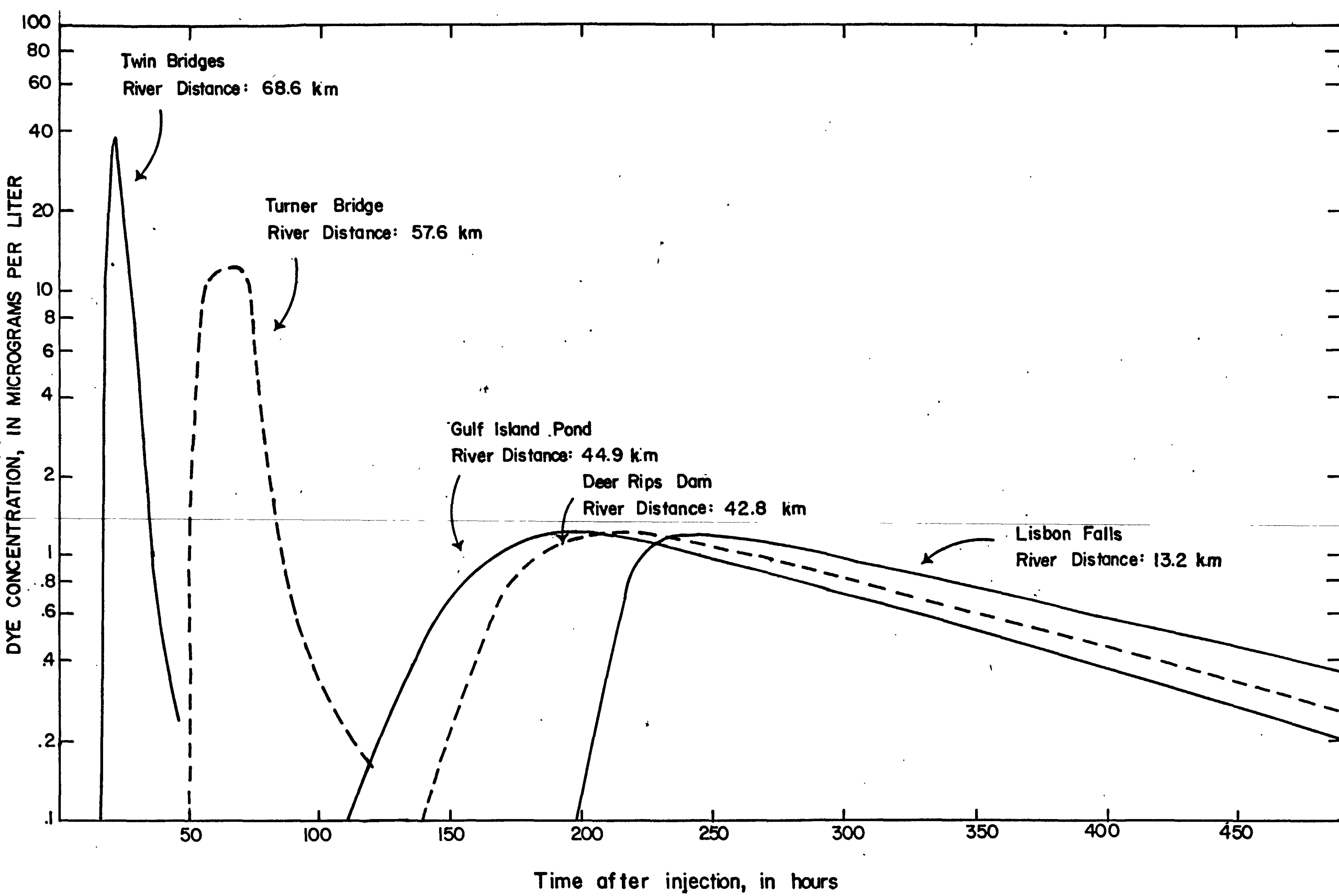


Figure 5.--Time concentration curves for August-September 1980 study

Dye Mass versus Time

The mass flow rate at a particular point on a river is defined as:

$$M_i = C_i Q_i \quad (2)$$

where: M_i = instantaneous rate of dye mass flow at a fixed point
C_i = observed dye concentration
Q_i = instantaneous discharge

The total dye mass observed (M_{obs}) in a passing dye cloud is estimated from the area of the MVT curve for a fixed point by:

$$M_{obs} = \int M_i dt = \int C_i Q_i dt \quad (3)$$

The integration is carried out between the time of the leading edge and time of the trailing edge as defined earlier. The centroid of an MVT curve is defined by:

$$\bar{T} = \frac{\int T_i M_i dt}{\int M_i dt} = \frac{\int T_i C_i Q_i dt}{\int C_i Q_i dt} \quad (4)$$

where: $\bar{T}$ = Time to the centroid of the dye cloud
T_i = the i-th hour after injection

For numerical calculation, equation 4 is given as:

$$\bar{T} = \frac{\Sigma C_i Q_i T_i \Delta t_i}{\Sigma C_i Q_i \Delta t_i} \quad (5)$$

For a steady state condition (constant discharge), equation 3 is replaced by:

$$M_{obs} = Q \int C_i dt \quad (6)$$

and equation 4 replaced by:

$$\bar{T} = \frac{\int T_i C_i dt}{\int C_i dt} \quad (7)$$

Thus, the mean traveltime for steady flow conditions can be obtained directly from a CVT curve. For numerical calculations equation 7 becomes:

$$\overline{T} = \frac{\Sigma T_i C_i \Delta t_i}{\Sigma C_i \Delta t_i} \qquad (8)$$

Comparison of equations 4 and 7 shows that for unsteady flow the centroid of the MVT curve is not always at the same time as the CVT curve.

Skewness (S) of a MVT curve (unsteady flow) is defined as:

$$S = \frac{\Sigma (T_i - \overline{T})^3 M_i \Delta t_i}{M_{obs}/V^{1.5}} \qquad (9)$$

where: V = Variance of a MVT curve

and:

$$V = \frac{\Sigma (T_i - \overline{T})^2 M_i \Delta t_i}{M_{obs}} \qquad (10)$$

For steady flow conditions equation 10 becomes:

$$S = \frac{\Sigma (T_i - \overline{T})^3 C_i \Delta t_i}{\Sigma C_i \Delta t_i / V^{1.5}} \qquad (11)$$

where:

$$V = \frac{\Sigma (T_i - \overline{T})^2 C_i \Delta t_i}{\Sigma C_i \Delta t_i} \qquad (12)$$

Dye conservation is an important indicator of data reliability. Dye-cloud anomolies can be identified where dye-mass recovery figures are inconsistent with recoveries determined from other fixed points in that study run. Percentage recovery (PR) is calculated from the mass of dye measured in the dye cloud (M_{obs}) and the mass of dye injected (M_{inj}) by the equation:

$$PR = \frac{M_{obs} \cdot 100}{M_{inj}} \qquad (13)$$

M_{obs} is calculated from equation (3) or (6) depending on discharge conditions (nonsteady state or steady state). For numerical calculations, equation (14) may be rewritten for nonsteady-state discharge:

$$PR = 0.36 \frac{\Sigma C_i Q_i \Delta t_i}{M_{inj}} \quad (14)$$

where M_{inj}, C_i, Q_i, and Δt_i are in units kg, µg/L, m³/s, and hours respectively. The constant (0.36) adjusts the units to permit a nondimensional answer. For steady-state discharge:

$$PR = 0.36 \frac{Q \Sigma C_i \Delta t_i}{M_{inj}} \quad (15)$$

All CVT and MVT curves are shown in the Appendix; all curves are segment computer plots. Although not pictured as being smooth, the computer plot allows easier comparison of data. At the Twin Bridge (fig. D1, D6) and Turner Bridge (fig. D2, D7) sites where discharge is constant, the CVT and MVT curves are identical. At the Gulf Island Dam, Deer Rips Dam, and Lisbon Falls sites (fig. D3-D5 and D8-D10, respectively) where flow is highly regulated, differences between the CVT and MVT curves are apparent.

MVT and CVT curve characteristics are summarized in table 3. At Twin Bridges and Turner Bridge, where discharge was constant, centroid time, skewness, and percentage recovery as computed from the MVT and CVT curves are identival because the corresponding equations are mathematicaly equivalent. However, the sites at Gulf Island Dam, Deer Rips Dam, and Lisbon Falls are highly regulated, and, at all three sites, time to centroid was faster (as much as 9 percent) by the MVT calculation than by CVT. Likewise, the skewness of the MVT and the CVT curves differed; the MVT curve at Gulf Island Dam and Deer Rips Dam was more skewed than the CVT curve by as much as 24 percent. To compare percentage recovery from MVT and CVT curves, a constant value of Q must be used according to equation (15). Consequently, an average value of all Q_i's was used.

Comparison of percentage recoveries by the two methods showed little difference. Anomolies are apparent in percentage recoveries as well as skewness data at the Lisbon Falls site and are probably due to nonrepresentative sampling or dye mass unaccounted for as a result of the long, low concentration tails at that site.

Table 3.--Dye-cloud characteristics at fixed sites

Site Name	Data Source*	Time to Centroid (h)	Skewness	Percentage Recovery
		May study		
Twin Bridges	1	18.1	0.65	64
	2	18.1	.65	64
Turner Bridge	1	31.6	.44	67
	2	31.6	.44	67
Gulf Island Dam	1	139	.86	63
	2	128	1.14	64
Deer Rips Dam	1	156	.77	67
	2	144	.98	65
Lisbon Falls	1	192	.66	64
	2	189	.45	59
		August study		
Twin Bridges	1	23.1	0.49	61
	2	23.1	.49	61
Turner Bridge	1	65.9	.20	58
	2	65.9	.20	58
Gulf Is. Dam	1	275	.68	66
	2	270	.82	58
Deer Rips Dam	1	296	.63	56
	2	288	.81	59
Lisbon Falls	1	350	.67	67
	2	355	.65	62

* 1 Equations 8, 11, and 15 respectively.
2 Equations 5, 9, and 14 respectively.

Dye Concentration versus Distance in Gulf Island Pond

During the two study runs in 1980, two different flow patterns were observed. In the May run, the temperature of the dye-tagged river water (15.5°C) most closely matched the water in the upper levels of Gulf Island Pond. The temperature in the pond ranged from 11°C at the bottom to 16°C at the surface (fig. C1). As seen in figures A1-A7, the tagged water passed across the top layer of the impoundment. It generally did not mix with the water in the deep part of the reservoir until the influence of Gulf Island Dam-induced mixing and (or) weather patterns began to exert an influence on dispersion. A hydrograph of Gulf Island Dam outflow is presented in figure D3. A listing of climatic data from the Portland, Maine, weather station is given in Table 4.

An example of flow patterns that resulted when inflowing water at 23°C closely matched the water near the bottom of Gulf Island Pond was observed in August 1980. The temperature in the Pond ranged from 22.5°C to 24.0°C (figs. C2, C3). As seen from figures B1-B11, the dye-tagged water was reasonably evenly distributed vertically to a point about 8 km upstream of Gulf Island Dam (fig. B4), where the cloud separated from the main body of the reservoir and plunged to the bottom of the pond. The boundary between the two separate bodies of water is called the plunge line (Fisher and others, 1979). The major part of the cloud continued its movement along the bottom of the pond until influenced by Gulf Island Dam outflow.

Table 4.--May 1980 weather data, Portland, Maine
(Data from National Oceanic and Atmospheric Administration, 1980)

Date	Average air temperature (°C)	Resultant wind direction (degrees [1])	Resultant wind speed (km/h)	Possible sunshine (percent)
May 20	13.0	80	5.3	97
May 21	10.0	110	6.1	4
May 22	19.0	300	12.9	78
May 23	15.5	130	2.7	51
May 24	13.5	140	2.9	72
May 25	14.5	340	12.4	83
May 26	10.5	330	10.5	57
May 27	14.5	320	7.2	64
May 28	13.5	320	8.7	85
May 29	14.0	210	6.3	65
May 30	13.5	190	12.1	87
May 31	15.5	190	14.2	23

[1] Degrees azimuth relative to true north.

The plunge line, beginning at a point about 8 km upstream of Gulf Island Dam, persisted for several days after the peak concentration had passed into lower levels of Gulf Island Pond. The hydrograph of Gulf Island Dam outflow is presented in figure D4. Table 5 lists the weather data for the same period of time.

Inspection of the plots in figures A1-7 and B1-11 indicates that the tagged water in Gulf Island Pond stratified into layers until broken up by Gulf Island Dam outflow. Stratification, or separation of water into layers, is primarily due to density differences which are a function of temperature and (or) chemistry. A review of water chemistry data collected during this study (conductivity, pH, dissolved oxygen, and several anions) indicates no significant differences in water chemistry. Therefore, the separation observed during the May and August trials seems to be primarily due to density differences created by slight temperature differentials between incoming tagged water and reservoir water.

Table 5.--August-September 1980 weather data, Portland, Maine (Data from National Oceanic and Atmospheric Administrarion, 1980)

Date	Average air temperature (°C)	Resultant wind direction (degrees [1])	Resultant wind speed (km/h)	Possible sunshine (percent)
Aug. 12	18.0	80	5.6	0
Aug. 13	21.0	280	6.4	72
Aug. 14	20.0	180	6.8	24
Aug. 15	24.5	280	11.1	66
Aug. 16	18.0	320	16.6	35
Aug. 17	20.5	330	12.4	93
Aug. 18	20.0	170	5.6	88
Aug. 19	17.0	130	9.0	0
Aug. 20	17.0	60	16.9	0
Aug. 21	18.5	60	14.0	46
Aug. 22	19.0	60	5.8	52
Aug. 23	20.5	150	0.8	100
Aug. 24	24.5	320	5.3	95
Aug. 25	22.0	110	2.3	90
Aug. 26	24.0	190	5.5	84
Aug. 27	26.5	290	6.3	29
Aug. 28	21.0	320	2.9	53
Aug. 29	20.0	180	6.1	83
Aug. 30	20.0	150	3.5	62
Aug. 31	25.5	220	12.6	36
Sept. 1	25.0	200	7.7	44
Sept. 2	28.0	200	11.1	61
Sept. 3	21.5	280	13.2	97
Sept. 4	18.0	160	4.2	99

[1] Degrees azimuth relative to true north.

The depth at which the inflowing water separates from the main body of the reservoir water to move either near the surface, in the subsurface, or along the bottom may be estimated from the following equation (Fischer and others, 1979):

$$H = \left[\frac{2Q^2}{F^2 \cdot \Delta\rho \cdot \tan^2 \alpha} \right]^{1/5} \qquad (16)$$

where:

H = depth of the reservoir where inflowing water separates from reservoir water (beginning of the plunge line).

Q = Discharge, in cubic meters per second

Q = 130 m^3/s (May).
Q = 56.6 m^3/s (August).

F = Froude number (as defined by Chow, 1959) based on inflow at Twin Bridges.

F = 0.166 (May).
F = 0.144 (August).

$\Delta\rho$ = Density difference between inflowing and surface reservoir water.

$\Delta\rho$ = 0.090 kg/m^3 for density difference of water at 16.0°C and 15.5°C in May

$\Delta\rho$ = 0.232 kg/m^3 for water at 24.0°C and 23.0°C in August.

α = 1/2 base angle of average channel cross-section for Gulf Island Pond based on data in table 1;

α = 88.5°.

Equation 16 is solved for both dye runs:

H = 6.2 m for the May study.
H = 3.9 m for the August study.

These values of H indicate that the plunge line for incoming water in May would begin in deeper water (farther into the reservoir) than in August. Comparison of figures A3 and B4 indicates that separation did occur at a greater depth in May than in August as predicted.

Vertical temperature profiles at points within the pond and temperature measurements of incoming water at Twin Bridges were made intermittently during May and August. The isotherms (lines of equal temperature) are shown in figures C1-C4. Generally, temperature differences in each profile are small, only 5°C and 2°C during May and August, respectively, when the plunge line first occurs. Inspection of the August isotherms (fig. C3) shows a remarkable similarity to the dye distribution on the same date (fig. B5).

The temperature of the dye cloud as it entered the pond on August 12 was 23.0°C, which is close to the bottom temperature near the deeper part of the pond. The similarities suggest that the stratified flow observed in August is due to differences in thermal density despite the difference of only 0.463 kg/m^3 at 24°C and 22°C (the maximum and minimum temperature observed in most vertical profiles during most of the August study run). Pockets of 14°C water (not shown in figures C2-4) were observed to be confined to the areas below 20 m near the dam. Water in the deepest parts of the pond did not mix with the main body of the reservoir, probably because of velocities too low to break the stratification bonds.

During the May study the dye cloud entered Gulf Island Pond at about 15.5°C, similar to the reservoir surface temperature of 16°C. The dye cloud remained at the surface near the 15°C isotherm and moved through the pond over the more dense underlying water. See fig. A3 and C1. Both sets of data from May and August indicate that very slight differences in water density, where combined with low water velocity, have a profound impact on the travel path of inflowing water through the impoundment.

Stratified Flow in Gulf Island Pond

As mentioned in the preceding section, the dye-tagged water in Gulf Island Pond seemed to be well mixed vertically until reaching the Upper Narrows site. See fig. B3. Under well-mixed conditions, average velocity between Upper Narrows and Lower Narrows would simply be the distance divided by the traveltime of the centroids of the CVT curve. However, as shown in figure B4, the vertical distribution of dye changes between Upper Narrows and Lower Narrows. At Lower Narrows, nonuniform mixing becomes evident and indicates the presence of a plunge line and stratification.

The cross sections at Upper Narrows and Lower Narrows were arbitrarily divided into three layers of near equal thickness and were defined as top, middle, and bottom layers. From dye-concentration data collected at the deepest vertical profile in each cross section, an average dye concentration in each layer was estimated. Subsequently, CVT curves for the three layers at both the sites were developed, assuming steady flow. The six CVT curves are shown in figure 6. Essential characteristics describing the individual curves (area under the CVT curve, skewness, and centroid) were calculated and are shown in table 6. According to Yotsukura and Fiering (1964), the similarities in the two characteristics of dye distribution at different locations in the vertical profiles is indicative of good mixing. In table 6, curve area and time to centroid at Upper Narrows are uniform with the middle layer showing the arrival of the centroid at 131 hours, slightly ahead of the top and bottom layers, which indicates near-complete mixing in the vertical direction. However, the data at Lower Narrows indicate a significant change has occurred between that site and Upper Narrows, especially in time to centroid. The traveltime in the bottom layer was 146 hours whereas the times were 172 hours for the middle and 222 hours for the top. The average area under the CVT curve for the 3 layers at Upper Narrows (225 µg/L-h) is close to the average at Lower Narrows (238 µg/L-h). Agreement indicates equal masses of dye passing through both sites.

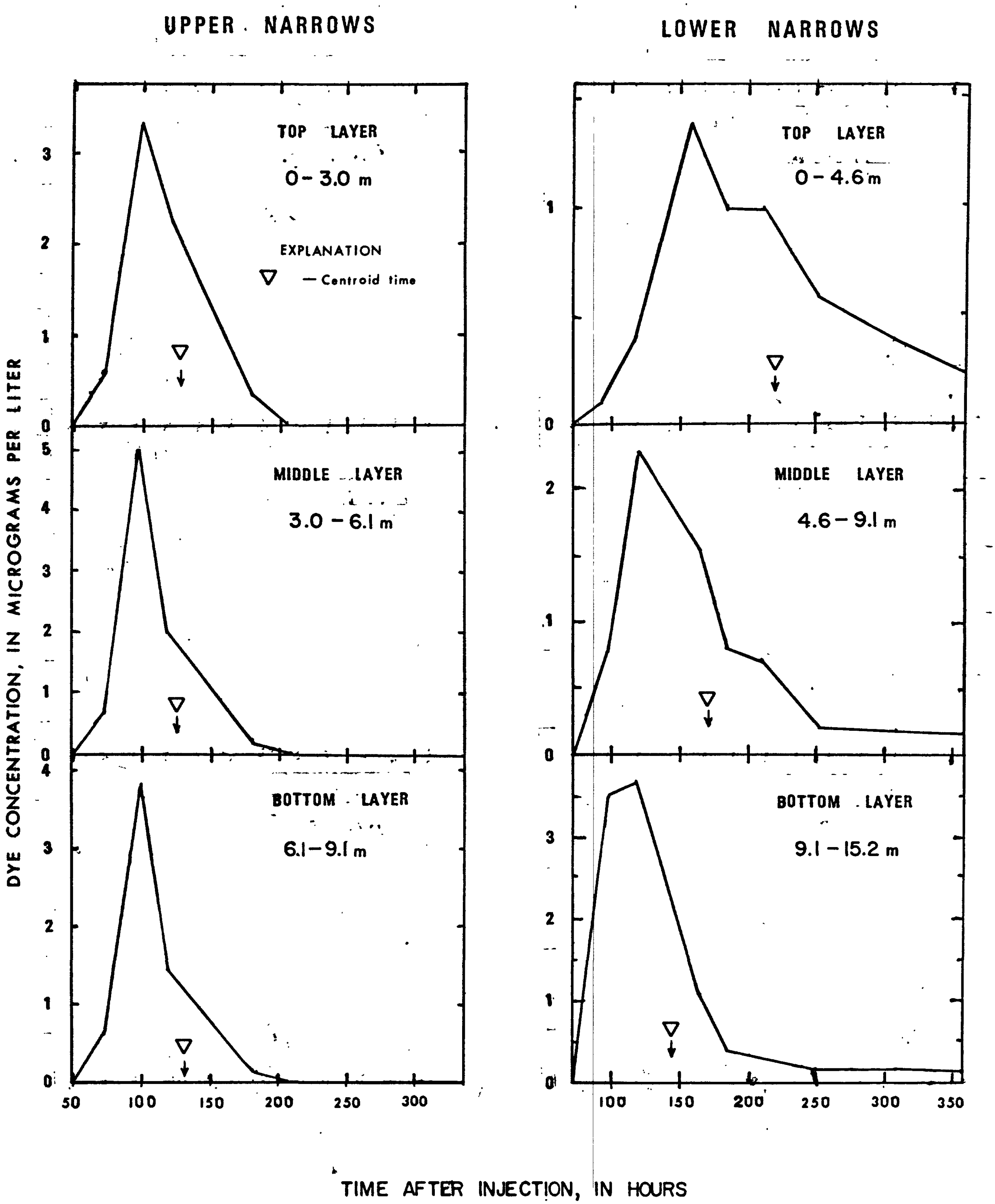


Figure 6.--Dye distribution with depth, August 1980

Comparison of the CVT curves for Upper Narrows and Lower Narrows indicates changes in flow patterns. Between the two sites the area for the CVT curve defined for the top layer decreases from 230 to 186 µg/L-h, while the area for the bottom layer increases from 198 to 302 µg/L-h (table 6). The areas of the middle layers are about the same. Although the divisions of cross sections were not made along streamtube lines, the change in areas beneath the CVT curves indicates some redistribution of flow between Upper Narrows and Lower Narrows. Average velocities of the centroid within the layers are readily calculated from the distance (3.5 km) between the two sites and the difference in times to centroid given in table 6. For the August dye study, average velocities from top to bottom were 0.012, 0.024, and 0.082 m/s. Thus, water near the bottom of the reservoir between Upper Narrows and Lower Narrows traveled seven times faster than water near the surface during the August study.

Table 6.--Characteristics of CVT curves for Upper and Lower Narrows, August 1980
(Locations are shown in fig. 8)

Section of water column	Area under CVT curve (µg/L-h)	Time to Centroid (h)
	UPPER NARROWS	
Top layer	230	139
Middle layer	248	131
Bottom layer	198	134
Average	225	
	LOWER NARROWS	
Top layer	186	222
Middle layer	227	172
Bottom layer	302	146
Average	238	

CONCLUSIONS

To accurately describe dye-cloud characteristics in unsteady flow, a concept of dye mass versus time was used to analyse data collected at fixed sites downstream of Gulf Island Dam. This approach allowed more accurate calculation of centroid traveltimes, skewness, and percentage recovery. Measurable differences were found between dye cloud characteristics determined from mass-versus-time curves and those determined from concentration-versus-time curves.

Separation and stratification of inflowing dye-tagged water significantly altered its traveltime. The observed alterations of flow patterns were due to temperature-related density differences between inflowing water and reservoir water. Separation was observed at differences of 0.5°C in May and 1.0°C in August 1980. In both the May and August studies, the depth at which the tagged water separated from the main body of reservoir water closely agrees with theory (Fisher and others, 1979).

In August 1980, centroid traveltimes estimated from concentration versus time curves were developed for three layers of a center channel profile at Upper Narrows and Lower Narrows. The average water velocity was estimated to be seven times faster near the bottom than near the surface.

REFERENCES

Chow, V. T., 1959, Open-channel hydraulics: New York, McGraw-Hill, 680 p.

Fisher, H. B., List, E. J., Koh, R. C. Y., Imberger, Jorg, and Brooks, N. H., 1979, Mixing in inland and coastal waters: New York, Academic Press, 483 p.

Fontaine, R. A., 1979, Drainage areas of surface water bodies of the Androscoggin River basin in southwestern Maine: U.S. Geological Survey open-file report, 42 p.

Hubbard, E. F., Kilpatrick, F. A., Martens, L. A., and Wilson, J. F., Jr., 1982, Measurement of time-of-travel and dispersion by dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations Book 3, Chapter A9, 44 p.

Kilpatrick, F. A., 1970, Dosage requirements for slug injections of rhodamine BA and WT dyes: U.S. Geological Survey Professional Paper 700-B, p. 250-253.

National Oceanic and Atmospheric Administration, 1980, Local Climatological Data, monthly summary, May 1980 at Portland, Maine, 2 p.

_____1980, Local Climatological Data, monthly summary, August 1980 at Portland, Maine 2 p.

New England-New York Inter-Agency Committee, 1954, Androscoggin River basin, Maine-New Hampshire: The resources of the New England-New York region, Part two, Chapter VII, p.398.

Wilson, J. F., 1968, Fluorometric procedures for dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigation Book 3, Chapter A12, 31 p.

Yotsukura, Nobuhiro, and Fiering, M. B., 1964, Numerical solution to a dispersion equation: American Society of Civil Engineers, Journal of the Hydraulics Division Proceeding Paper 4046, 19 p.

APPENDIX

CONTENTS

APPENDIX

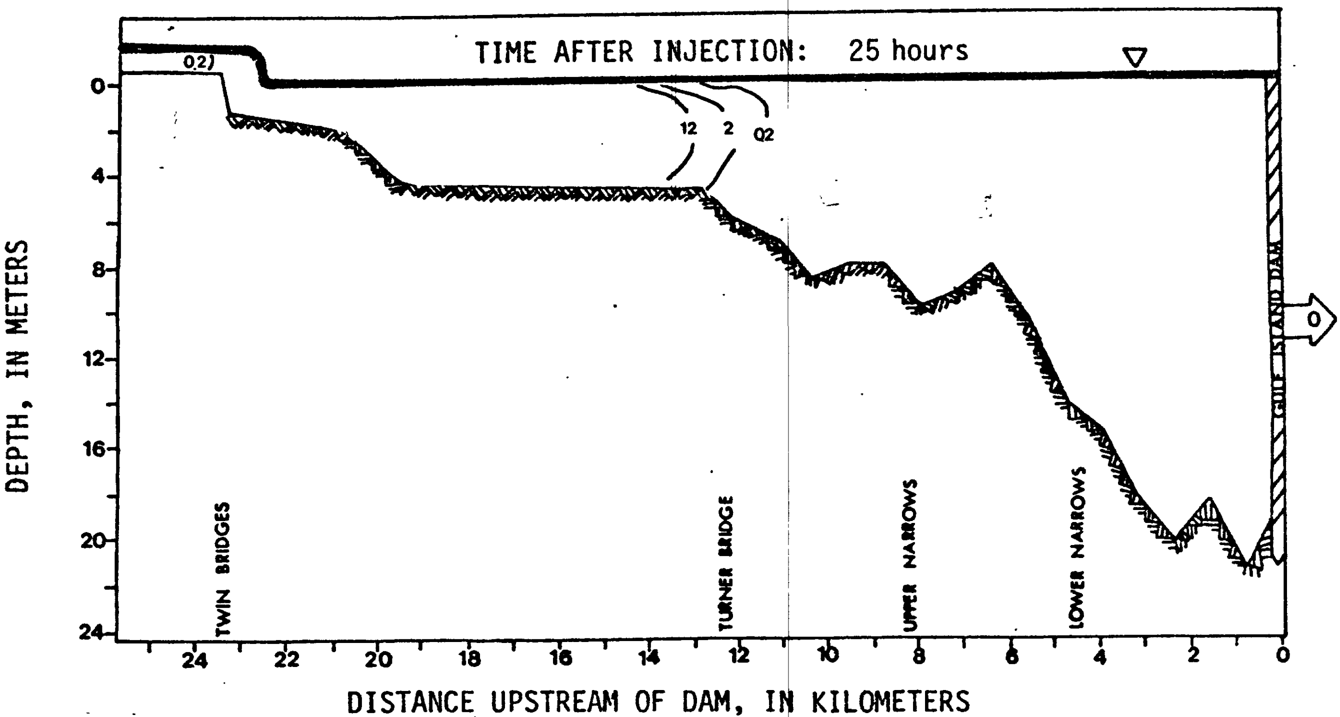
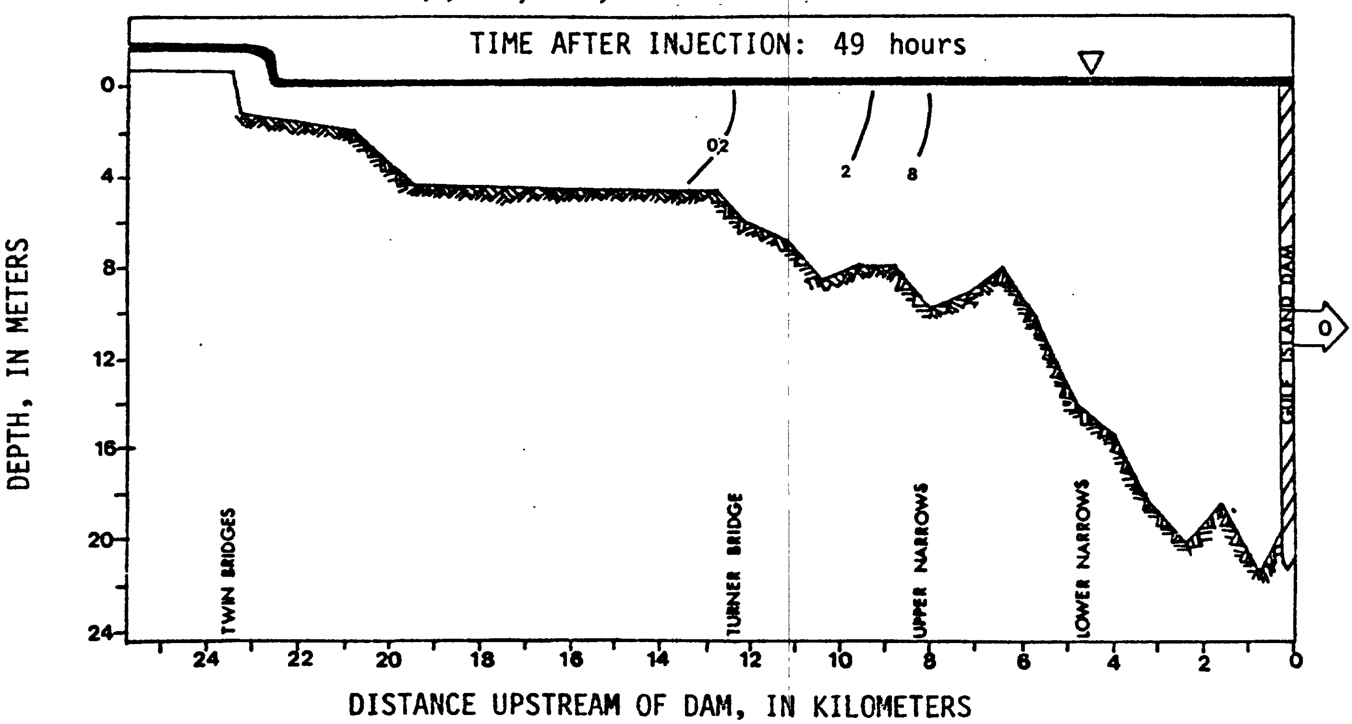


Figure A1.--Plots showing dye distribution in Gulf Island Pond, Tuesday, May 20, 1980.



EXPLANATION

Water Surface

Line of equal dye concentration in micrograms per liter

Streambed

Outflow dye concentration in micrograms per liter

Figure A2.--Plots showing dye distribution in Gulf Island Pond, Wednesday, May 21, 1980.

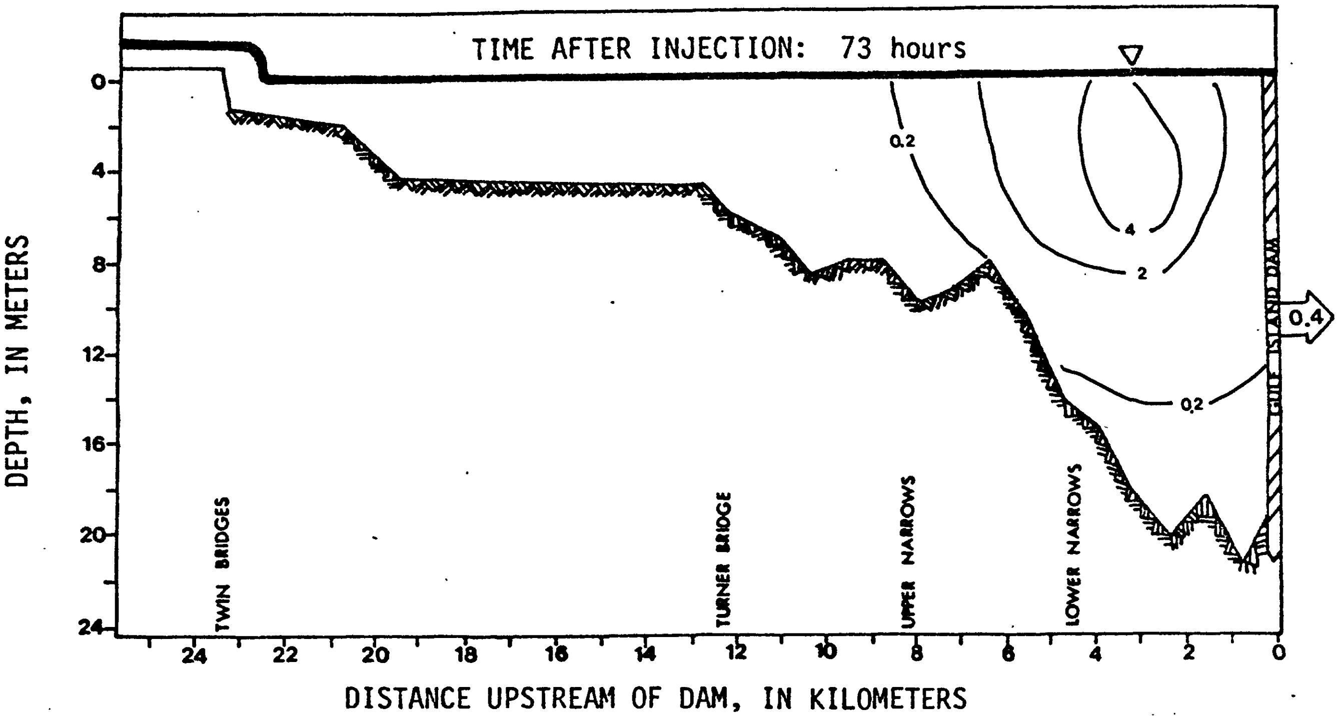
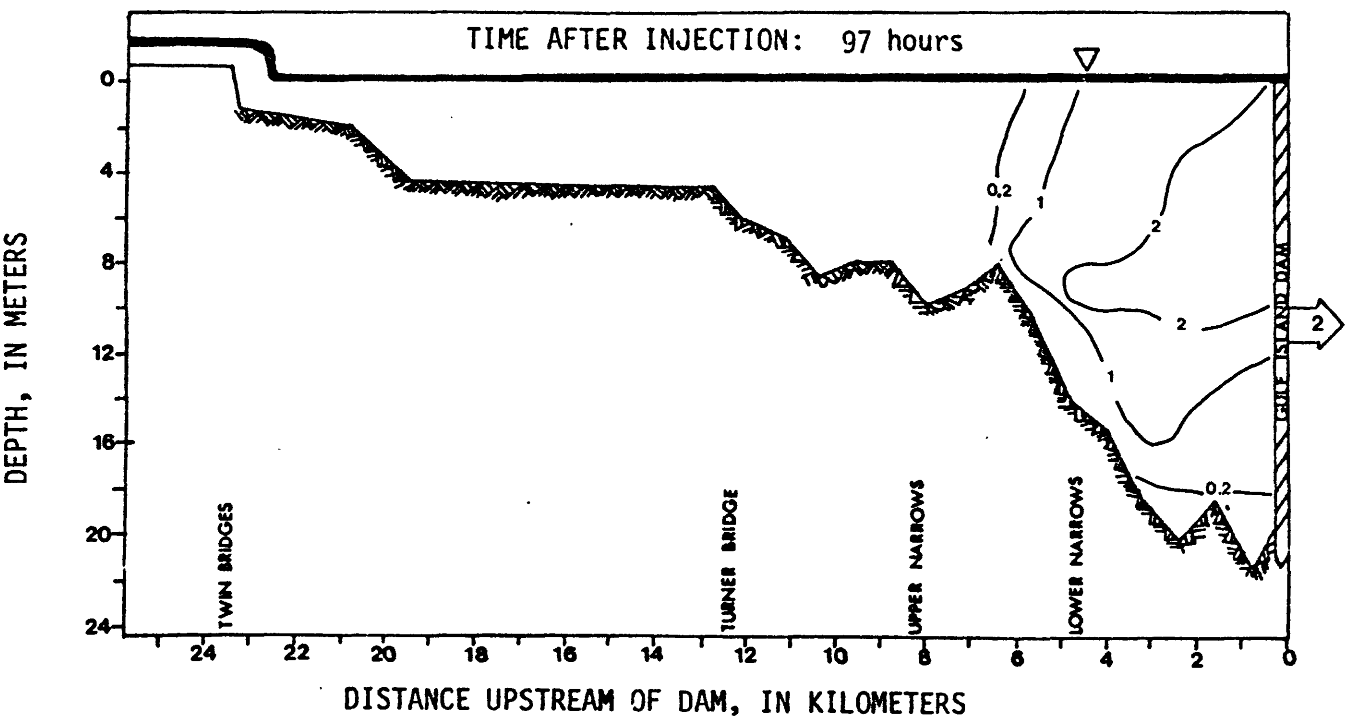


Figure A3.--Plots showing dye distribution in Gulf Island Pond, Thursday, May 22, 1980.



EXPLANATION

- Water Surface
- Line of equal dye concentration in micrograms per liter
- Streambed
- Outflow dye concentration in micrograms per liter

Figure A4.--Plots showing dye distribution in Gulf Island Pond, Friday, May 23, 1980.

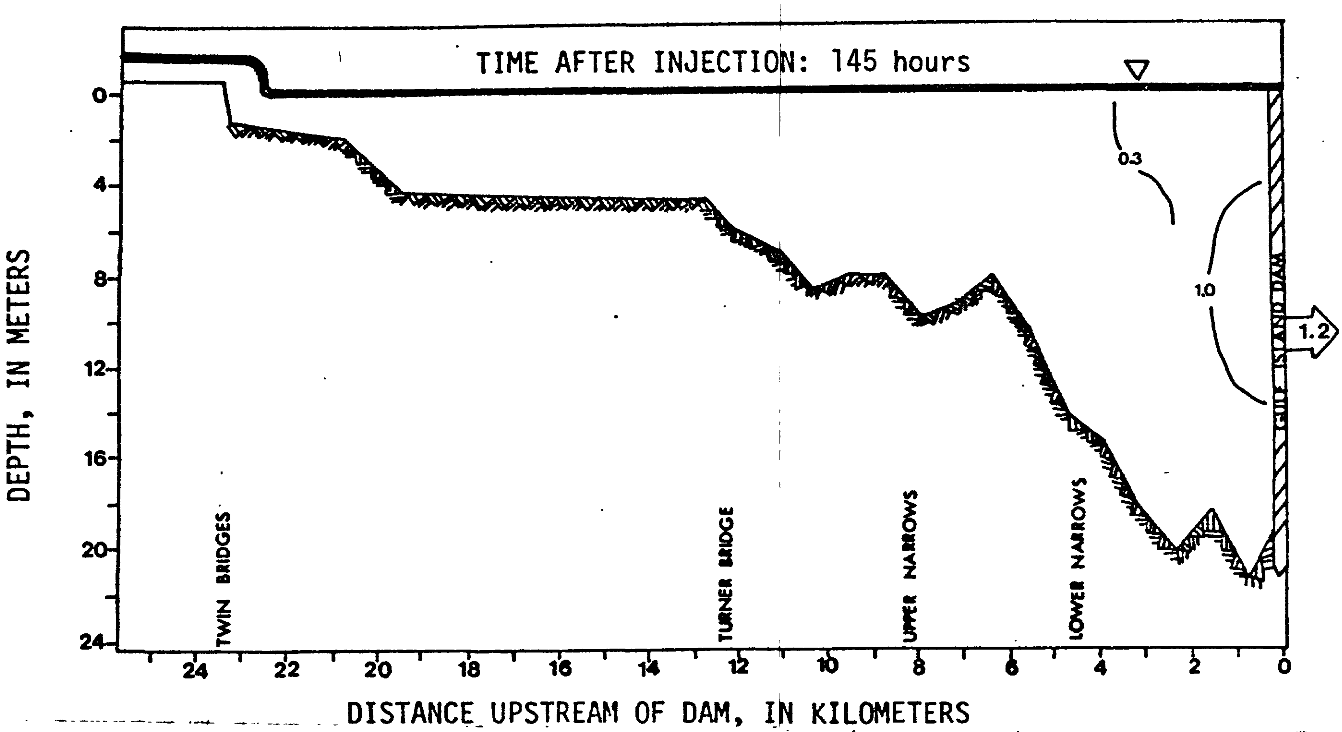
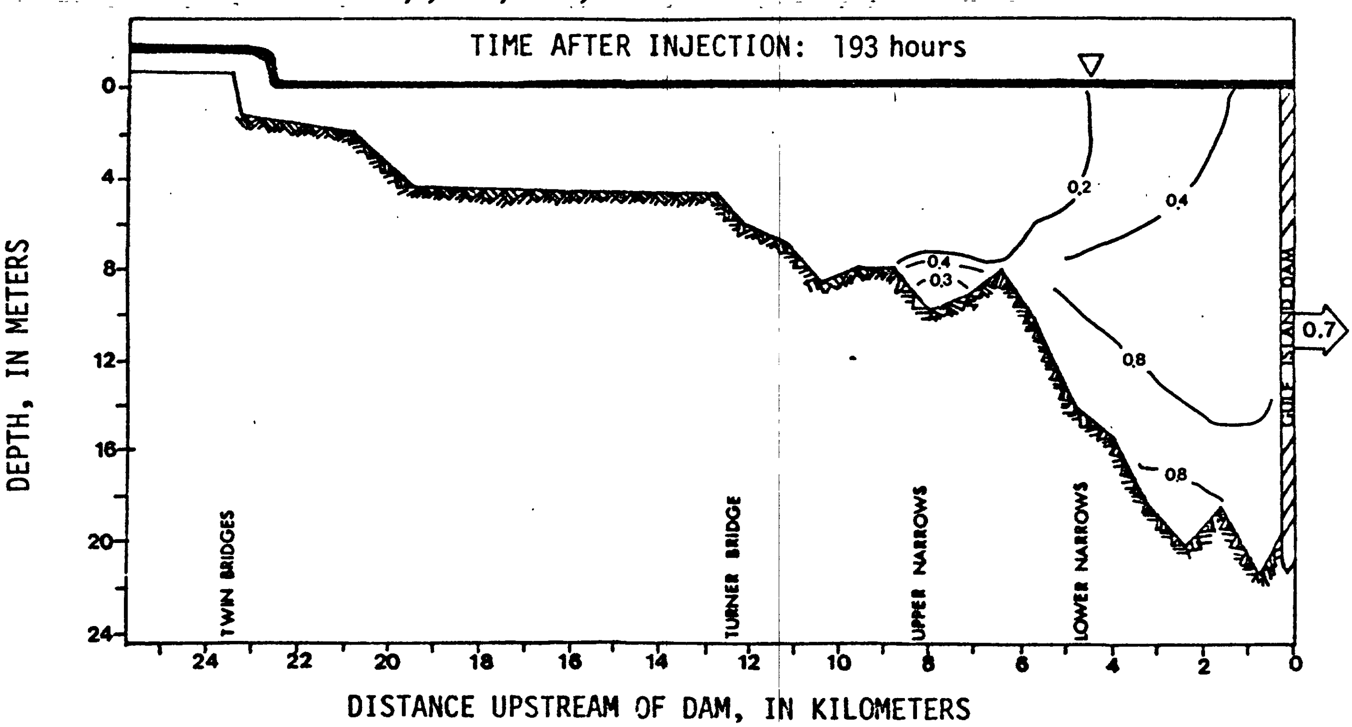


Figure A5.--Plots showing dye distribution in Gulf Island Pond, Sunday, May 25, 1980.



EXPLANATION

Water Surface

0.2 Line of equal dye concentration in micrograms per liter

Streambed

0.7 Outflow dye concentration in micrograms per liter

Figure A6.--Plots showing dye distribution in Gulf Island Pond, Tuesday, May 27, 1980.

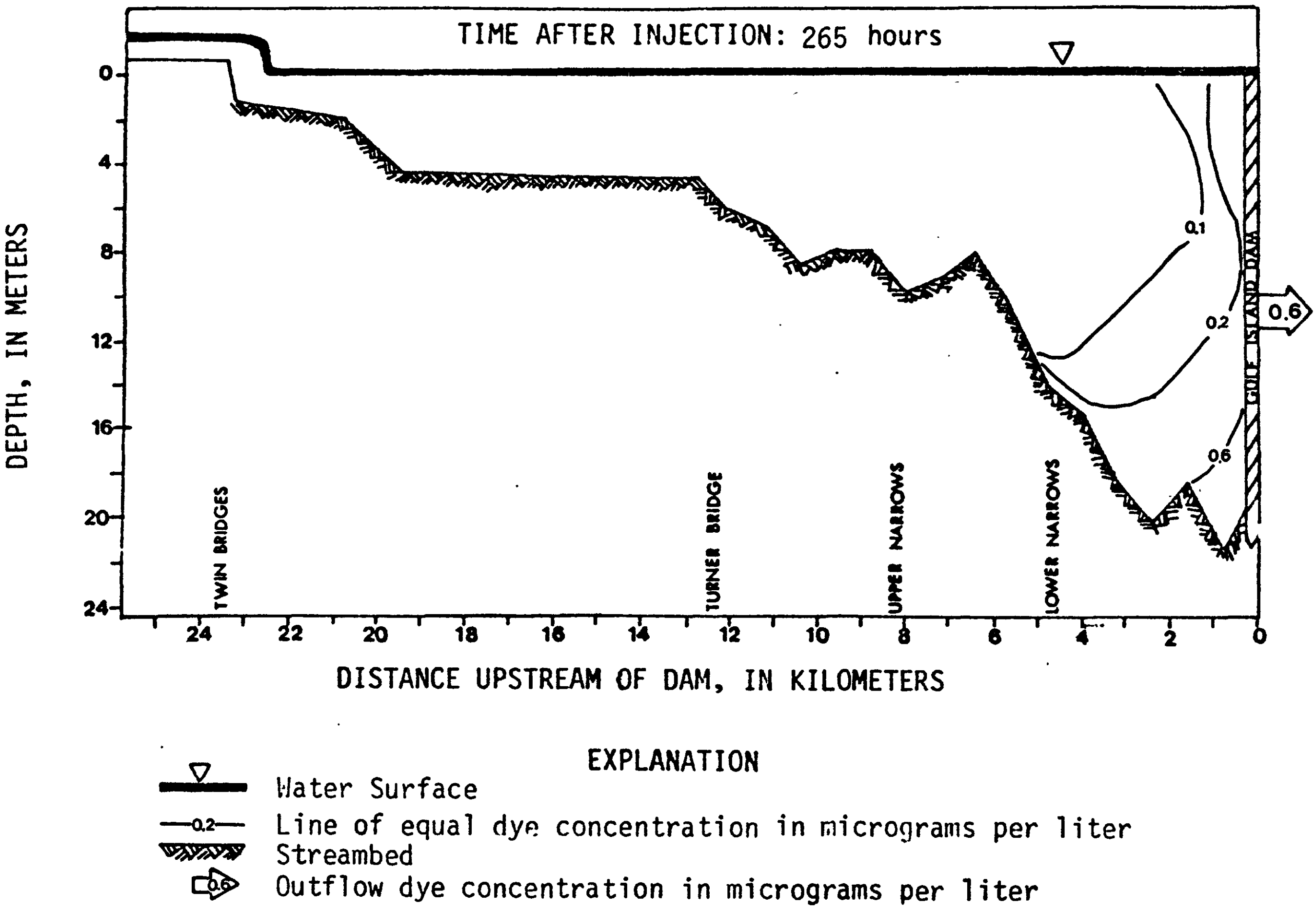


Figure A7.--Plots showing dye distribution in Gulf Island Pond, Friday, May 30, 1980.

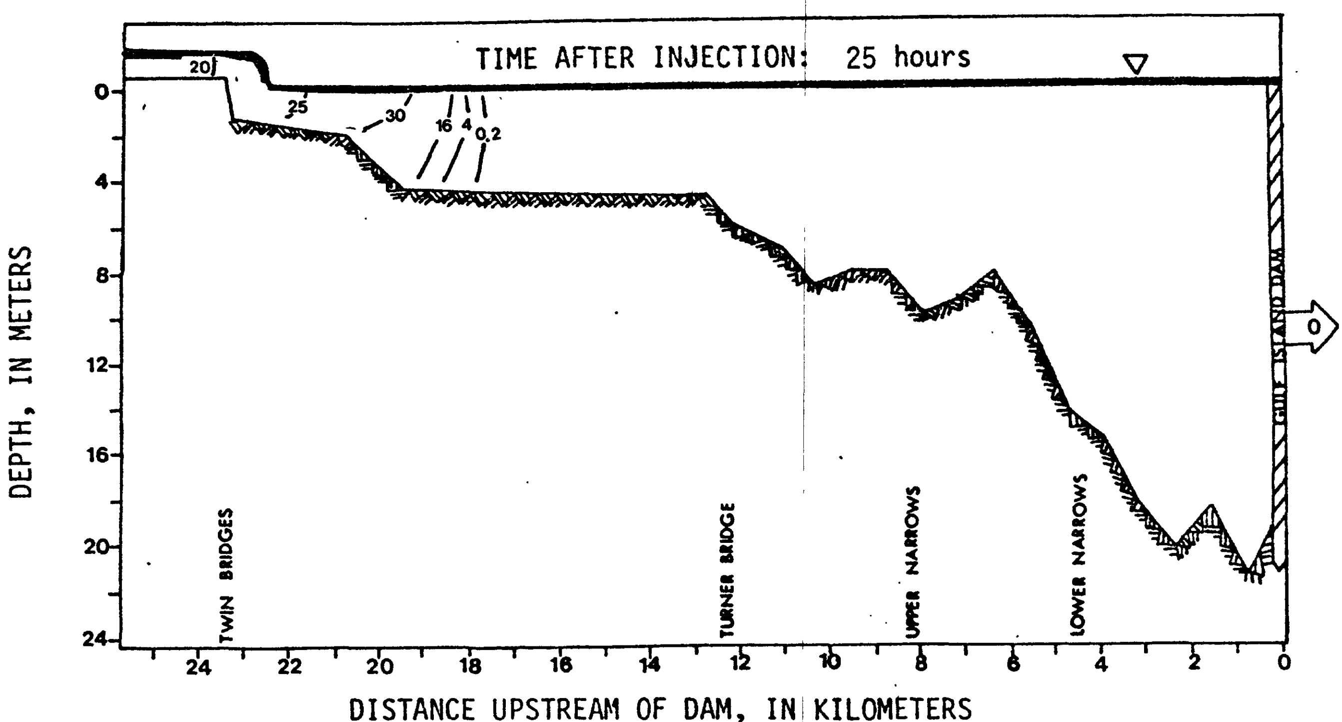
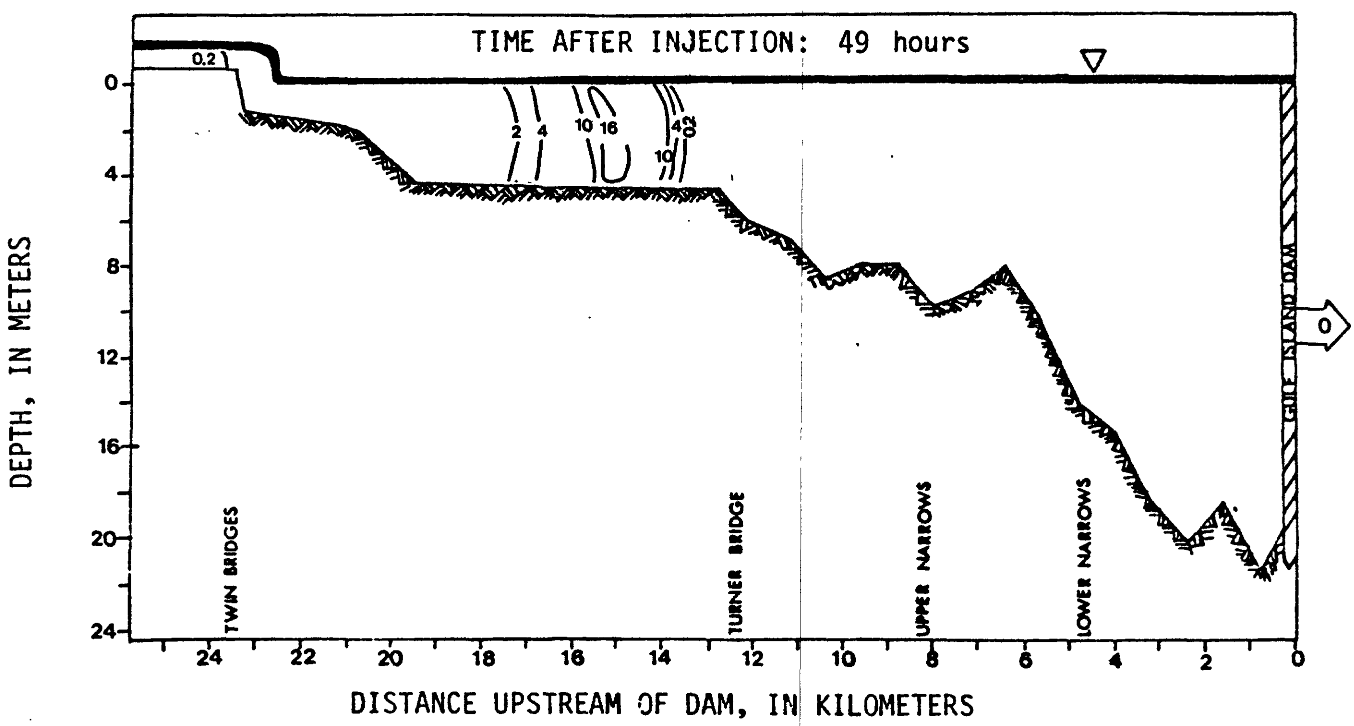


Figure B1.--Plots showing dye distribution in Gulf Island Pond, Tuesday, August 12, 1980.



EXPLANATION

Water Surface

Line of equal dye concentration in micrograms per liter

Streambed

Outflow dye concentration in micrograms per liter

Figure B2.--Plots showing dye distribution in Gulf Island Pond, Wednesday, August 13, 1980.

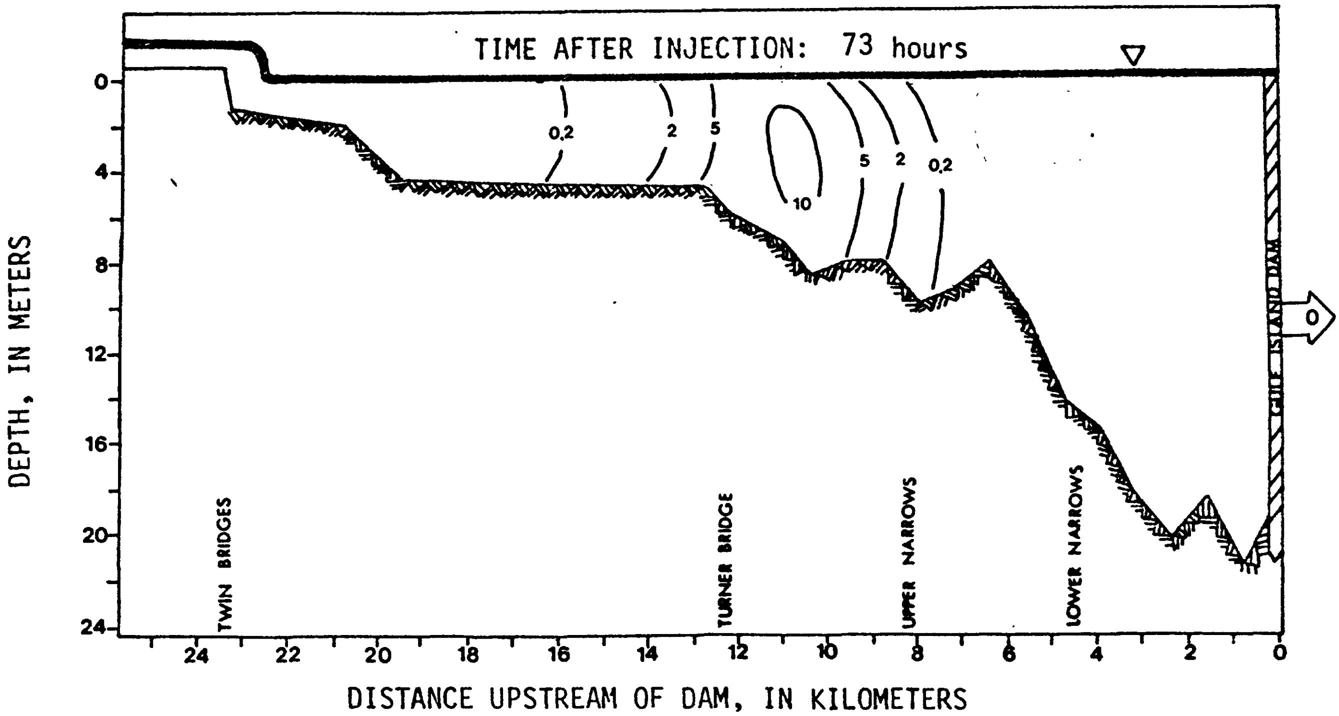


Figure B3.--Plots showing dye distribution in Gulf Island Pond, Thursday, August 14, 1980.

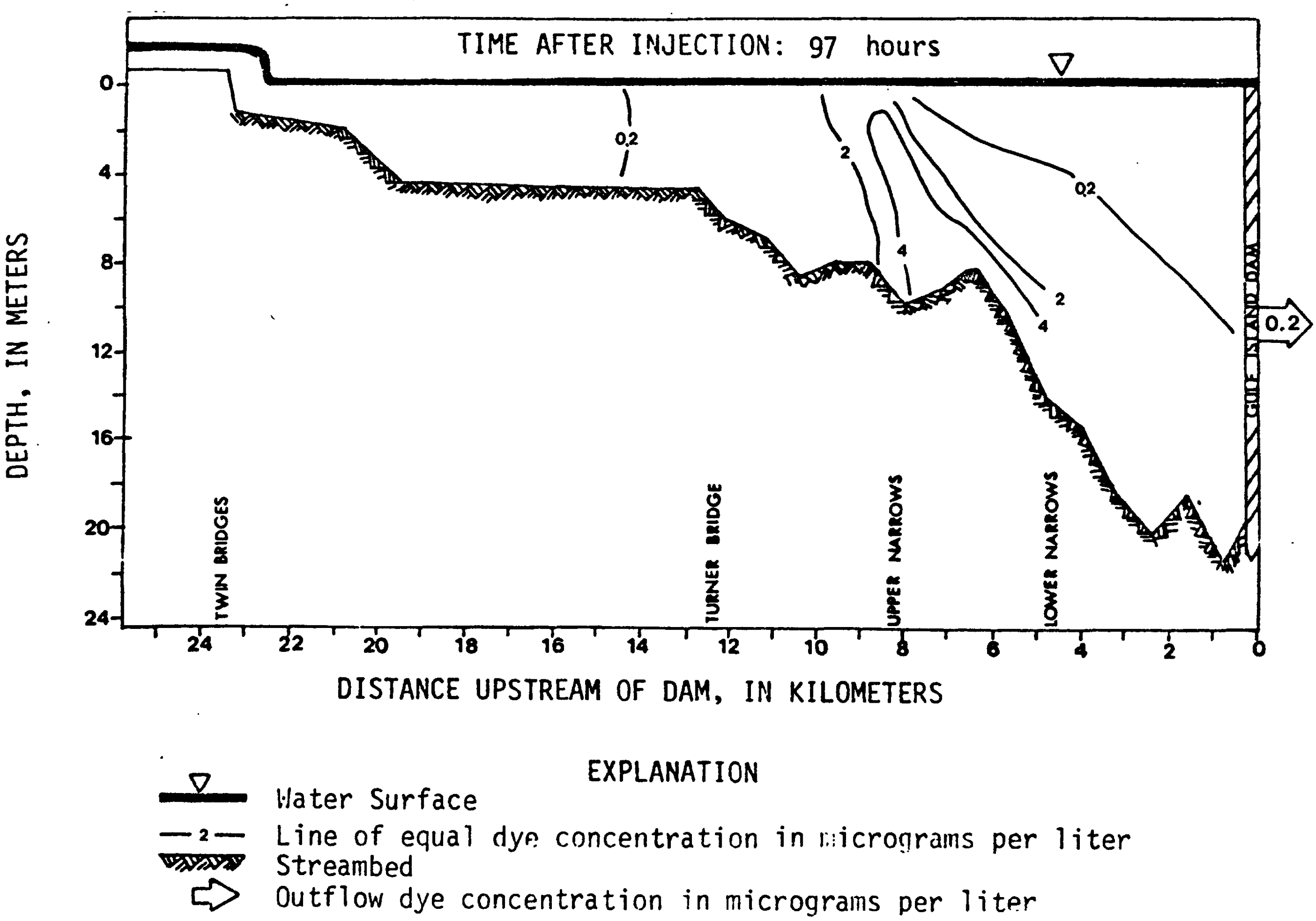


Figure B4.--Plots showing dye distribution in Gulf Island Pond, Friday, August 15, 1980.

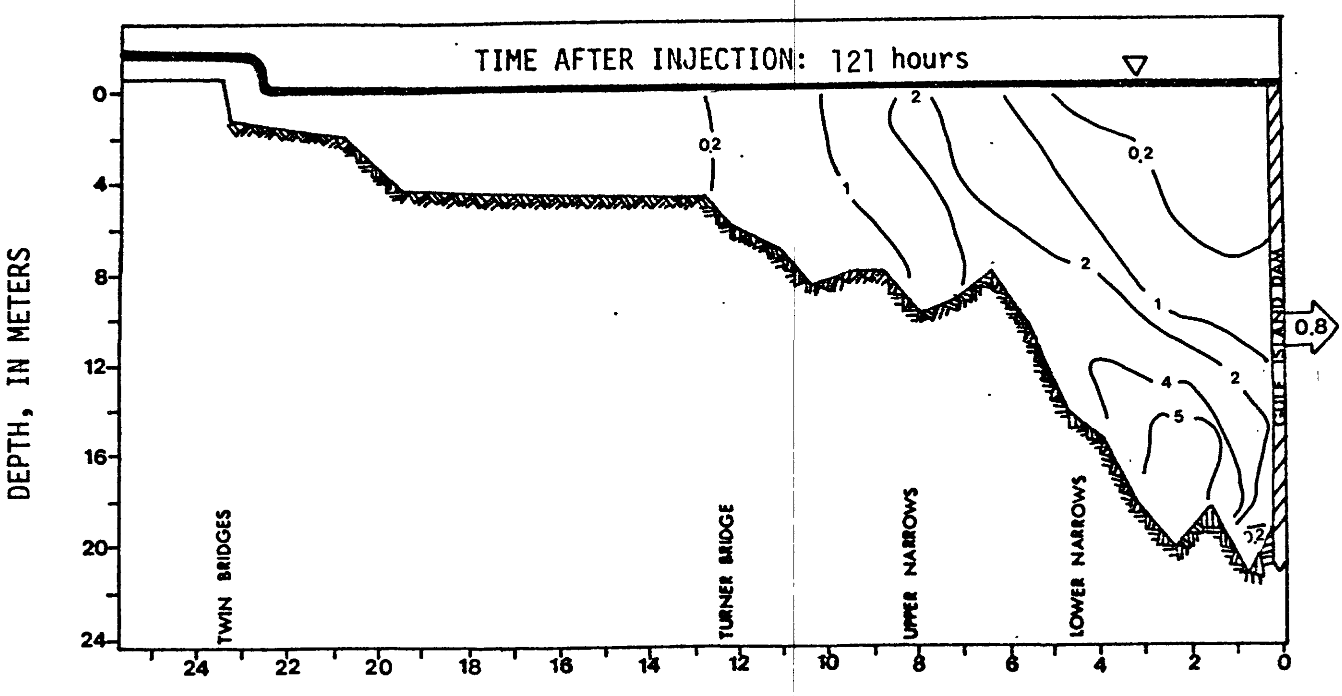
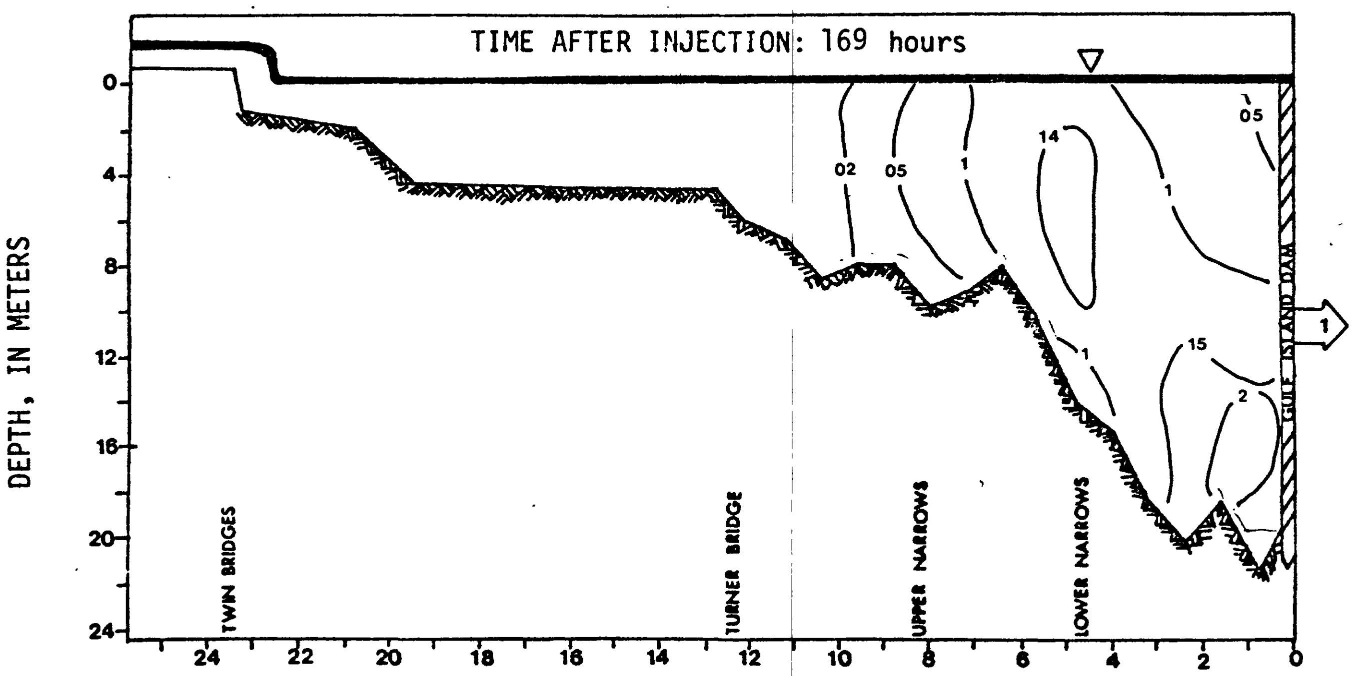


Figure B5.--Plots showing dye distribution in Gulf Island Pond, Saturday, May 16, 1980.



EXPLANATION

Water Surface

Line of equal dye concentration in micrograms per liter

Streambed

Outflow dye concentration in micrograms per liter

Figure B6.--Plots showing dye distribution in Gulf Island Pond, Monday, August 18, 1980.

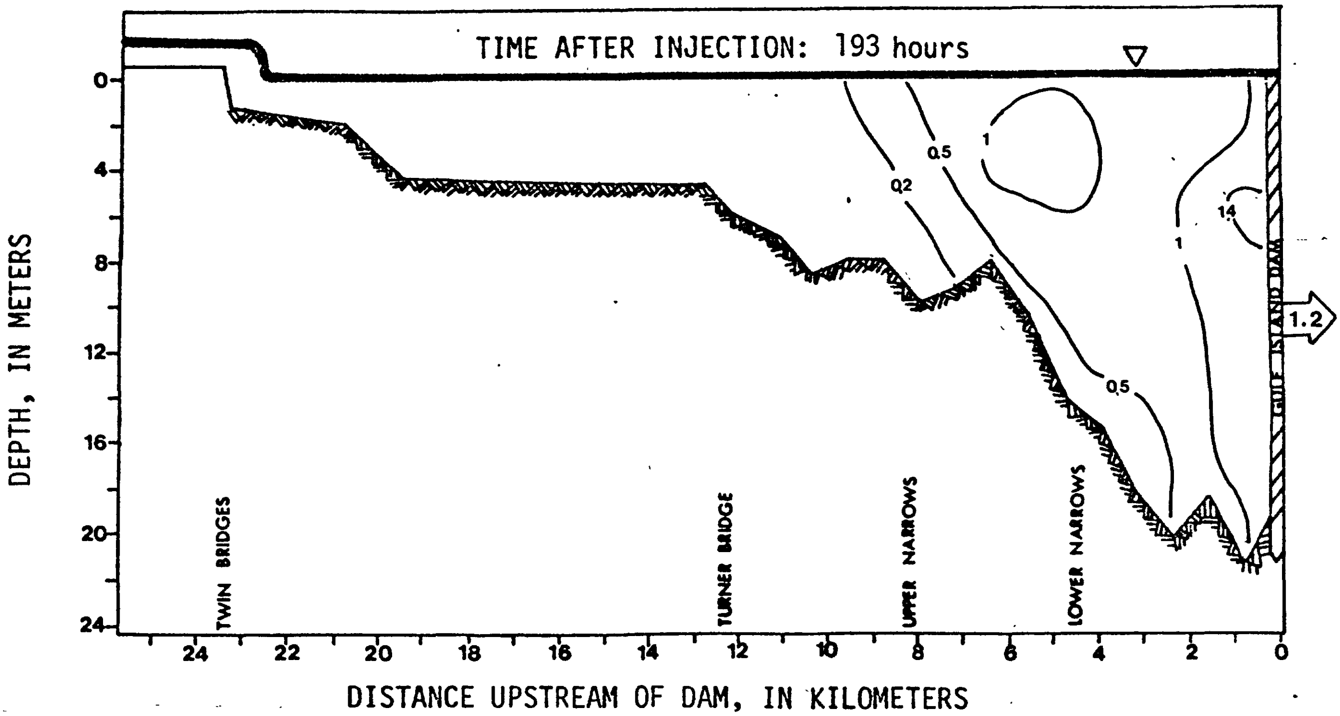
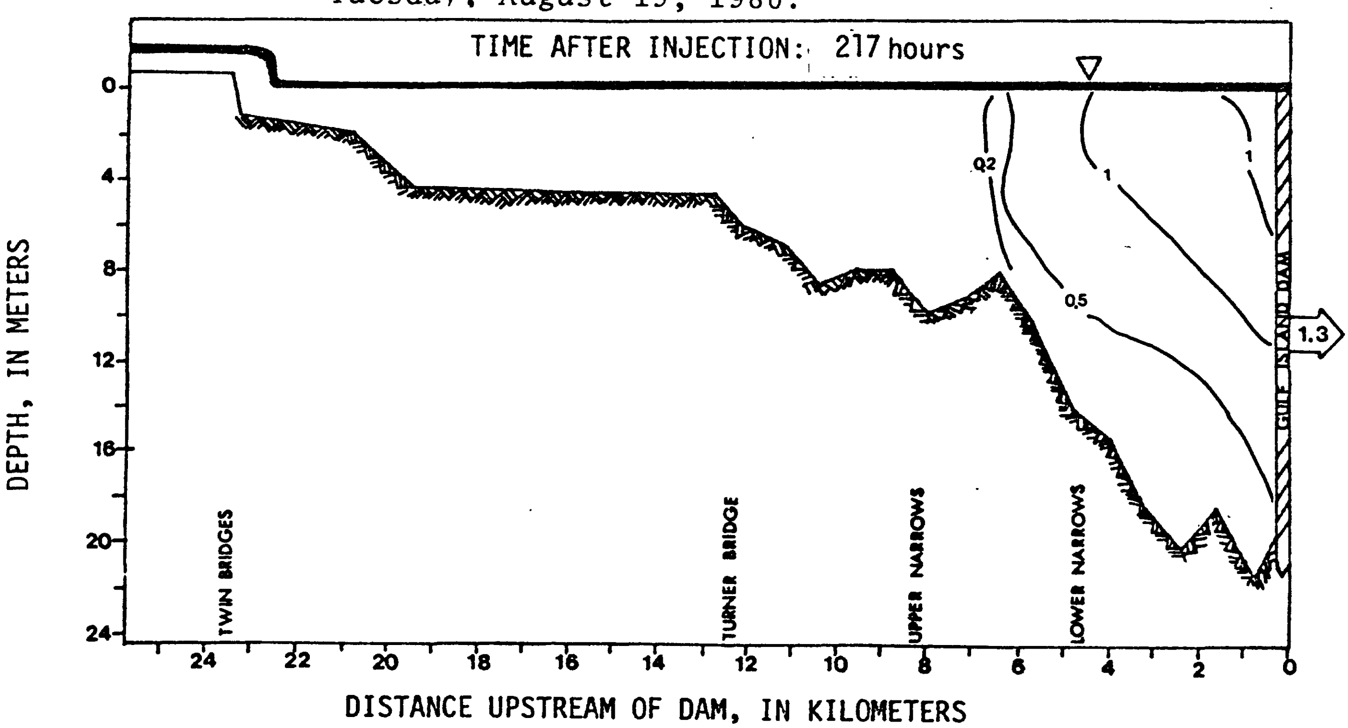
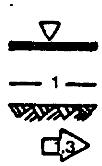


Figure B7.--Plots showing dye distribution in Gulf Island Pond, Tuesday, August 19, 1980.



EXPLANATION



Water Surface

Line of equal dye concentration in micrograms per liter

Streambed

Outflow dye concentration in micrograms per liter

Figure B8.--Plots showing dye distribution in Gulf Island Pond, Wednesday, August 20, 1980.

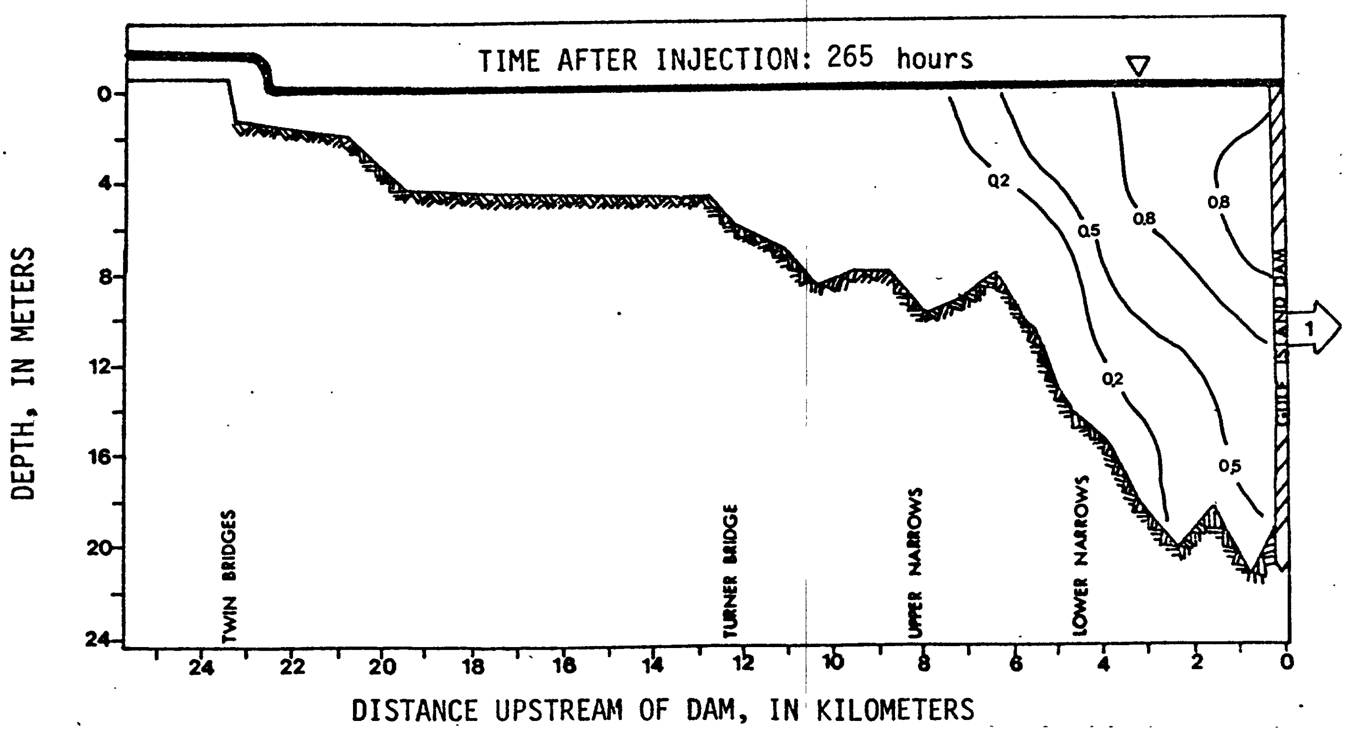
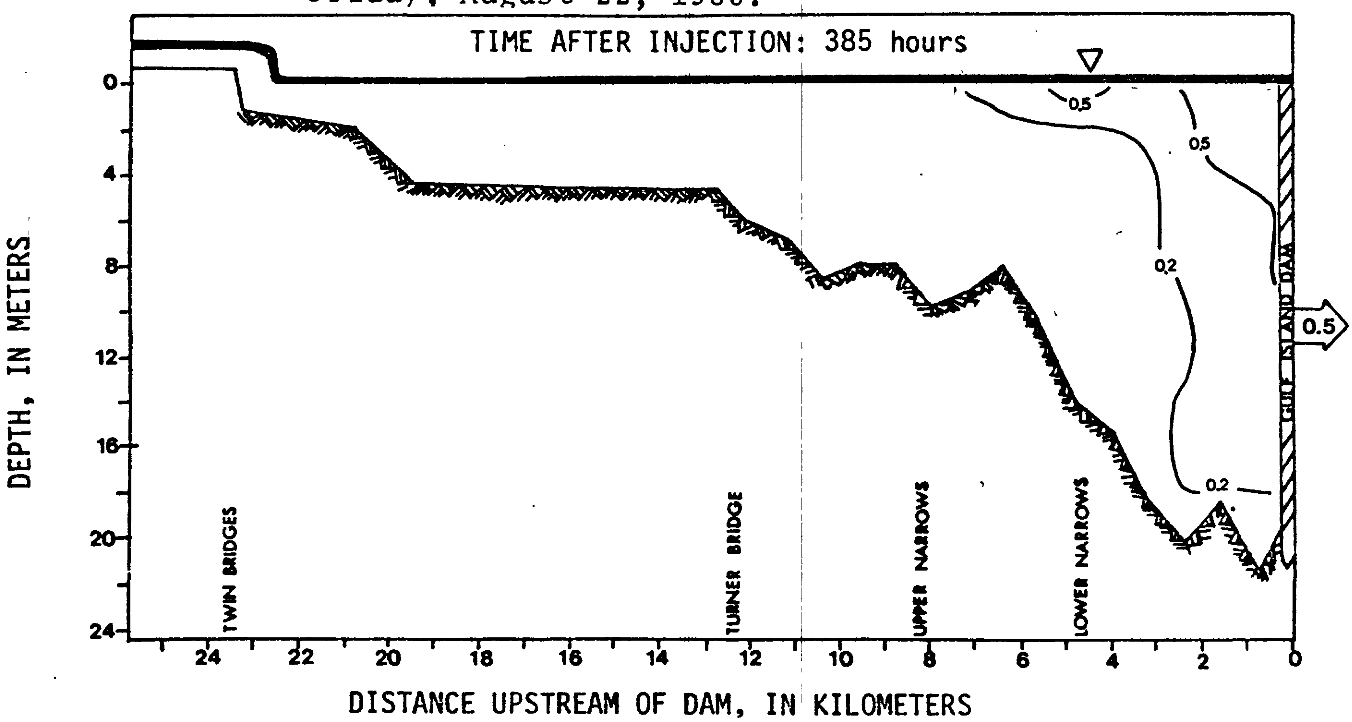


Figure B9.--Plots showing dye distribution in Gulf Island Pond, Friday, August 22, 1980.



EXPLANATION

Water Surface

Line of equal dye concentration in micrograms per liter

Streambed

Outflow dye concentration in micrograms per liter

Figure B10.--Plots showing dye distribution in Gulf Island Pond, Wednesday, August 27, 1980.

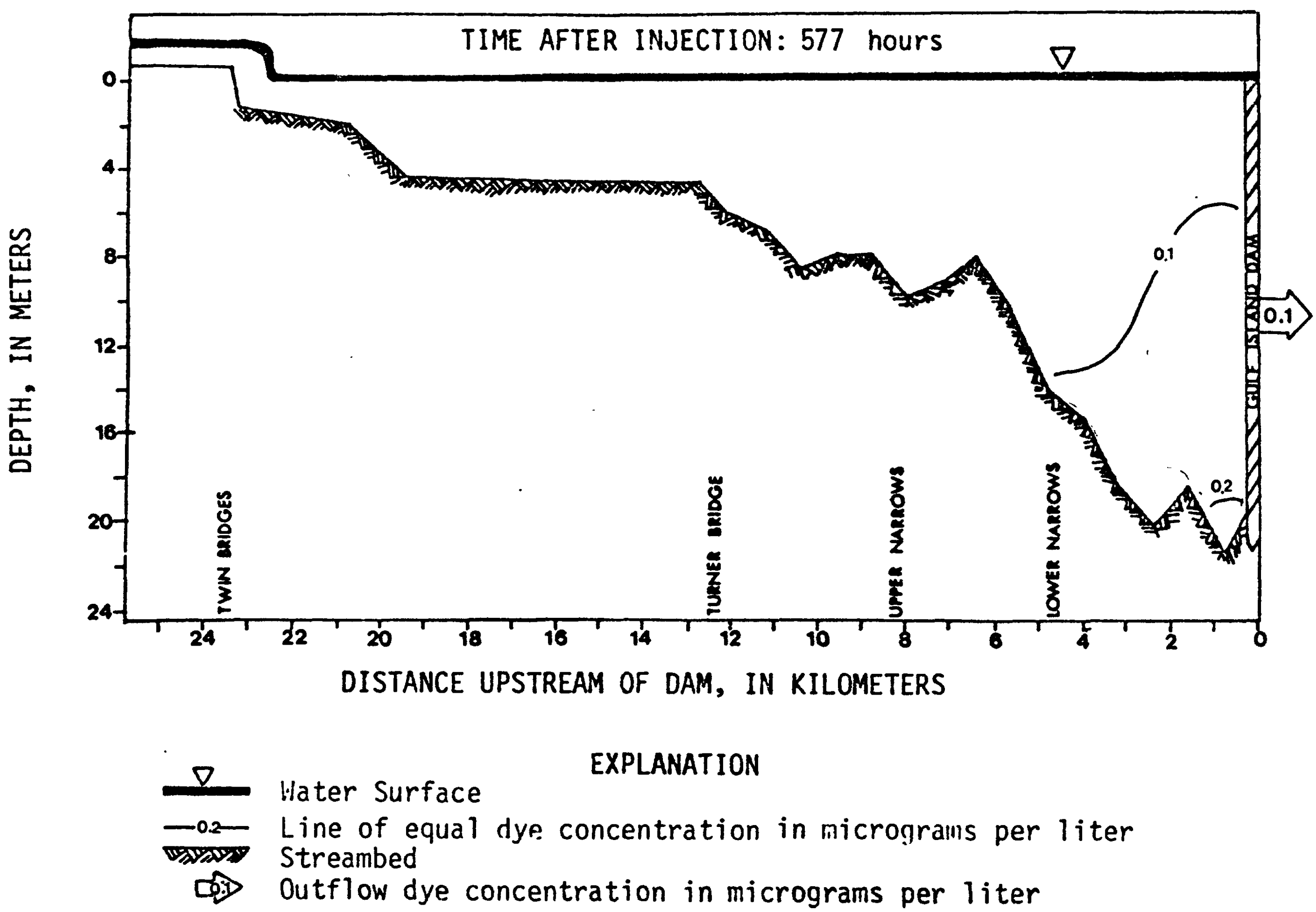


Figure B11.--Plots showing dye distribution in Gulf Island Pond, Thursday, September 4, 1980.

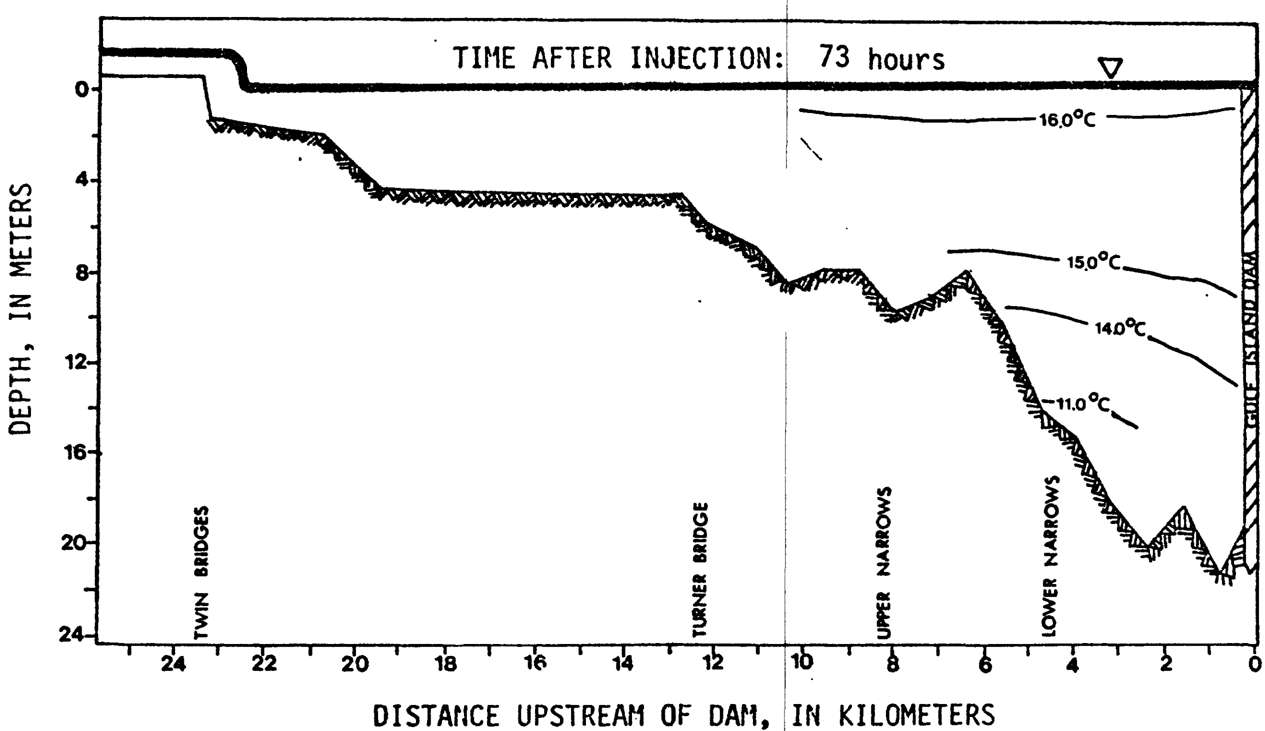


Figure C1.--Plots showing isotherms in Gulf Island Pond, Thursday, May 22, 1980.

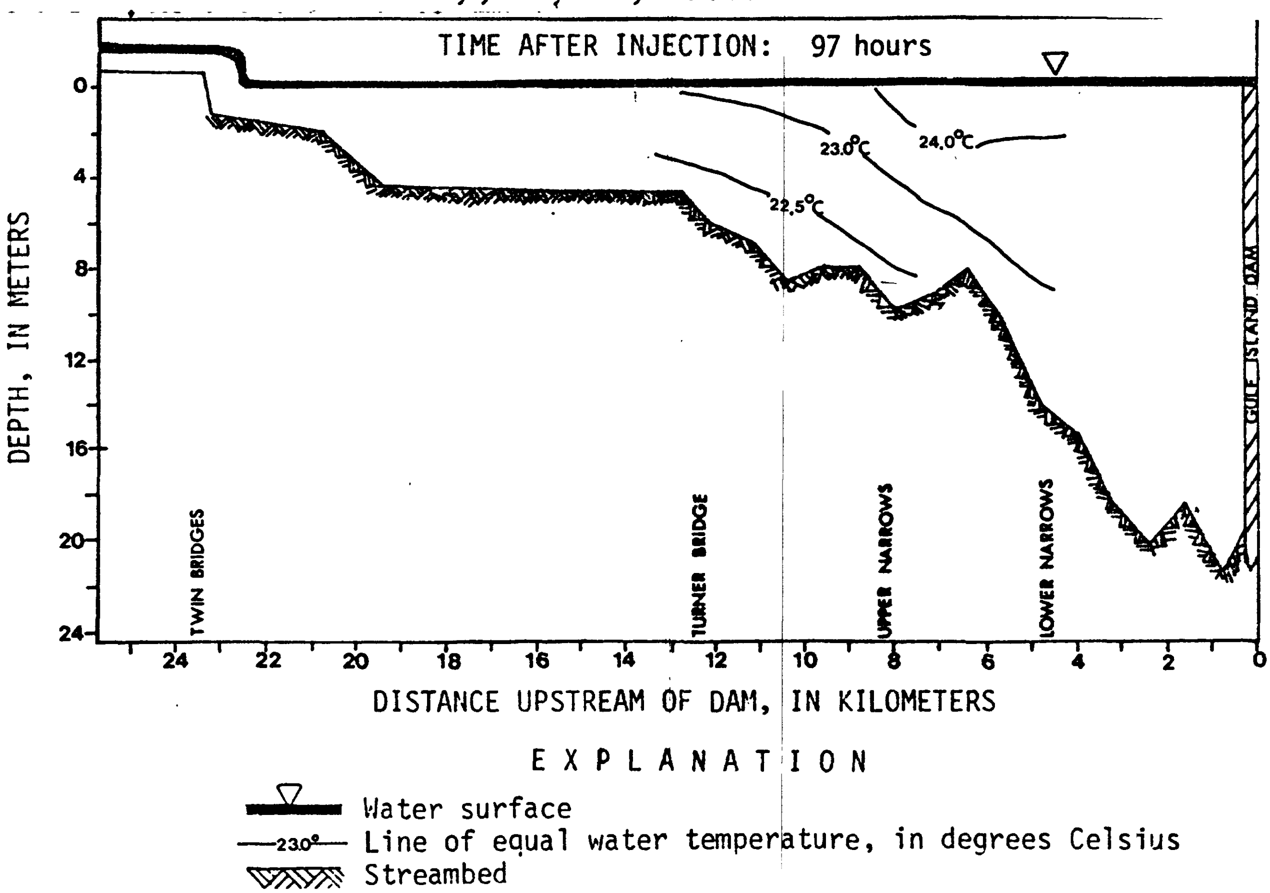


Figure C2.--Plots showing isotherms in Gulf Island Pond, Friday, August 15, 1980.

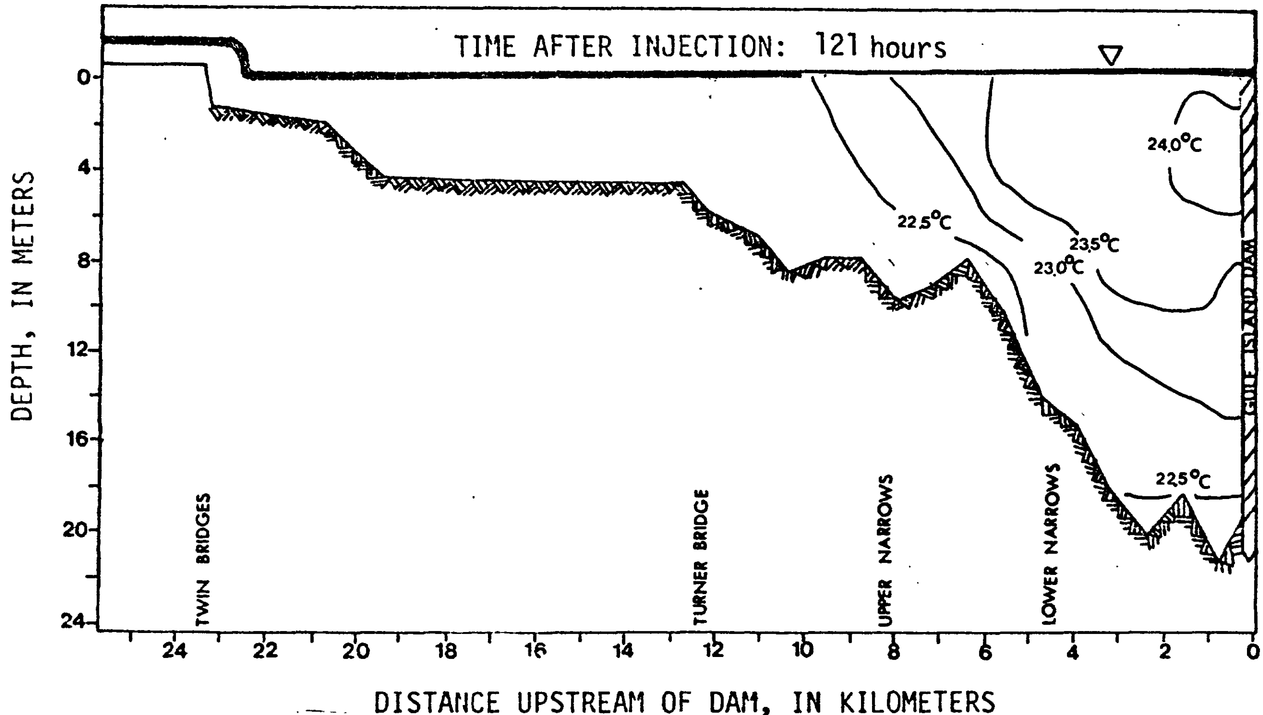


Figure C3.--Plots showing isotherms in Gulf Island Pond, Saturday, August 16, 1980.

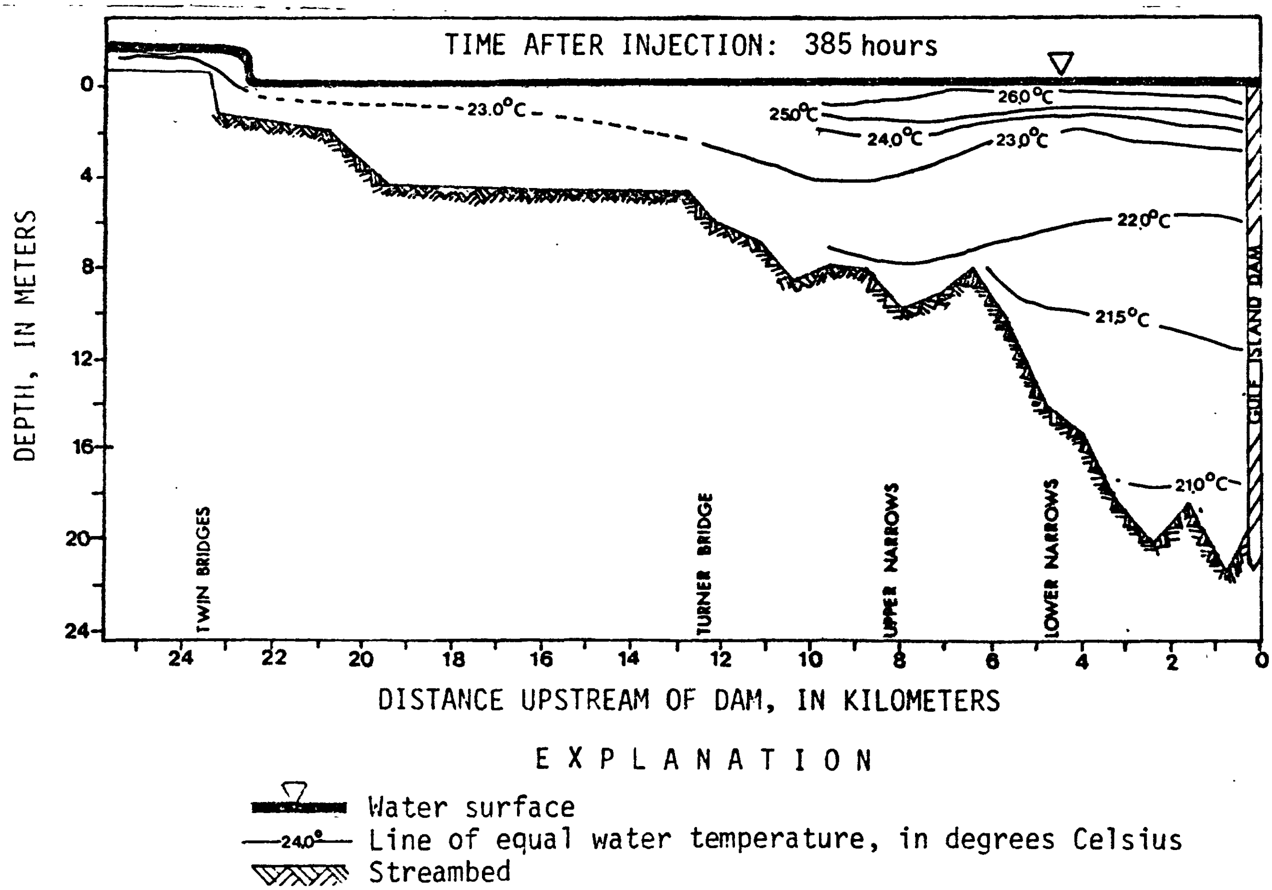


Figure C4.--Plots showing isotherms in Gulf Island Pond, Wednesday, August 27, 1980.

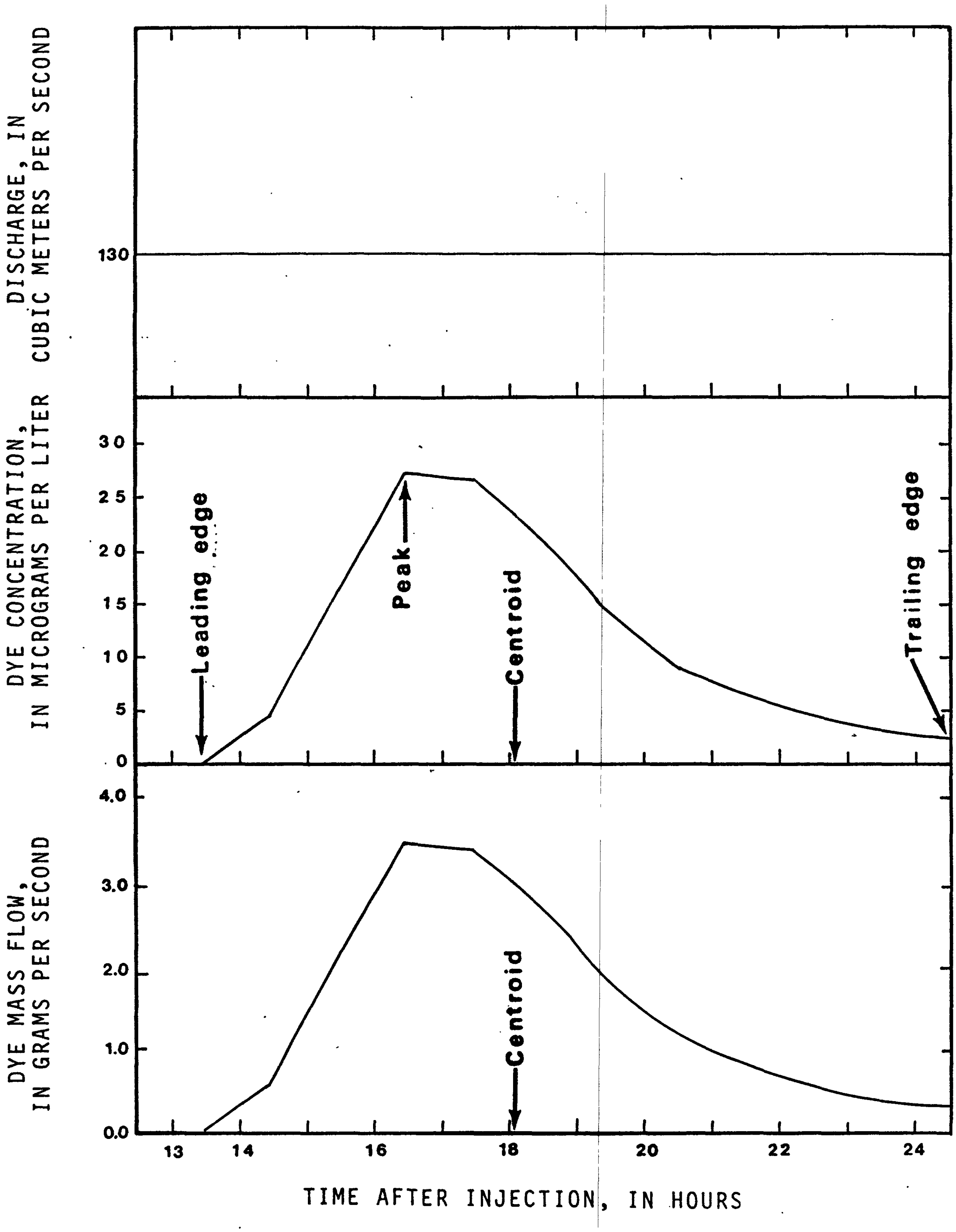


Figure D1.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Twin Bridges, May, 1980.

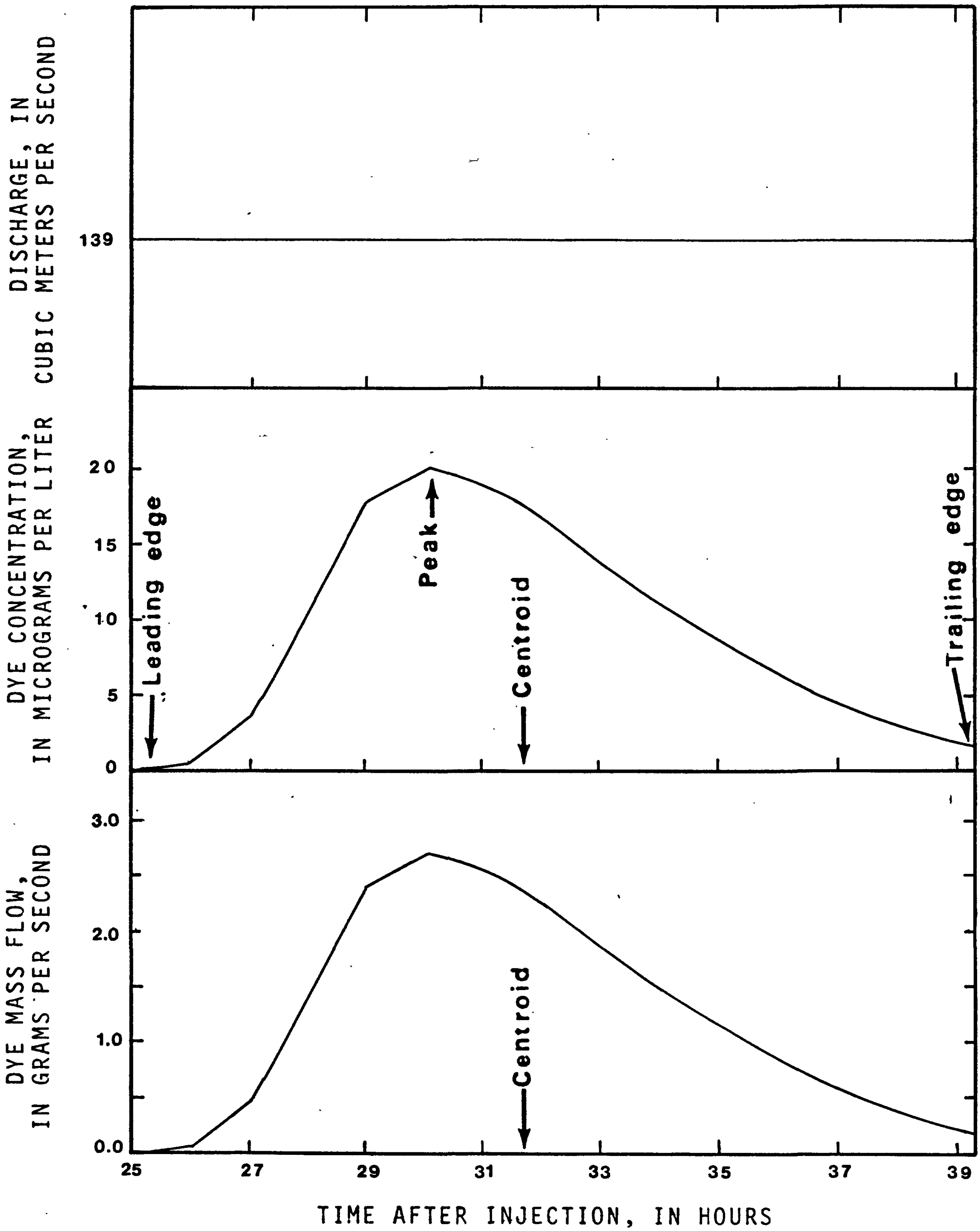


Figure D2.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Turner Bridge, May 1980.

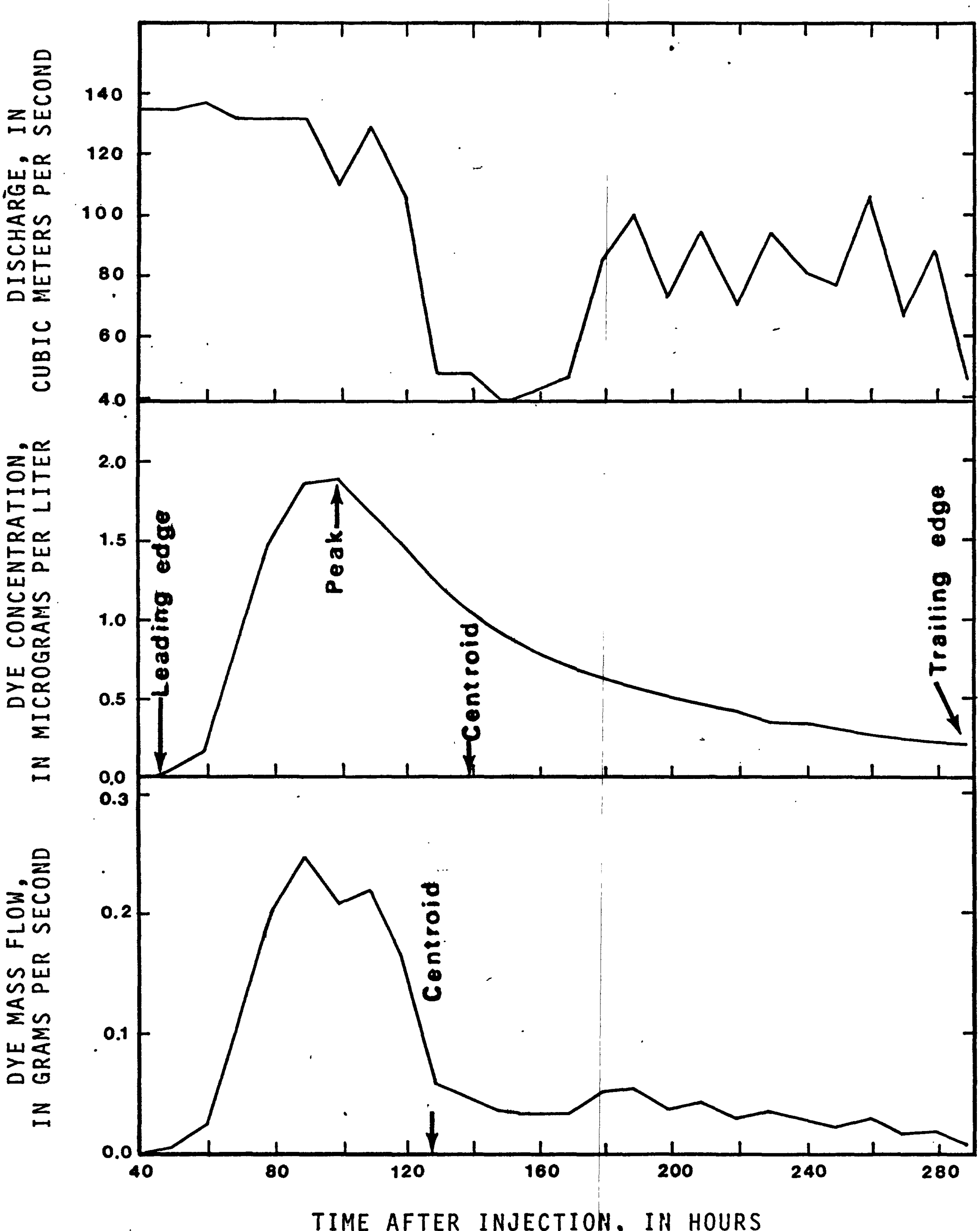


Figure D3.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Gulf Island Dam, May, 1980.

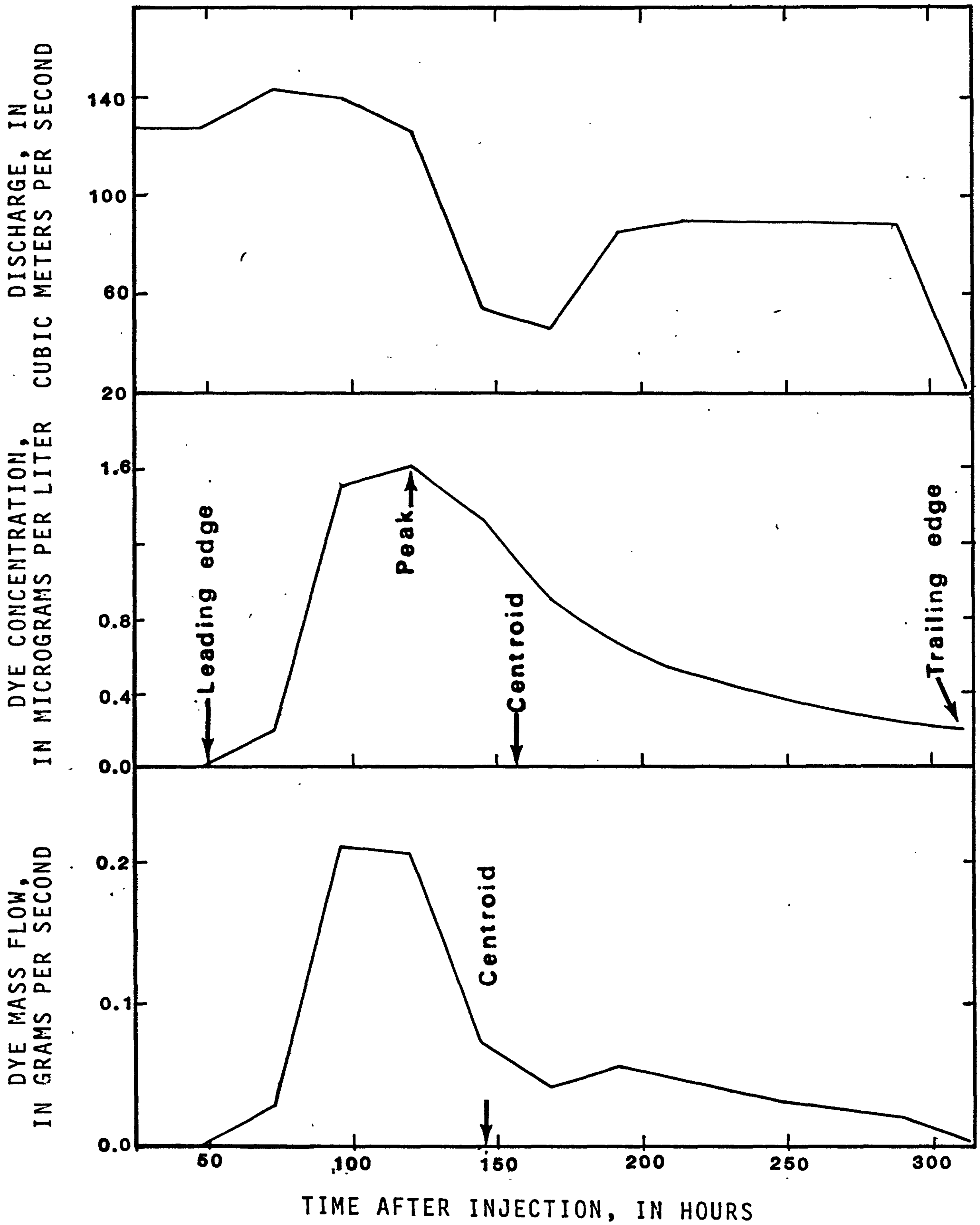


Figure D4.--Plots showing discharge, dye concentration, and dye-mass flow versus time after imjection at Deer Rips Dam, May, 1980.

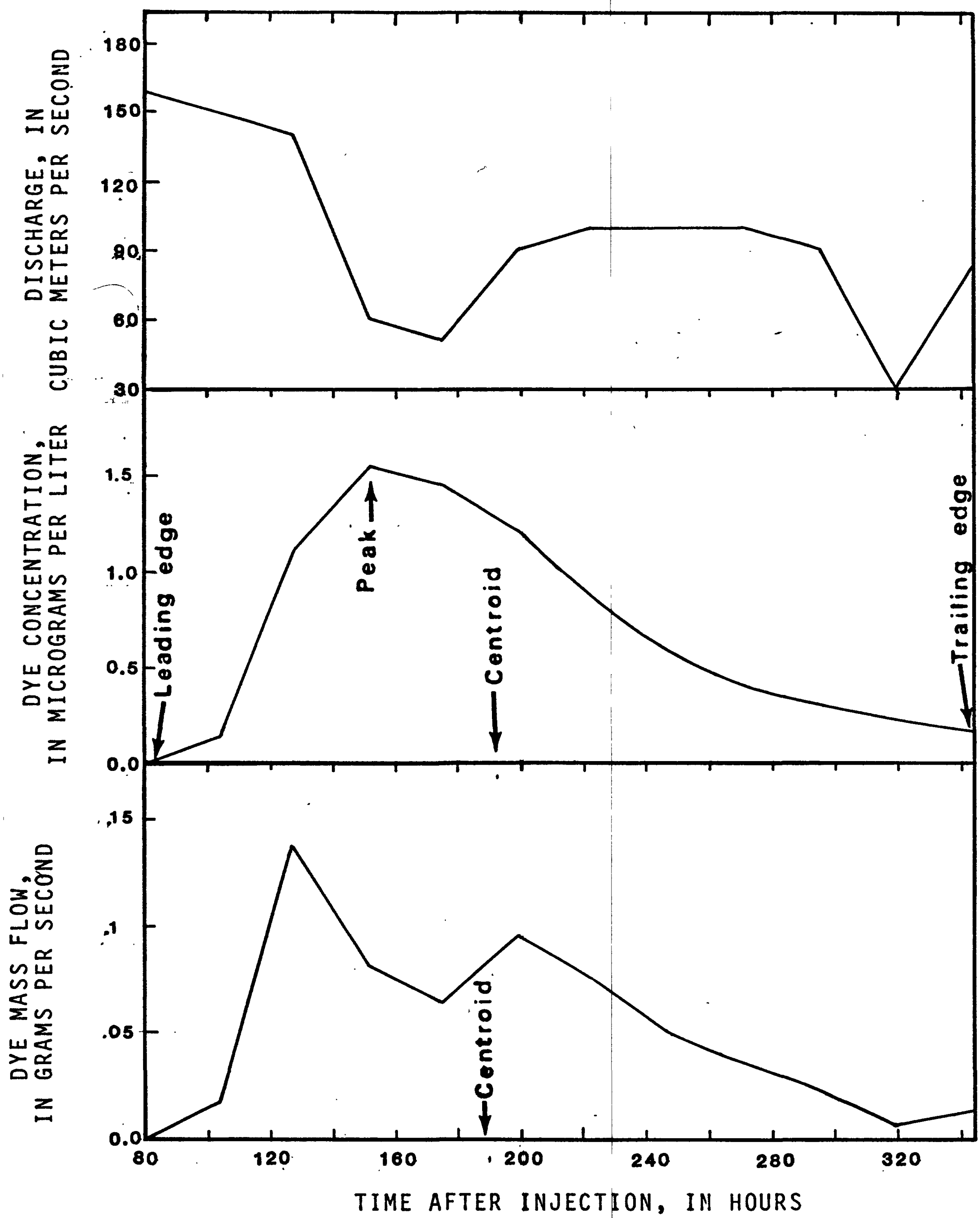


Figure D5.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Lisbon Falls, May, 1980.

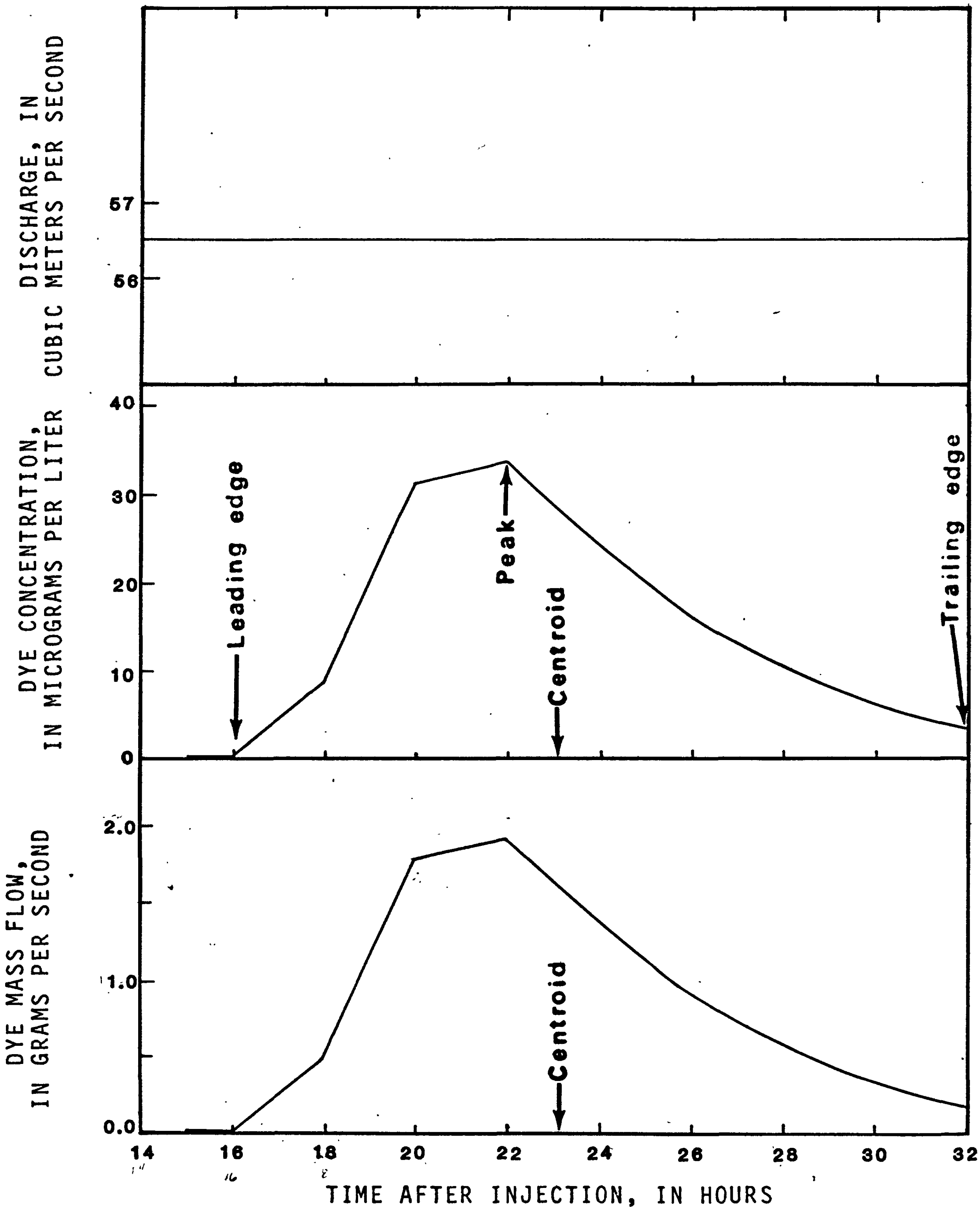


Figure D6.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Twin Bridges, August, 1980.

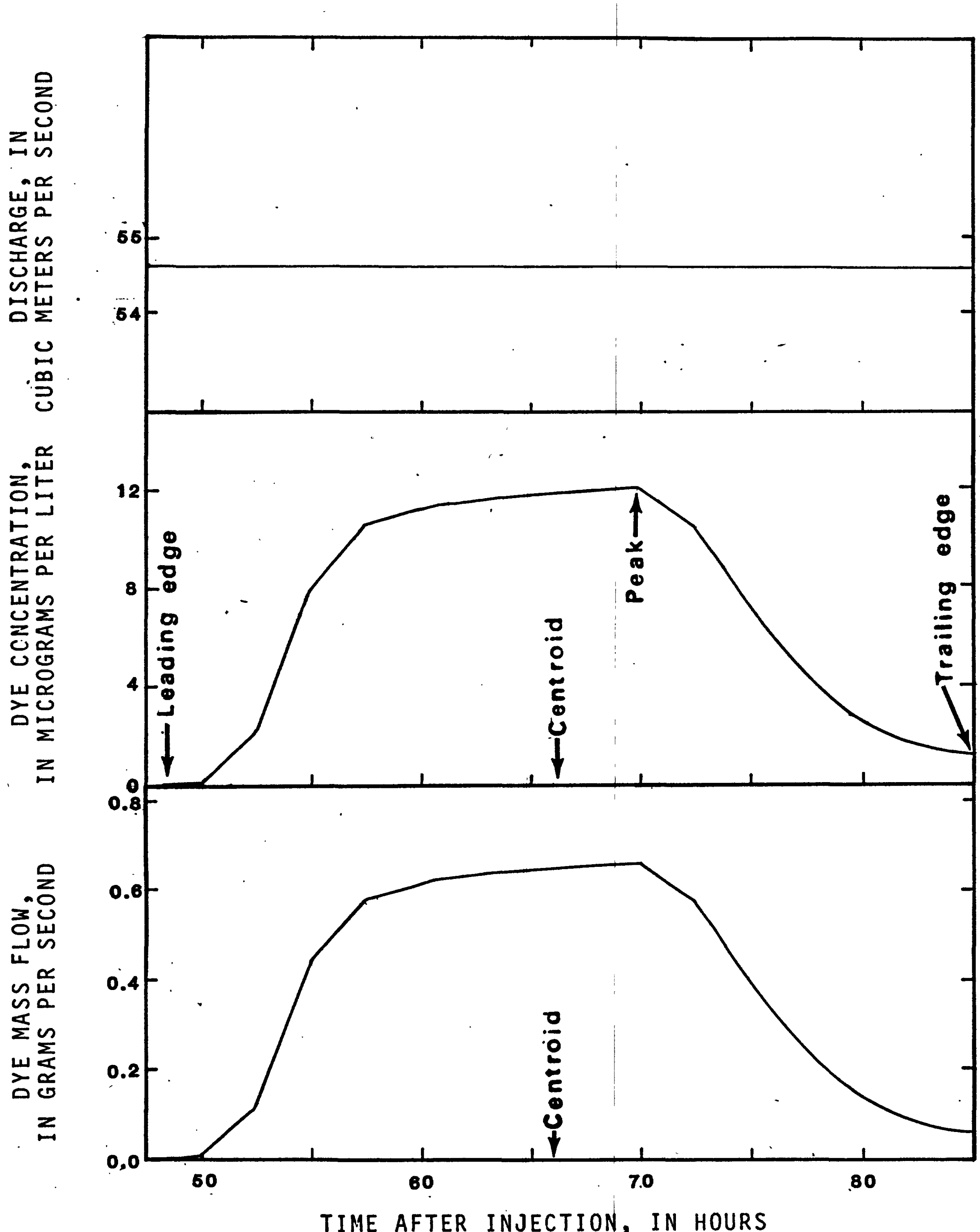


Figure D7.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Turner Bridge, August, 1980.

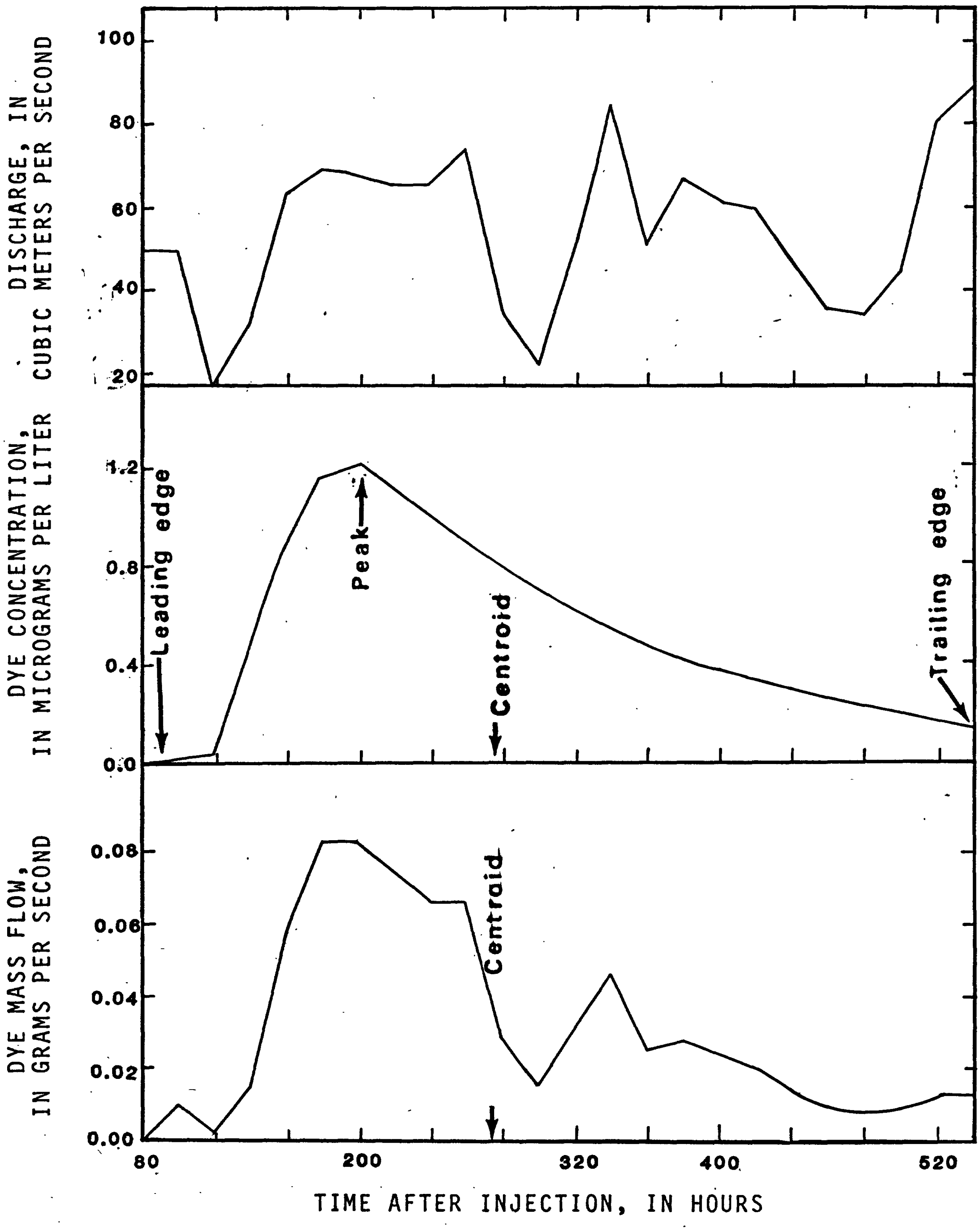


Figure D8.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Gulf Island Dam, August, 1980.

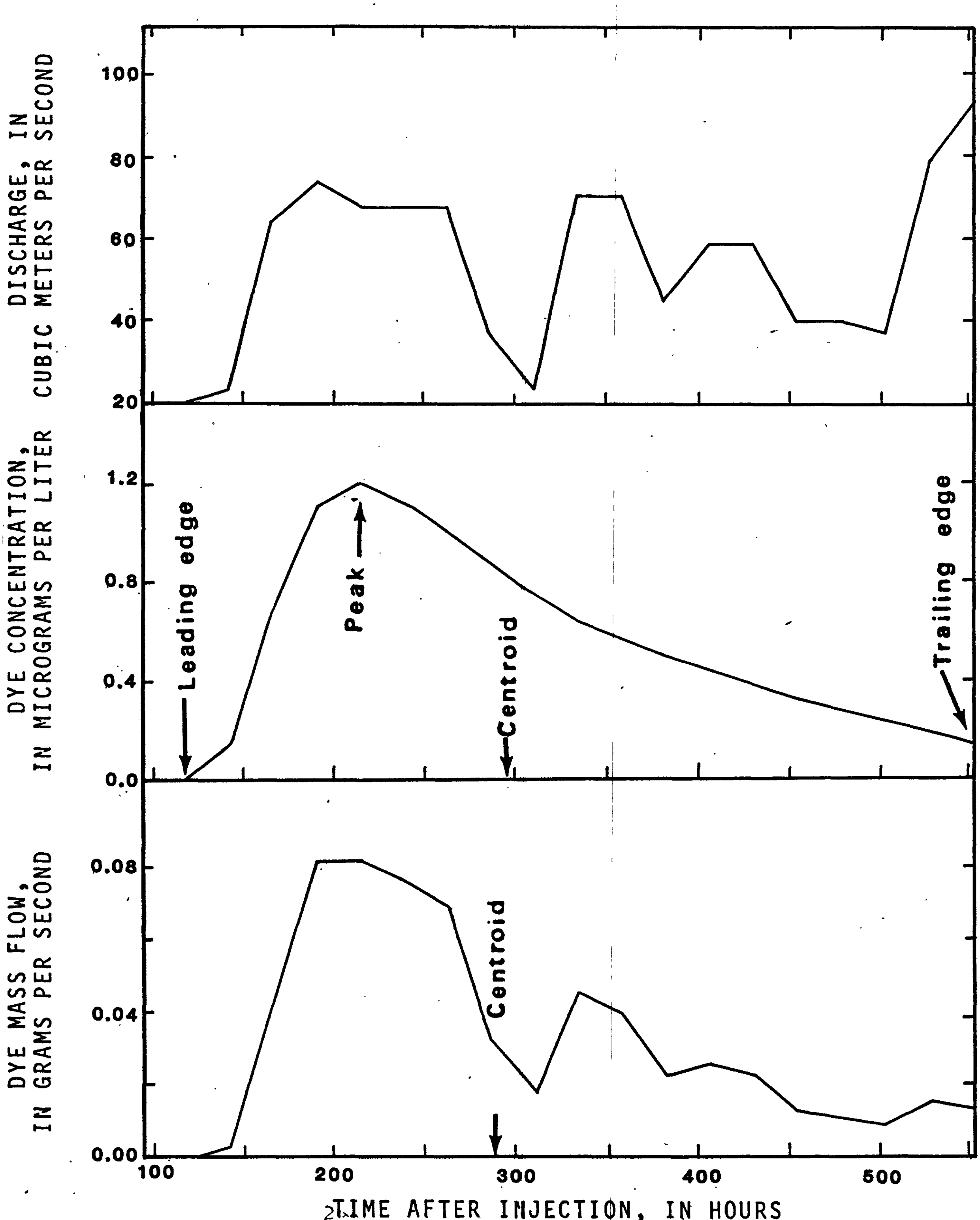


Figure D9.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Deer Rips Dam, August, 1980.

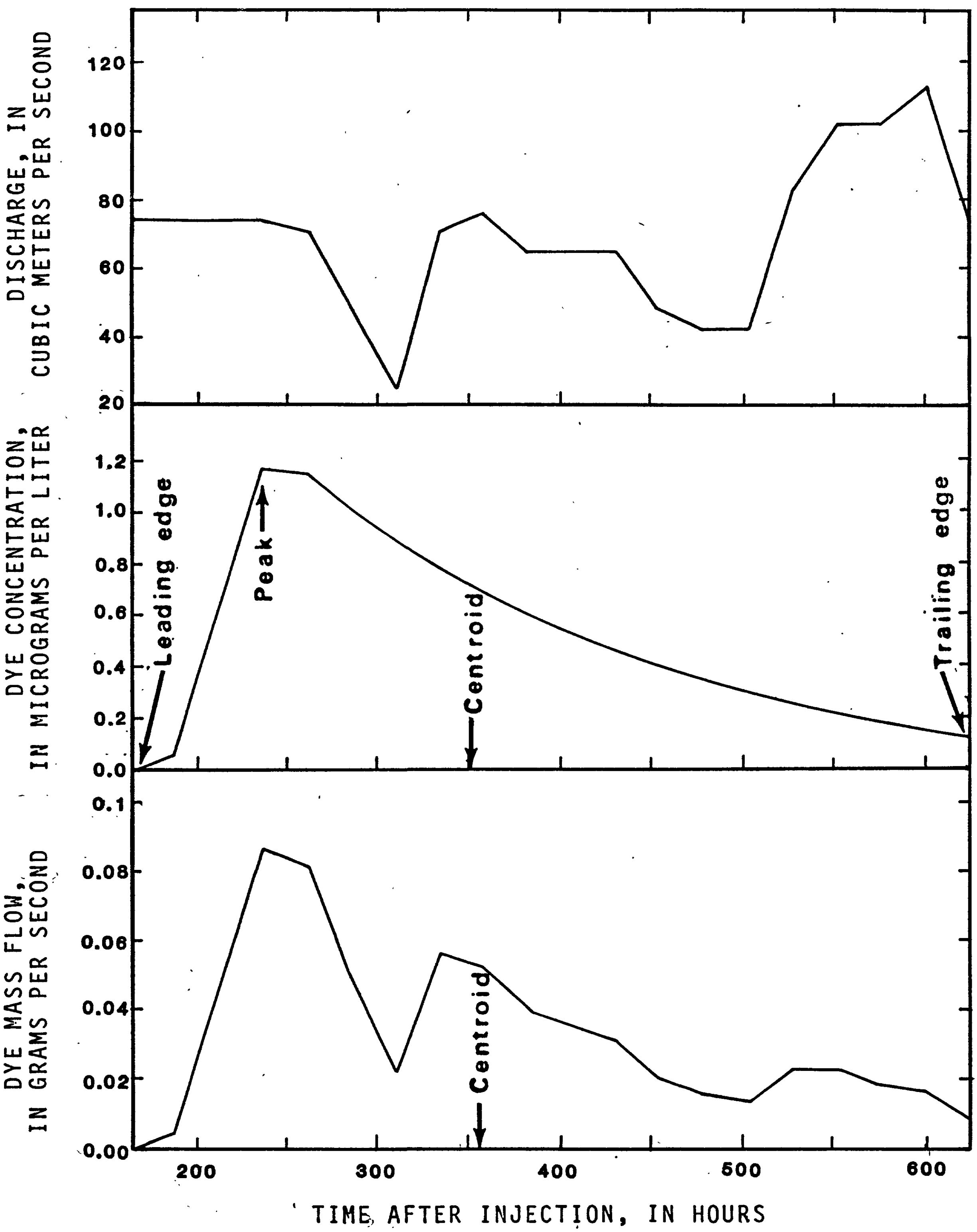


Figure D10.--Plots showing discharge, dye concentration, and dye-mass flow versus time after injection at Lisbon Falls, August, 1980.