TIME OF TRAVEL AND DISPERSION STUDY IN THE ANDROSCOGGIN RIVER BASIN, MAINE

By Gene W. Parker, Gary S. Westerman,
Gardner S. Hunt and Gloria L. Morrill

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

Multiply SI units	By	To obtain inch-pound units
	<u>Length</u>	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	<u>Area</u>	
square kilometer (km^2)	0.3861	square mile (mi^2)
	<u>Flow</u>	
cubic meter per second (m^3/s)	35.32	cubic foot per second (ft^3/s)
	<u>Velocity</u>	
meter per second (m/s)	3.281	foot per second (ft/s)
	<u>Temperature</u>	
degree Celsius (°C)	$°F=9/5°C+32$	degree Fahrenheit (°F)
	<u>Mass</u>	
gram (g)	0.002205	pound (lb)

<u>National Geodetic Vertical Datum of 1929</u>: 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 AND SYMBOLS

C_i	-	observed dye concentration of T_i
CVT	-	concentration versus time
D	-	longitudinal dispersion coefficient
F_D	-	Froude number
g	-	acceleration due to gravity
H	-	mean depth
L	-	reservoir length
M_{inj}	-	mass of dye injected
MVT	-	mass versus time
PR	-	percent recovery
Q	-	average discharge
Q_i	-	discharge at T_i
QVT	-	discharge versus time
r	-	correlation coefficient
$\bar{T}$	-	time of centroid of a dye cloud
T_i	-	i^{th} hour after injection
V	-	mean velocity
X	-	distance downstream of injection point
$\Delta_i t$	-	i^{th} time interval $(T_{i+1} - T_{i-1})/2$
ε	-	average normalized vertical density gradient
κ	-	skewness
σ_t^2	-	variance

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IN THE ANDROSCOGGIN RIVER BASIN, MAINE

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ABSTRACT

In a series of dye tracer studies at discharges ranging from 45 to 212 cubic meters per second, time of travel and dispersion characteristics were determined at 12 sampling sites along 123 kilometers of the Androscoggin River, Maine (Rumford to Pejepscot Dam). Dye-cloud centroid traveltimes ranged from approximately 120 hours at high discharges to 410 hours at flows approaching 95 percentile duration. Longitudinal dispersion coefficients ranged from 21.3 to 76.7 square meters per second.

In the 37.2-kilometer reach of unsteady flow from Gulf Island Dam to Pejepscot Dam, the concept of mass flow versus time was applied to relate centroid traveltime to average discharge at five sites. This information was used to develop traveltime versus discharge relationships, traveltime versus distance relationships, and longitudinal dispersion coefficients.

In Gulf Island Pond, a 70.4 million-cubic-meter impoundment, three complete dye clouds were traced. The range of observed centroid traveltimes was 110 hours at a mean discharge of 84 cubic meters per second to 260 hours at 59 cubic meters per second. Traveltimes are dependent upon reservoir stratification and mixing as well as discharge. During 1981, inflowing dye-tagged water at 19.0 and 19.5 degrees Celsius was observed to seek its own temperature density level during movement along the thalweg.

INTRODUCTION

Background

The U.S. Geological Survey entered into a cooperative program with the Maine Department of Environmental Protection in October 1977 to:

1) Evaluate and describe traveltime and dispersion characteristics of selected streams with known or potential water-quality problems; and
2) use the information gathered to calibrate and verify models that simulate the effects of waste loading to the stream.

The Androscoggin River was one of the streams selected as part of this program.

Purpose and Scope

The purpose of this report is to describe the time of travel and dispersion in the reach of the Androscoggin River between Rumford and Pejepscot Dam, Maine. The report also describes the mixing patterns of inflow within Gulf Island Pond, Maine. Time of travel and dispersion were defined by:

1) time versus dye concentration curves in steady flow reaches;
2) in reaches having unsteady flow, dye mass flow versus time curves;
3) longitudinal dispersion coefficients; and
4) stratification patterns in Gulf Island Pond.

Eight dye tracer studies were conducted through three subreaches (123 kilometers) of the Androscoggin River. The studies were conducted during the periods of no ice cover during 1980 and 1981. Four of the eight studies were conducted through Gulf Island Pond.

Acknowledgements

For their assistance in both the office and the field, at all stages of the project, the authors are indebted to several individuals from the Maine Department of Environmental Protection. Alfred C. Lavallee was an integral part of the planning and review process, James Jones provided expertise in field operations, and Carolyn Rand provided valuable secretarial services.

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) (fig. 1). Total drainage area is 9,127 km^2 (Fontaine, 1979), and the drop in elevation from Umbagog Lake to Brunswick is 379 m.

The flow of the Androscoggin River is extensively regulated by numerous dams, both on the river itself and on its tributaries. The existing dams essentially control all but peak flows in the basin. Over 90 percent of the present storage capacity is in the headwaters of the basin above the outlet of Umbagog Lake at Errol, New Hampshire. Downstream from Errol, the largest storage source is Gulf Island Pond formed by Gulf Island Dam, built in 1928 near Lewiston, Maine. Gulf Island Pond accounts for 3.5 percent of the usable storage in the basin (New England-New York Inter-Agency Committee, 1954).

The section of the Androscoggin River under study extends from Rumford to Brunswick, Maine and includes nine impoundments (fig. 2). Low hills and broad valleys characterize the basin along this stretch of the river. The surficial geology is sand, gravel, and marine silts and clays overlying till and bedrock. The streambed is generally covered with a deposition of silt-sized organic matter, although there are some reaches with clean bedrock exposures. The climate in the study area is temperate with an average annual temperature around 5.5°C. The average annual precipitation is 1070 mm with snowfall averaging nearly 2030 mm.

The Geological Survey operates 11 gaging stations in the Androscoggin River basin. In addition, continuous water-quality data is collected at two sites in the basin. Location, flow, and water-quality data for these sites are published in the Survey annual data reports for Maine. Two gaging stations are located within the study area on the main stem of the Androscoggin River. The site in Rumford has an average flow of 105 m^3/s with 88 years of record. The site in Auburn has an average flow of 174 m^3/s with 52 years of record.

Over the entire 130.8 km study reach, channel geometry and general hydrologic characteristics differ considerably. If dye clouds were passed through the entire reach, they would be irregularly dispersed, making data inconclusive and difficult to interpret. In addition, the logistics and manpower requirements for 130-km dye runs would be prohibitive. Therefore, the study reach was divided into three more homogeneous and manageable subreaches that would allow reasonable interpretation of dye-tracer data. The subreaches are: (A) Rumford to Twin Bridges, (B) Livermore Falls to Deer Rips Dam, and (C) Gulf Island Dam to Brunswick. See figure 2. The overlap between subreaches A and B (Livermore Falls to Twin Bridges) and B and C (Gulf Island Dam to Deer Rips Dam) enabled accumulation of traveltime data from adjacent subreaches.

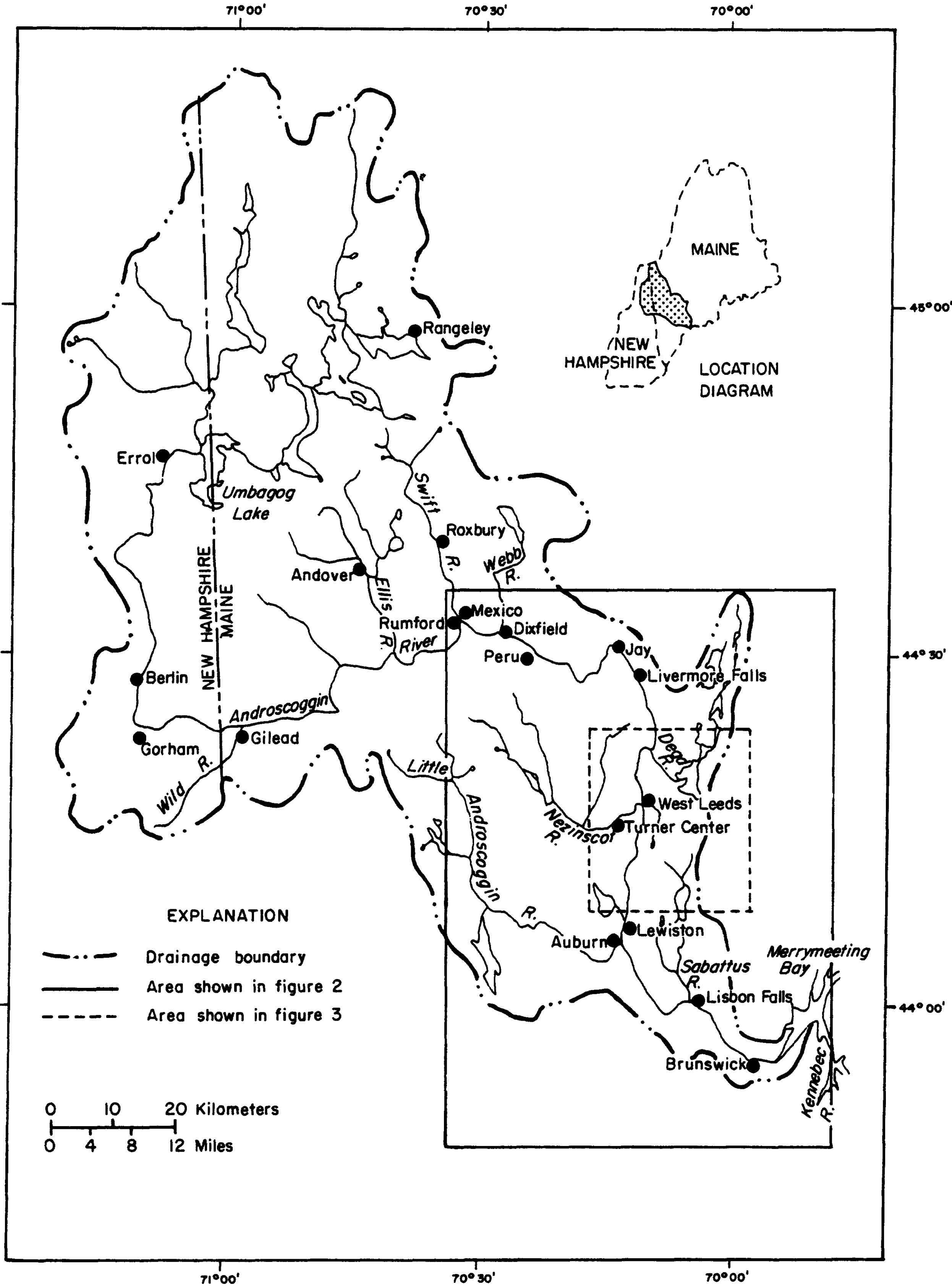

Figure 1.--Drainage basin of the Androscoggin River

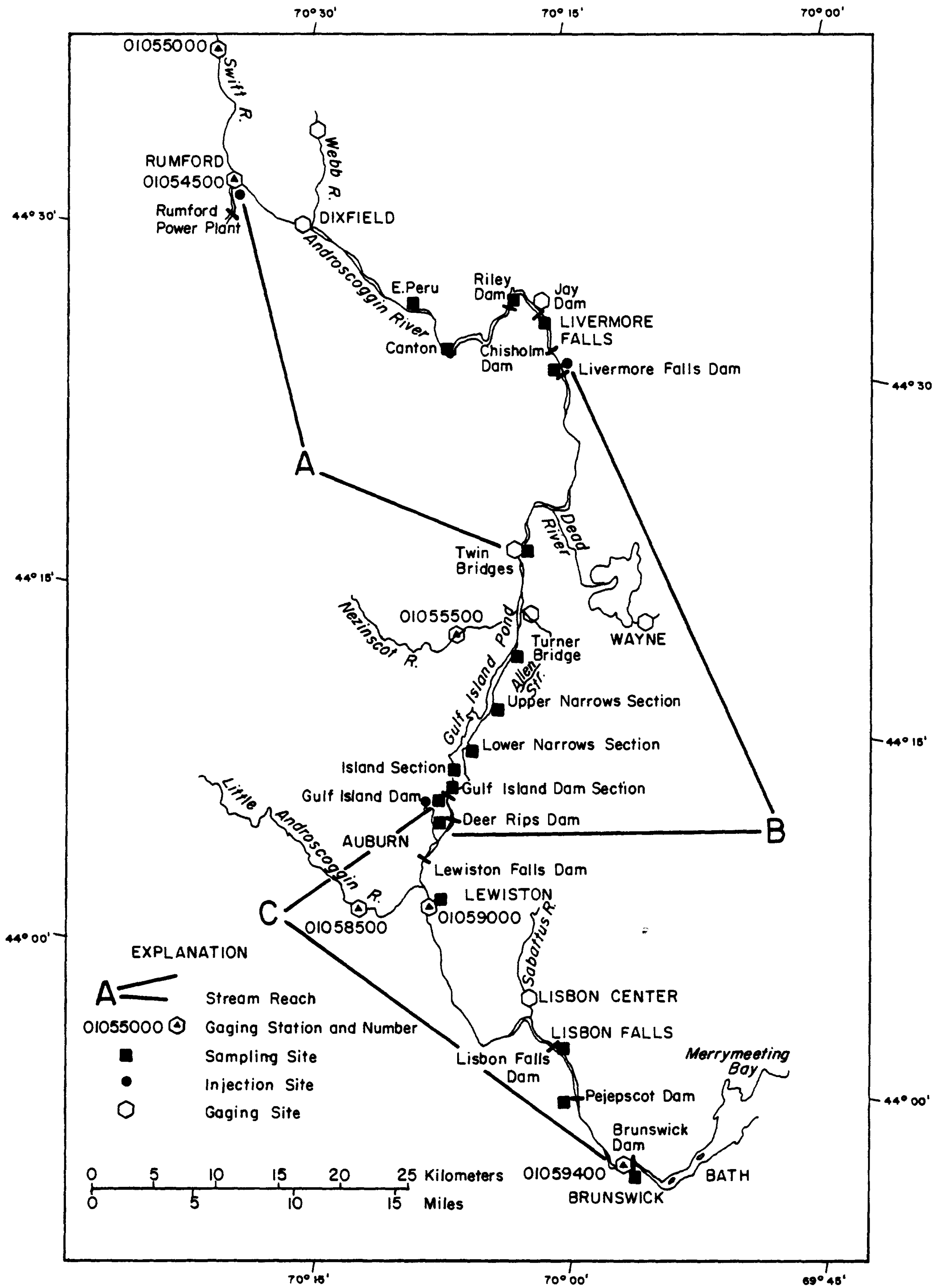

Figure 2.--Androscoggin River study sites

Subreach B is of particular interest because of the unique hydrologic aspects of Gulf Island Pond. The pond, formed by Gulf Island Dam (fig. 3), is used primarily for hydropower generation with depths in some sections of the pond exceeding 20 m. Gulf Island Pond has 3 m of usable head, but is usually operated in a manner such that weekly inflow equals outflow. Selected physical characteristics of the pond are given in table 1.

The flow conditions in subreach C are unique from those of the other subreaches because of the amount of regulation of Gulf Island Dam. Within subreach C, hourly changes in discharge of 57 m^3/s, as measured at the Survey gage near Auburn, are not unusual during medium-and low-flow conditions.

Table 1.--Physical characteristics of Gulf Island Pond

Normal pond elevation:	79.9 m*
Length:	23.3 km
Capacity:	70,400,000 m^3
Surface area:	11.1 km^2
Drainage area:	7415 km^2
Mean width:	476 m
Maximum depth:	22.9 m
Mean depth:	6.4 m
Mean annual residence time:	5 days

* Above the National Geodetic Vertical Datum of 1929

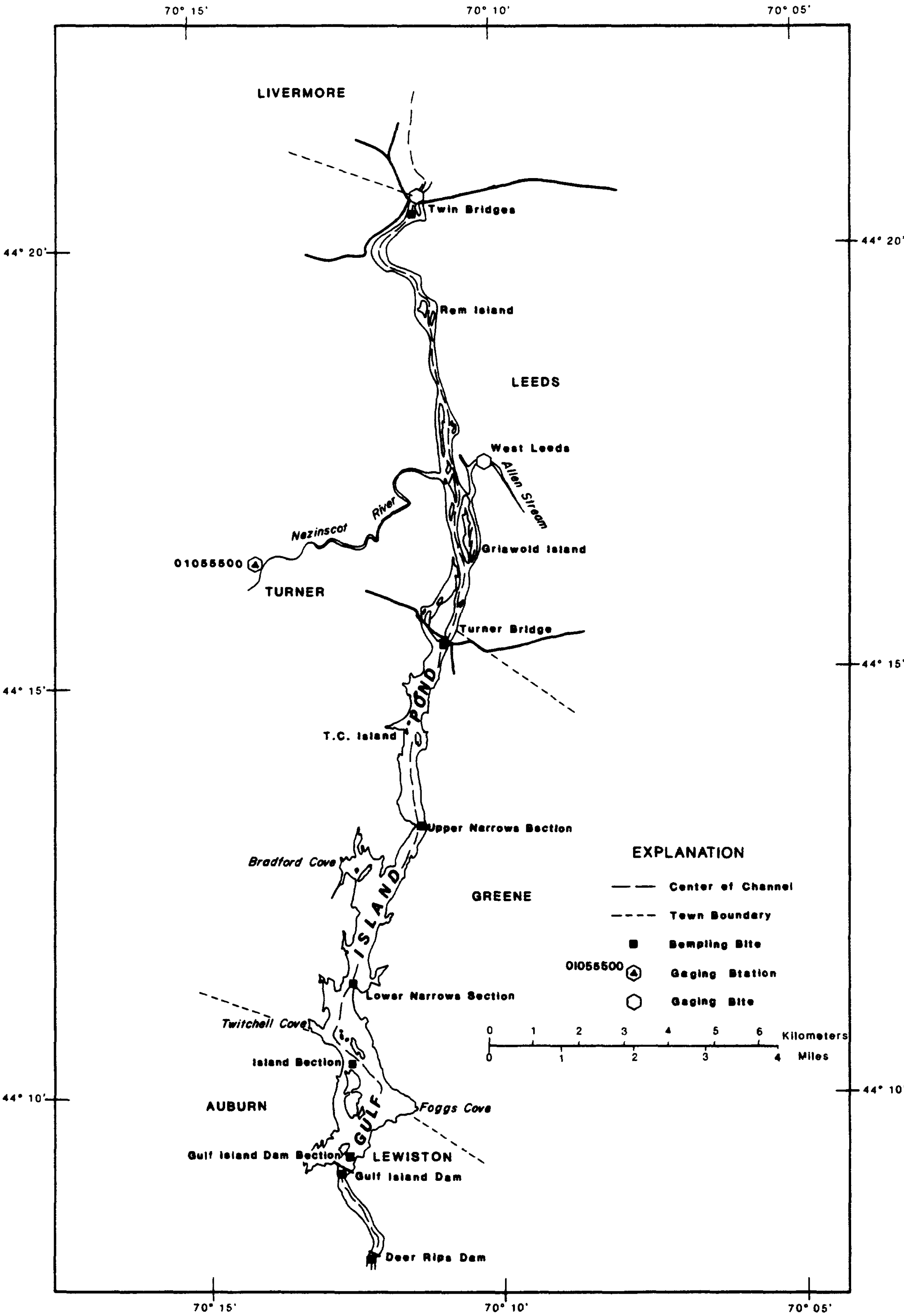

Figure 3.--Gulf Island Pond study area

PROJECT DESIGN

Discharge Data

Target discharges of 190, 120, and 50 m^3/s (25, 50 and greater-than-90 percentile flow durations) were selected. These discharge values range from average annual discharge to mean 7-day, 10-year low flow at the Survey gage on the Androscoggin River near Auburn, Maine (01059000) 10.6 km downstream of Gulf Island Dam. Although this gage was selected as the principal reference or index gage for the study area, the regulation of flows at Gulf Island Dam required the use of the Survey gage at Rumford (01054500) as the index gage for subreach A and subreach B above Gulf Island Dam.

In addition to continuous discharge records from the permanent Survey gages, hourly discharges at Gulf Island Dam were provided by Central Maine Power Company. The records were supplemented with measurements at temporary sites as indicated in table 20. Discharge at each of the ungaged dye sampling sites (fig. 2) was estimated from discharges determined at nearby permanent and temporary gaging sites on the Androscoggin River with adjustments for intervening drainage area. Adjustments in discharge were based on runoff per square mile as computed from discharges determined at nearby gaged tributaries. River distance and drainage area for selected gaged and ungaged sites on the Androscoggin River and its major tributaries are also listed in table 2.

Dye Selection and Injection

Rhodamine WT[1] dye in 20-percent solution was used as the tracer. This dye was selected because of its miscibility in water, fluorescence, availability, conservancy, and detectability at very low concentrations. Once subreach boundaries were determined, the amount of dye required to produce a peak concentration of 5 μg/L at the end of the subreach was calculated according to methods outlined by Kilpatrick (1970).

Dye injection points were selected for each subreach: For subreach A, through the wastewater treatment diffuser of the Boise-Cascade paper mill in Rumford; for subreach B, through the active turbines of the Livermore Falls hydroelectric dam; for subreach C, at the outfall of Gulf Island Dam. It was anticipated that the turbulance created at these sites would contribute to quicker tranverse mixing of the dye before reaching the first downstream collection site.

Dye Sampling Sites

Fixed sites for dye data collection were selected and site suitability was confirmed by field reconnaissance. Sites selected are shown in figure 2 and are detailed in table 2.

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

Table 2.--Injection and sample design for Androscoggin River, Maine

Site Name	Geological Survey Station number	River Distance[a] (km)	Drainage Area (km^2)	Actual Test reaches 1980 May	1980 Aug.	1980 Sept.	1981 Apr.	1981 June	1981 Sept.	Remarks
Survey Gage at Rumford	01054500	130.8	5,356	I		I	I			Qr
Survey Gage at Swift River near Roxbury	01055000	130.5[b]	251							Qr, t
Dixfield		122.8	5,708							Qr
Webb River near Dixfield		122.5[b]	300							Qr, t
East Peru		111.2	--	S		S	S			
Canton Bridge		106.5	--	S		S	S			Qm
Riley Dam		97.3	6,387	S		S	(1)			
Jay Dam		93.2	6,444	S		S	S			Qm
Livermore Falls Dam		88.5	6,465	S,I	I	S	S	I	I	
Twin Bridges		68.6	6,835	S,S	S	S	S	S	S	Qr
Survey Gage on Nezinscot River at Turner Center	01055500	61.5[b]	438							Qr, t
Turner Bridge		57.6	--	S	S			S	S	L, Qm
Upper Narrows Section		53.4	--	S	S			S	S	L, V
Lower Narrows Section		49.5	--	S	S			S	S	L, V
Island Section		47.6	--					S	(2)	L, V, (3)
Gulf Island Dam Section		45.1	--					S	(2)	L, V, (3)
Gulf Island Dam		44.9	7,415	S	S		I	S	(2)	Qp
Deer Rips Dam		42.8	7,420	S	S		S	S	(2)	
Survey Gage on Little Androscoggin River near Auburn	01058500	36.9[b]	850							Qr, t
Survey gage near Auburn	01059000	34.3	8,451				S	S	(2)	Qr, (3)
Sabattus River near Lisbon Center		17.5[b]	188							Qr, t
Lisbon Falls		13.2	8,759	S	S		S	S	(2)	
Pejepscot Dam		7.7	8,860				S	S	(2)	(3)
Survey Water Quality gage near Brunswick	01059400	0.1	8,894	(1)	(1)		S	S	(2)	Qm

[a] River distance above tide effect(0.1km below most downstream dam at Brunswick, Maine.)
[b] River distance point where tributary enters main stem.

(1) Sampler failure
(2) Large increase in flow
(3) Site added in 1981

I Injection site
S Sample site
Qr Discharge rated site
V Vertical sampling

Qm Miscelaneous discharge measurements made
Qp Discharge provided
t Tributary
L Lateral sampling

DATA COLLECTION

Dye Study Runs

Subreach A

Three dye injections were made in subreach A at 74, 45, and 204 m^3/s in May 1980, September 1980, and April 1981, respectively. These flows are at 79, 91, and 24 percentile flow durations based on the survey gage at Rumford record. All three dye clouds were observed at Twin Bridges, thereby providing an overlap with subreach B. No data from the April 1981 run are available for Riley Dam due to sampler failure. All three clouds were observed at all the other sampling sites in the reach.

Subreach B

A total of four dye injections were made through subreach B. The first two dye studies were made in May and August 1980 at 113 and 57 m^3/s, corresponding to 54 and 87 percent duration. The last two dye studies were made in June and September 1981. The June study was made during a flow of 127 m^3/s (flow duration of 47 percentile), and dye was observed at all study sites in subreach C as well as subreach B. The flow was 85 m^3/s when the September dye injection was made (a flow duration of 74 percentile). The entire dye cloud was observed at Twin Bridges, Turner Bridge, Upper Narrows, and Lower Narrows sites. A flood wave of peak 901 m^3/s at the Survey gage near Auburn passed through the study reach on September 24, 1981 effectively flushing the dye cloud through the remainder of the reach. For this reason, data analysis was only done for the first two sites in subreach B.

Subreach C

Five dye clouds were followed through subreach C. Four of the clouds originated at Livermore Falls on May 1980, August 1980, June 1981, and September 1981. The fifth injection in April 1981 was made at Gulf Island Dam with a constant discharge of 190 m^3/s at the 26 percentile flow duration based on the survey gage near Auburn record. Repeated equipment problems experienced at Brunswick, combined with major hydrologic changes due to redevelopment of a hydroelectric dam at Brunswick, rendered all data from the subreach downstream of Pejepscot of questionable value. Brunswick data are, therefore, not included. The leading edge of the September 1981 dye cloud injected in subreach B was observed at all sites in subreach C but a complete data set of information could not be collected due to the extreme increase in discharge that occurred as noted before.

Sampling Techniques

Water samples were collected at 17 sites in the entire reach to be analyzed for dye concentration (fig. 2). At East Peru, automatic syringe samplers which draw from the uppermost 0.1 m of the water column were used. During the 1980 study runs, samplers were placed at two evenly spaced points laterally in the channel; however, during the 1981 study run, the syringe samplers were placed approximately 5 m from the left shore as high flows prevented placement further into the mainstream. The other use of automatic syringe samplers at Turner Bridge, Upper Narrows, and Lower Narrows are detailed by Parker and Hunt (1983). In general, at bridge sampling sites (Canton Bridge, Twin Bridges, Turner Bridge) automatic pumping samplers were spaced evenly across the section and set to collect water at a depth of 1 m. At dam sampling sites, samples were collected by automatic pumping samplers at either the outfall (Jay Dam, Gulf Island Dam, and Deer Rips Dam) or at active intake points (Riley Dam, Livermore Falls Dam, Pejepscot Dam). At Auburn, Lisbon Falls, and Brunswick samples were collected at 3 to 9 m from shore, as necessitated by flow fluctuations, again by automatic pumping samplers. Sampling periods range from 15-minute intervals to 6-day intervals.

During the 1980 studies, movement of the dye cloud through Gulf Island Pond was determined from a boat moving generally along the thalweg (Parker and Hunt, 1983). This sampling scheme did not account for the lateral distribution of dye at specific sites. During the two 1981 study runs, a different approach was used for dye measurement as a result of the previous years experience. Sampling points were located laterally and vertically at four cross sections: Upper Narrows, Lower Narrows, Island, and Gulf Island Dam sections. Each sampling section was identified with an anchored marker buoy.

At each sampling location, water was pumped from specific depths through a fluorometer equipped for flow-through measurements. Concentration values were recorded once the fluorescence readings stabilized. Water temperature was also recorded for later correction of dye concentration to a base temperature.

Dye-Concentration Measurement

Water samples were analyzed in the field for dye concentration using a fluorometer equipped with either a flow-through system or 40-ml discrete sample cuvette. The instrument was supplied with a constant voltage source. The fluorometer was calibrated at the beginning and end of each work shift. Due to the large volumes needed, different lots of dye were used in each injection. Dye-concentration standards were not made from composites of the various dye lots. However, variation in concentration of less than 10 percent was observed in the standards prepared throughout the study period. During the 1980 study run, no samples were retained for reanalysis. During the 1981 studies, a single sample was saved for each site, from each set collected during a sampling period, to be reanalyzed later in the laboratory. Of each set collected, water temperature was recorded of the first, middle, and last sample as well as the retained sample. The retained sample was reanalyzed at a base temperature to determine the correction needed to standardize field concentration readings.

Water-Temperature Measurement

Water temperature was measured at Turner Bridge, Upper Narrows section, Lower Narrows section, Island section, and Gulf Island Dam section. The data are summarized in appendixes B and D. At Turner Bridge, a monitor recorded water temperature at 2 and 6 m above the stream bed in the center of the channel from May 27 to October 8, 1981. The maximum recorded difference in temperature between the two levels was 1.5°C on August 2 and 3. In general, the difference was less than 0.5°C over the depth. The complete record for Turner Bridge is reported in U.S. Geological Survey (1982). At Upper Narrows, Lower Narrows, Island, and Gulf Island Dam sections, water temperature was measured at the same points and depths in the cross section as were the dye concentrations.

ANALYTICAL TECHNIQUES

Concentration Versus Time

The primary analytical procedure selected to interpret dye concentration measurements was CVT (concentration versus time) curves. Dye concentrations were plotted against time since injection for a point on the river. A smooth curve was drawn through the plotted points, compensating for background fluorescence and occasional anomalies. From the curves, the elapsed time of each of three important features of the dye cloud was determined for each study site. The features are:

- Leading edge - arrival of dye at the sampling point;
- Peak - maximum dye concentration at the sampling point; and
- Trailing edge - point on the dye cloud tail equal to 5 percent of the peak concentration at the sampling point.

The elapsed time to a fourth feature was determined by one of two methods as discussed by Parker and Hunt (1983):

- Centroid - the center of mass of the dye cloud between the leading and trailing edges.

In the first method used to describe centroid in reaches having steady flow, the CVT curve provides the necessary information. Integrating the curve according to equation 1 provides centroid arrival time ($\bar{T}$):

$$\bar{T} = \frac{\int_{LE}^{TE} T_i C_i \, dt}{\int_{LE}^{TE} C_i \, dt} \qquad (1)$$

where:
- T_i = the i^{th} hour since injection;
- C_i = observed dye concentration, in µg/L;
- dt = change of time between observations;
- LE = time of leading edge; and
- TE = time of trailing edge.

In the second method, used for unsteady flow conditions, observed concentrations must be weighted according to discharge to obtain an accurate dye mass flow representation. MVT (mass versus time) curves are thus created and, by integrating according to equation 2, enable determination of centroid arrival time of the mass for unsteady conditions[2]:

$$\bar{T} = \frac{\int_{LE}^{TE} T_i C_i Q_i \, dt}{\int_{LE}^{TE} C_i Q_i \, dt} \qquad (2)$$

where: Q_i = instantaneous discharge in m^3/s.

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[2] See Parker and Hunt (1983) for more detail.

Presentation of Dye Data

Gulf Island Pond

Isopleths of dye concentration depicting the data collected during the June and September 1981 studies are presented in appendixes A and C. The span of time after each injection for which samples were collected is given on each figure.

Concentration-Versus-Time Curves

Measured dye concentrations at each sampling site were plotted against time since injection for each dye study run. Background levels were determined from samples collected ahead of the arrival of the dye cloud and were generally less than 0.2 µg/L. All individual-site CVT curves are shown in Appendix E, figures E-1 through E-6. In figures E-2 and E-3, the peak concentrations for East Peru are lower than those for the next downstream site, Canton Bridge. The lower concentrations are probably due to sampler location and malfunction problems rather than lack of complete transverse mixing. Comparison of CVT curves developed for two points at the East Peru cross-section indicated that mixing was complete. At sites where discharge is constant, the CVT and MVT curves are identical. However, at Gulf Island Dam, Deer Rips Dam, Survey gage near Auburn (01059000), Lisbon Falls, and Pejepscot Dam, where flow can be unsteady, differences between the CVT and MVT curves are apparent (figs. E-7 through E-12). In figures E-7 through E-12, computer-drawn segmented curves of discharge, dye concentration, and dye mass flow at discrete times are shown using a common time axis for ease of comparison. The 1980 dye runs for subreaches B and C are presented by Parker and Hunt (1983).

Dye Curve Characteristics

An important dye curve characteristic is the total dye mass observed having passed a fixed point. If the dye mass is not conserved along the length of the river, the assumption that river water is not exchanged with ground water and with dead zones in the streams may be in question. Therefore the simple techniques of analyzing the data would be too inaccurate to be used. Errors in discharge and dye measurements that may make it seem that dye is lost or gained are independent of non-conservancy due to hydrologic reasons.

Percent Recovery

One method to determine if dye is conserved is to compute the PR (percent recovery). PR is defined as the mass of dye in the dye cloud divided by the mass of dye injected. Computational equations, for unsteady and steady flow respectively, are as follows[3]:

$$PR = 0.36 \frac{\sum_{i=LE}^{TE} C_i Q_i \Delta_i t}{M_{inj}} \tag{3}$$

and:

$$PR = 0.36 \frac{\sum_{i=LE}^{TE} C_i \Delta_i t}{M_{inj}} \tag{4}$$

where: $\Delta_i t$ = i^{th} interval $(T_{i+1} - T_{i-1})/2$;
M_{inj} = mass injected; and
0.36 = constant necessary for PR to be non-dimensional.

Variance

Variance of a CVT or MVT curve is a measure of distribution of the dye concentration or mass about the centroid. The variance (σ_t^2) is defined by:

$$\sigma_t^2 = \sum_{i=LE}^{TE} \frac{(T_i - \bar{T})^2 C_i Q_i \Delta_i t}{C_i Q_i \Delta_i t} \tag{5}$$

Where flow is constant, equation 5 becomes:

$$\sigma_t^2 = \sum_{i=LE}^{TE} \frac{(T_i - \bar{T})^3 C_i \Delta_i t}{C_i \Delta_i t} \tag{6}$$

3 These are explained in more detail in Parker and Hunt (1983).

Skewness

The skewness (κ) of a CVT or MVT curve is a measure of asymmetry of a dye cloud and is defined as:

$$\kappa = \sum_{i=LE}^{TE} \frac{(T_i - \overline{T})^3 C_i Q_i \Delta_i t}{C_i Q_i \Delta_i t \, (\sigma_t^2)^{2/3}} \tag{7}$$

Where flow is constant, equation 7 reduces to:

$$\kappa = \sum_{i=LE}^{TE} \frac{(T_i - \overline{T})^3 C_i \Delta_i t}{C_i \Delta_i t \, (\sigma_t^2)^{2/3}} \tag{8}$$

For a symmetrical curve, the peak concentration or dye mass arrives at the same time as the centroid. Where the dye distribution is non-symmetrical (values of skewness other than zero), differences between centroid and peak arrival times will be observed.

Discharge Versus Time

Once a dye cloud is well mixed, observed traveltimes can be correlated with discharge to produce unique QVT (discharge versus time) relationships for each sampling site on a reach. Once developed, these relationships are useful for estimating times of travel at discharge levels other than those encountered during the dye studies. As with a CVT curve analysis, the steadiness of discharge during each study run is a factor in how reliable a QVT relationship would be. In the case of cyclic, unsteady flow, a QVT relationship between dye study runs can be made when the time period of the cloud is longer than that of the cyclic flow. In this instance, the mean discharge observed for a cycle period at any point on a reach would be representative of the whole reach. A reliable QVT relationship can then be developed from MVT centroid traveltimes although not for the other cloud characteristics. The combination of a storm event and a short period dye cloud would not be as simple to analyze. Considering these conditions, a centroid traveltime could be determined for the resulting MVT curve developed for a sampling site, but the mean discharge would not be representative of the whole reach.

Distance Versus Time

One method of summarizing time-of-travel data is to plot the traveltime of centroids versus the distance of each sampling point below the injection site at several discharges. From this relation, traveltimes can be estimated for any portion of a reach. Estimation of traveltime at flows other than for those measured can also be made by interpolation. Mean reach velocity estimates can be made by determining the inverse of the slope of the distance-versus-time plots.

Longitudinal Dispersion

When a tracer is injected into a reach, three-dimensional mixing begins. Vertical mixing is usually completed first with transverse mixing completed next some distance downstream from the injection site. Longitudinal mixing continues downstream reducing the peak concentration and lengthening dye cloud with ever increasing distance. After an initial period where advection dominates dispersion, the longitudinal dispersion coefficient (D) is a measure of this process (Taylor, 1954). Using Taylor's hypothesis, D may be determined empirically during the dispersive period by (Tsai and Holley 1979):

$$D = \frac{V^3 \Delta \sigma_t^2}{2 \Delta X} \tag{9}$$

where: X = distance downstream of the injection point; and
V = mean subreach velocity determined by the slope of the least squares regression time of $\bar{T}$ against X.

Numerically, D is the slope of the least square line formed by plotting $V^3\sigma_t^2/2$ versus X for each sampling site.

ANALYSIS AND DISCUSSION

Subreach A

This subreach is characterized by relatively steady flows and short traveltimes. Four run-of-river dams in this subreach provide very limited storage capacity. Because discharge is relatively steady, equation 1 was used to calculate the dye cloud centroid time. These calculations for subreach A are summarized in table 3. The measured dye curves are shown in appendix E, figures E-1 through E-3.

QVT curves for the reach originating at Rumford are presented in figures 4 through 9. The apparently linear QVT relationship over a discharge range of 45 to 212 m^3/s for the entire subreach indicates that traveltime can be predicted with confidence. Similarly, the linear aspect of the individual curves indicates that the dye cloud disperses uniformly with changes of discharge.

Subreach B

The Gulf Island Pond has a considerable effect on dye movement through reach B. The dye-tagged water is slowed as it enters the reservoir and is diluted. Thermal stratification determines the path and speed of a dye cloud through the pond. The velocity is also affected by the discharge at the dam.

The regulation of flow at Gulf Island Dam requires that a MVT curve be developed for each study run at those sites downstream of Gulf Island Dam. See appendix E, figures E-7 through E-12. The time to centroid was determined using equation 2. Table 4 presents a summary of time-of-travel data for this subreach.

The QVT relationships for this subreach are presented in figures 10 through 13. Cloud characteristics versus discharges at two sites upstream of Gulf Island Dam are shown in the normal fashion in figures 10 and 11. Gulf Island Dam and Deer Rips Dam data are presented differently due to the following reasons:

(1) Because of daily and seasonal changes in water temperature, the dye cloud followed different routes through Gulf Island Pond staying in the upper layers during May 1980 and dropping to the bottom layers during the August 1980 and June 1981 study runs.

(2) Regulation at Gulf Island Dam produced unsteady discharge conditions at Gulf Island Dam and Deer Rips Dam.

In figures 12 and 13, MVT centroid times are shown. Other cloud characteristics cannot be related to discharge for reasons previously mentioned. Additionally, irregularities in traveltime through the pond (reason 1 above) create uncertainty in the QVT relationships as shown in figures 12 and 13. The relation represented by the data has been indicated with a solid line. Interpolation from the relationships developed for these sites downstream of Gulf Island Pond should be limited, with reliance primarily on centroid traveltimes as rough approximations.

Table 3.--Summary of traveltime data from the Rumford injection site

Sampling Site	River distance[a] (Km)	Discharge (m^3/s)	Elapsed time from injection to: Leading edge (h)	Peak (h)	Centroid (h)	Trailing Edge (h)	Percent recovery	Variance (h^2)	Skewness
				June 1980					
East Peru	111.2	74[b]	7.0	10.4	11.6	15.8	40	2.3	0.7
Canton Bridge	106.5	74[b]	10.8	13.6	14.7	20.7	72	3.2	.6
Riley Dam	97.4	76[b]	21.5	24.9	26.3	34.3	61	6.8	.7
Jay Dam	93.2	76	26.8	31.5	32.8	41.7	51	8.1	.6
Livermore Falls	88.5	79[b]	33.5	39.4	40.6	49.9	52	11.5	.5
Twin Bridges	68.6	79	49.0	57.0	59.1	74.4	55	25.4	.7
				September 1980					
East Peru	111.2	45[b]	9.0	11.2	14.1	25.5	68	9.9	.7
Canton Bridge	106.5	45[b]	14.2	19.0	20.6	29.2	62	8.9	.5
Riley Dam	97.4	45[b]	25.7	34.8	36.0	45.6	58	13.2	.2
Jay Dam	93.2	48	34.5	42.1	44.0	56.7	63	19.6	.5
Livermore Falls	88.5	48[b]	46.2	54.0	56.0	69.0	49	20.1	.4
Twin Bridges	68.6	48	63.0	81.9	82.6	103.5	71	60.6	.4
				April 1981					
East Peru	111.2	204[b]	3.8	5.0	5.2	6.8	28	.3	.6
Canton Bridge	106.5	204[b]	6.4	7.5	7.9	10.2	47	.6	.7
Riley Dam	97.4								
Jay Dam	93.2	207	13.2	15.2	15.8	19.5	44	1.6	.6
Livermore Falls	88.5	207[b]	16.4	19.0	19.8	24.7	49	2.8	.6
Twin Bridges	68.6	212	24.5	28.5	29.6	36.3	46	5.4	.5

[a] River distance above tide effect

[b] Estimated based on intervening drainage area.

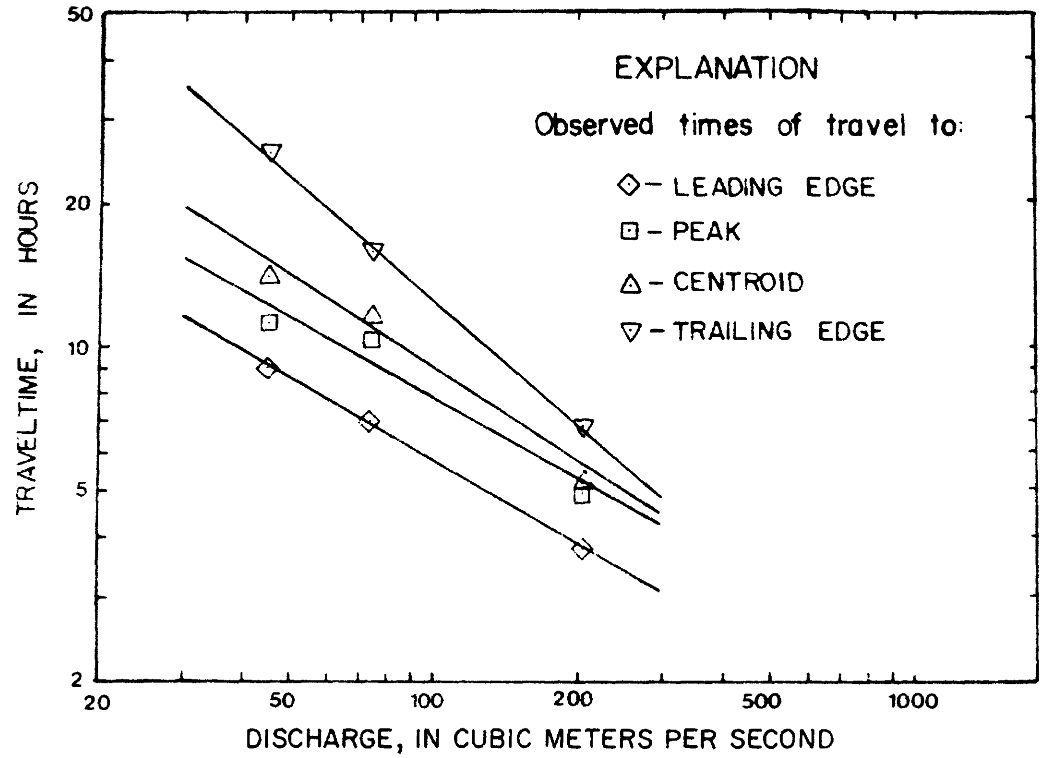

Figure 4.--Traveltime versus discharge for Rumford to East Peru, Maine

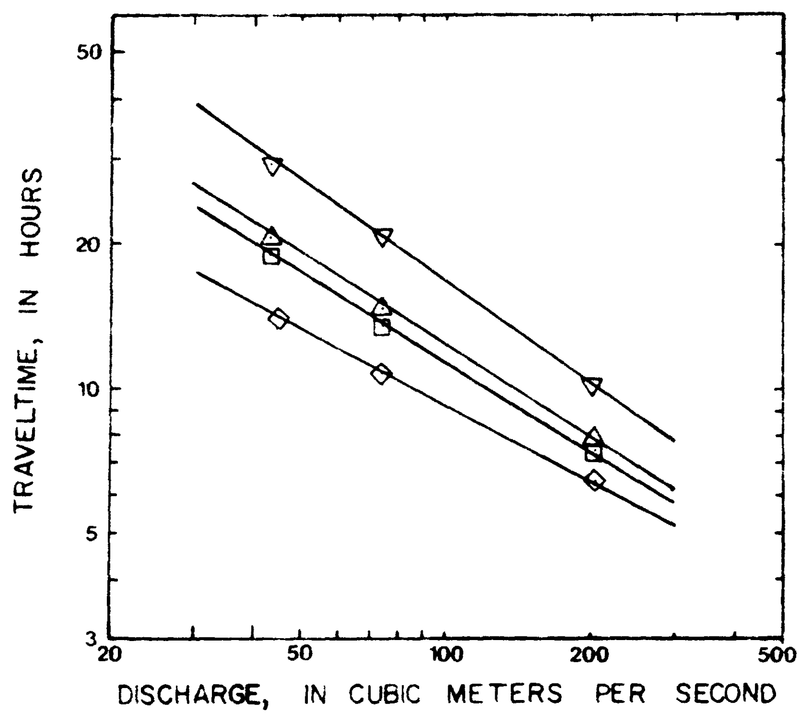

Figure 5.--Traveltime versus discharge for Rumford to Canton Bridge, Maine

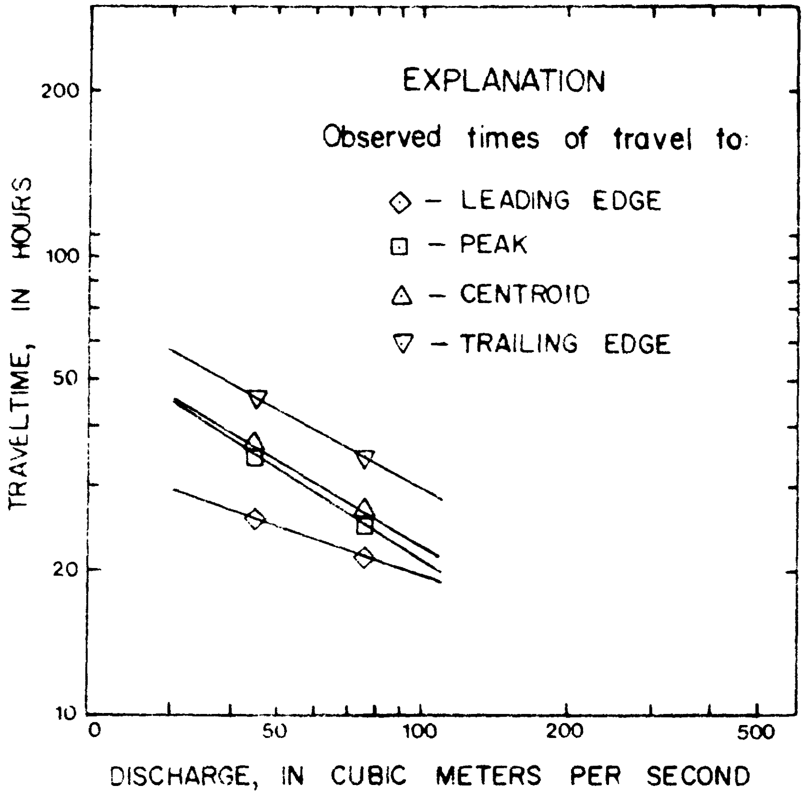

Figure 6.--Traveltime versus discharge for Rumford to Riley Dam, Maine

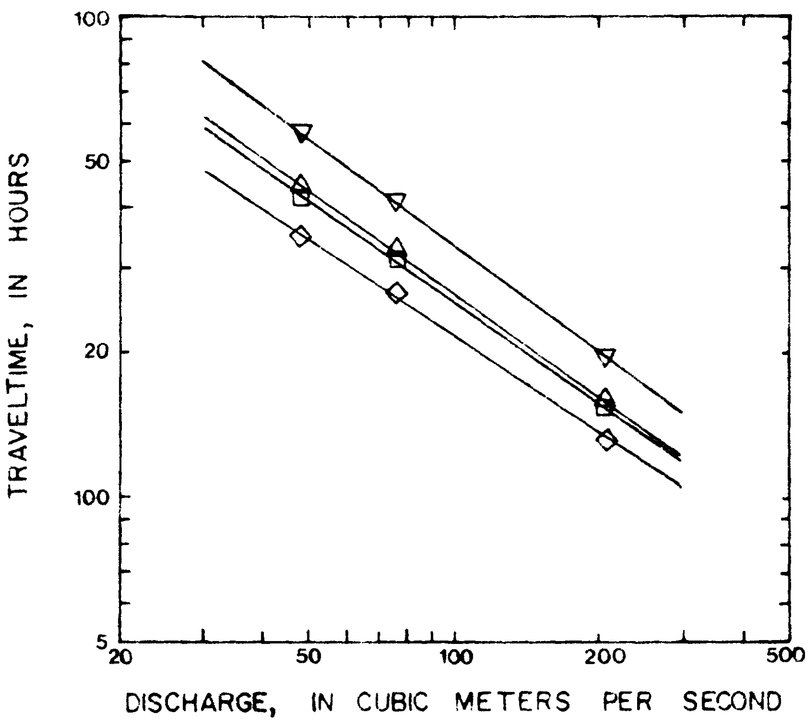

Figure 7.--Traveltime versus discharge for Rumford to Jay Dam, Maine

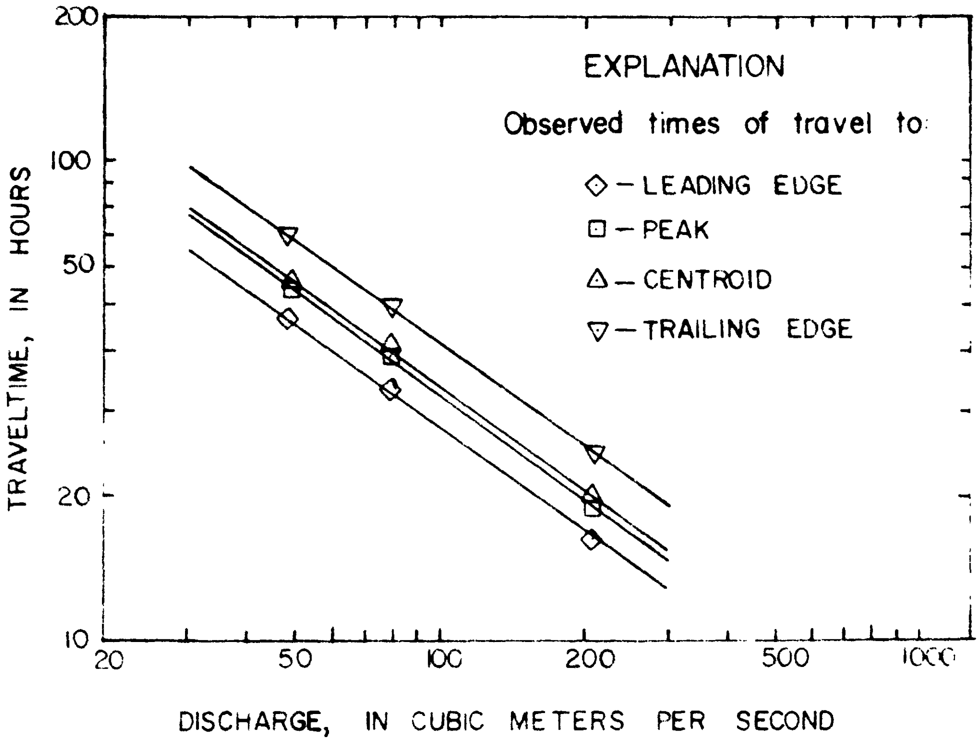

Figure 8.--Traveltime versus discharge for Rumford to Livermore Falls, Maine

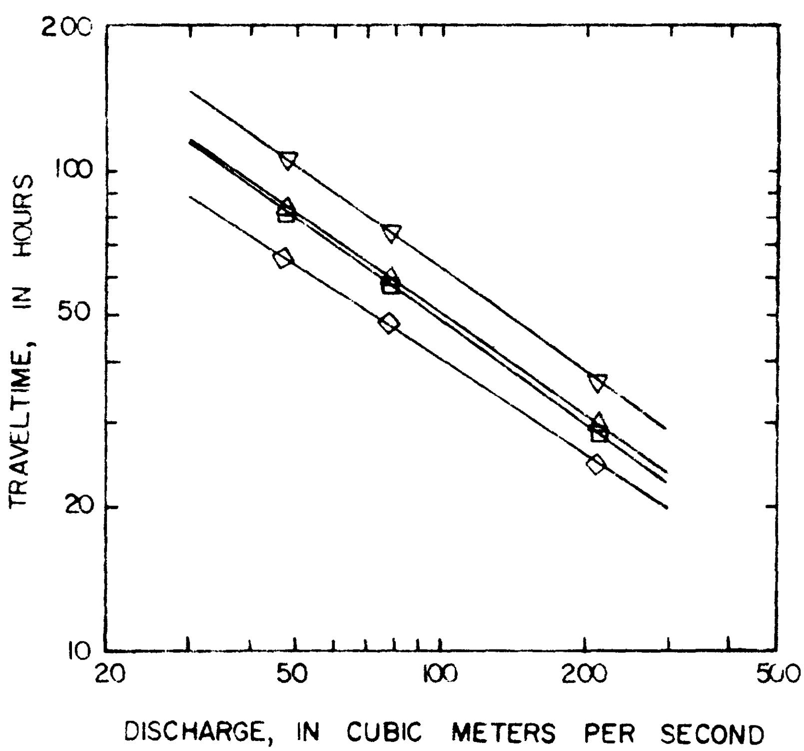

Figure 9.--Traveltime versus discharge for Rumford to Twin Bridges, Maine

Table 4.--Summary of traveltime data from the Livermore Falls injection site

Sampling Site	River distance[f] (Km)	Discharge (m^3/s)	Elapsed time from injection to: Leading edge (h)	Peak (h)	Centroid (h)	Trailing Edge (h)	Percent recovery	Variance (h^2)	Skewness
May 1980									
Twin Bridges	68.6	130	13.5	17.0	18.2	29.1	66	6.2	0.9
Turner Bridge	57.6	136[e]	25.5	29.5	31.8	40.2	67	8.6	.6
Gulf Island Dam	44.9	84[a]	52	107	132[b]	351	59[c]	3280[c]	1.3[c]
Deer Rips Dam[d]	42.8	93[a,e]	55	148	148[b]	362	67[c]	3970[c]	1.1[c]
Lisbon Falls[d]	13.2	92[a,e]	82	146	196[b]	396	61	4440[c]	.9[c]
August 1980									
Twin Bridges	63.6	56	16.2	21.0	23.4	33.8	62	14.3	.8
Turner Bridge	57.6	55[e]	49.7	70.2	66.2	89.9	59	60.9	.4
Gulf Island Dam	44.9	59[a]	105	192	282[b]	623	60[c]	12,100[c]	1.0[c]
Deer Rips Dam[d]	42.8	58[a,e]	132	207	299[b]	636	62[c]	12,500[c]	.9[c]
Lisbon Falls[d]	13.2	69[a,e]	190	247	360[b]	692	63[c]	14,000[c]	.7[c]
June 1981									
Twin Bridges	68.6	129	10.0	11.7	13.8	20.6	59	5.4	.8
Turner Bridge	57.6	127[e]	24.4	28.9	31.1	41.6	50	11.7	.8
Gulf Island Dam	44.9	117[a]	74	92	155[b]	354	61[c]	4030[c]	1.3[c]
Deer Rips Dam[d]	42.8	115[a,e]	80	94	163[b]	365	63[c]	4550[c]	1.2[c]
Auburn Gage[d]	34.3	123[a]	98	112	170[b]	375	59[c]	3880[c]	1.2[c]
Lisbon Falls[d]	13.2	119[a,e]	105	124	188[b]	395	60[c]	4670[c]	1.1[c]
Pejepscot Dam[d]	7.7	122[a,e]	119	143	199[b]	397	54[c]	4330[c]	.9[c]
Brunswick[d]	0.1	122[a,e]	122	146	204[b]	402	56[c]	4230[c]	.8[c]
September 1981									
Twin Bridges	68.6	87	12.7	15.4	18.1	27.9	68	10.2	.9
Turner Bridge	57.6	85[e]	35.3	45.6	47.6	64.0	56	26.9	.7

a Mean discharge while dye cloud is present
b Time to centroid of MVT curve
c Determined from MVT curve
d Overlap sites in Subreach C
e Estimated based on intervening drainage area
f River Distance above tide effect.

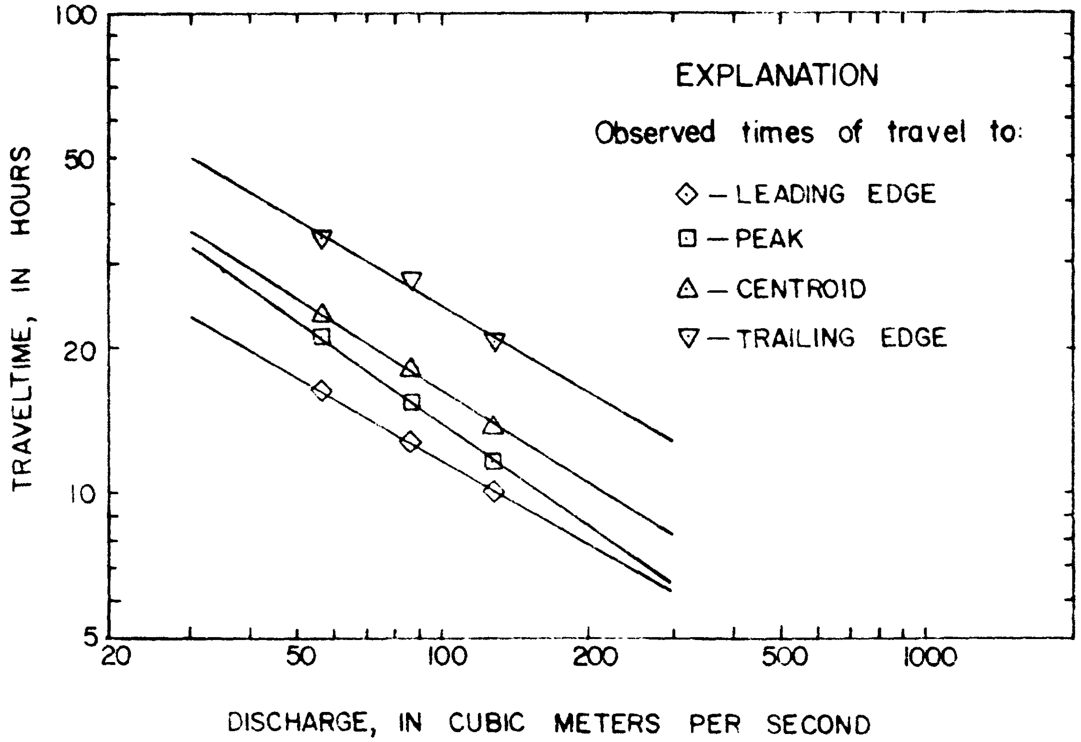

Figure 10.--Traveltime versus discharge for Livermore Falls to Twin Bridges, Maine

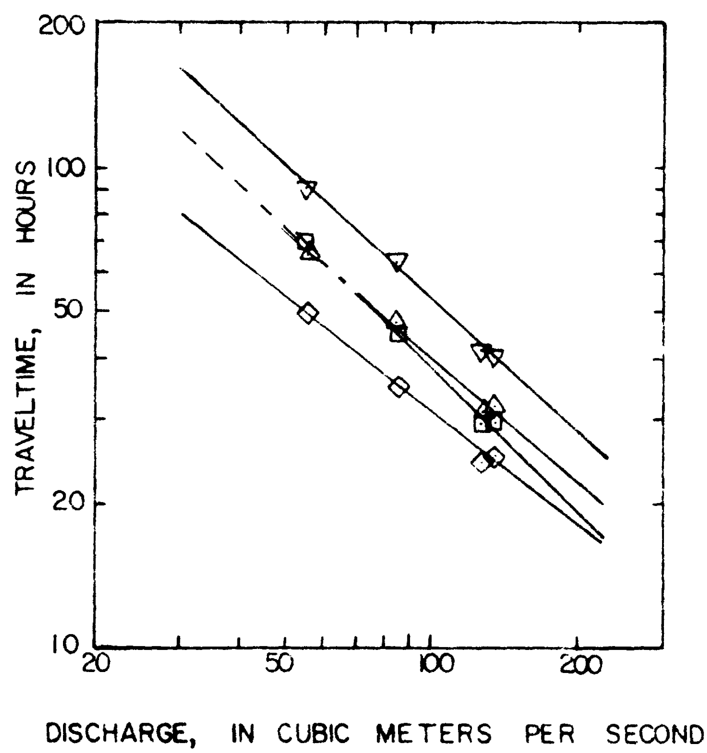

Figure 11.--Traveltime versus discharge for Livermore Falls to Turner Bridge, Maine

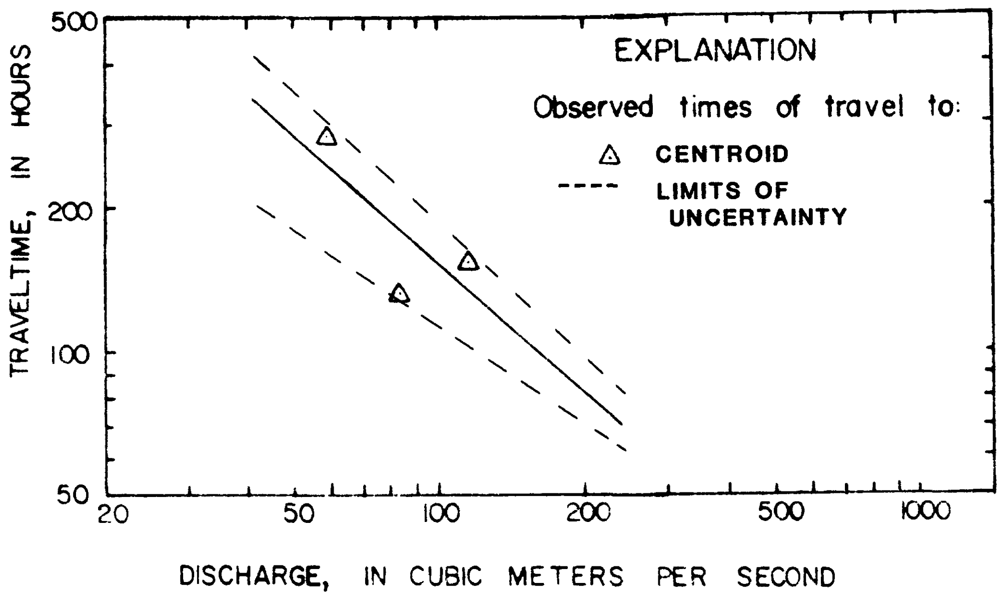

Figure 12.--Traveltime versus discharge for Livermore Falls to Gulf Island Dam, Maine

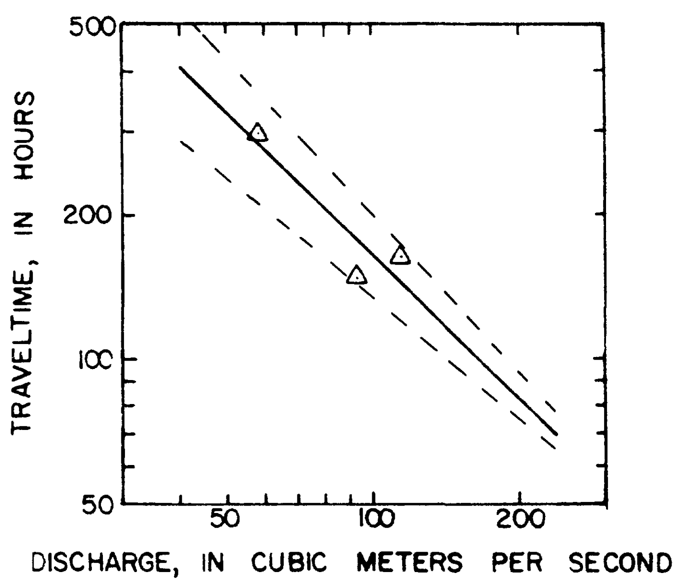

Figure 13.--Traveltime versus discharge for Livermore Falls to Deer Rips Dam, Maine

Mixing In Gulf Island Pond During June 1981 Study

Detailed cross-sectional sampling was conducted at Upper Narrows, Lower Narrows, Island, and Gulf Island Dam sections (fig.3). To facilitate calculations, each cross section was divided into 3-m thick layers from the water surface downward. Each layer was also divided into cells. The lateral cell boundaries were mid-way between sample points as shown in figures 14 to 17. Dye concentrations at any time was the average of all measurements within a cell, including its boundaries. Centroid arrival times for each cell are presented in table 5.

During the June 1981 study, the following was observed at the indicated sites:

Upper Narrows

The time to centroid for each cell shows little variation in traveltimes in the cross-section. See table 5 and compare with figures A-3 through A-6 in appendix A. The centroid arrived first at cell 12,1 (45.6 h) and last at cell 13,1 (53.7 h), a difference of 8 hours. The average time to centroid for the entire cross-section is 50.3 hours. This small difference is a good indication that complete mixing in the section was approached (Yotsukura and Fiering, 1964).

Lower Narrows

The time to centroid for each cell in table 5 shows a wider range in arrival times than those observed at Upper Narrows. The earliest centroid arrival time is in cell 10,3 (98.3 h) and the latest centroid arrival is in cell 10,5 (144 h), a difference of 45 hours. A review of the times to centroid indicates that the cloud arrived between the 3- and 9-m levels at approximately the same time. The average time for two layers is 101.5 hours. The times to centroid are about 10 hours later in the 0- to 3-m layer and the 9- to 12-m layer. The centroid arrival time in the bottom layer is approximately 40 hours later. This pattern indicates that the major portion of the dye cloud passed through the cross-section in a stratified manner with fairly even horizontal distribution within the layers.

Island section

This section is complicated by an island between vertical 5 and the rest of the cross-section. See figure 16. A comparison of centroid arrival times indicates that the horizontal uniformity evident at Lower Narrows had broken up at this point in the impoundment. See table 5. The earliest times to centroid occurred in cell 7,3 (120 h) and 7,4 (121 h). The latest centroid arrival time was near the bottom in cell 7,7 (186 h). The centroid arrival times increase with distance away from cell 7,3 and 7,4. Interestingly, the island does not seem to influence this pattern as the bulk of the cloud appears to be following the thalweg.

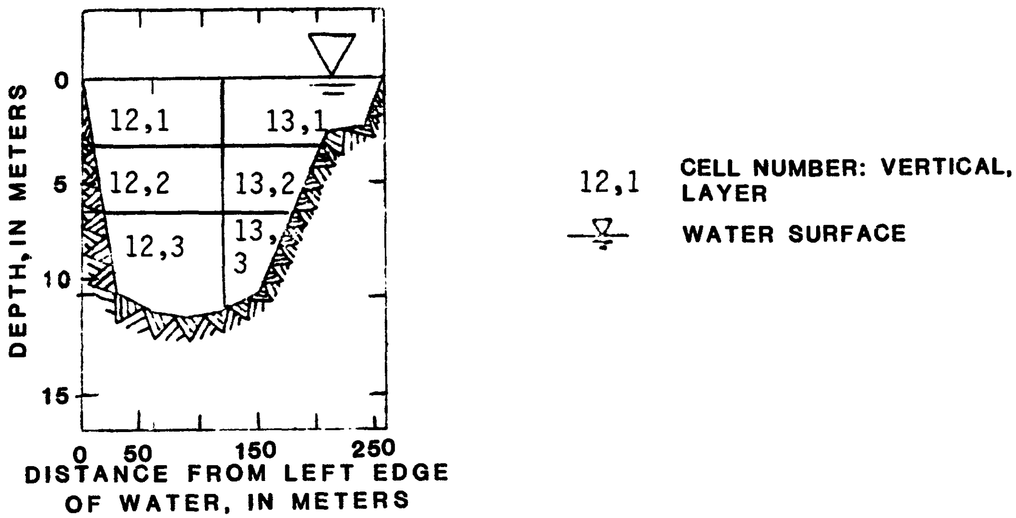

Figure 14.--Upper Narrows section showing cell division

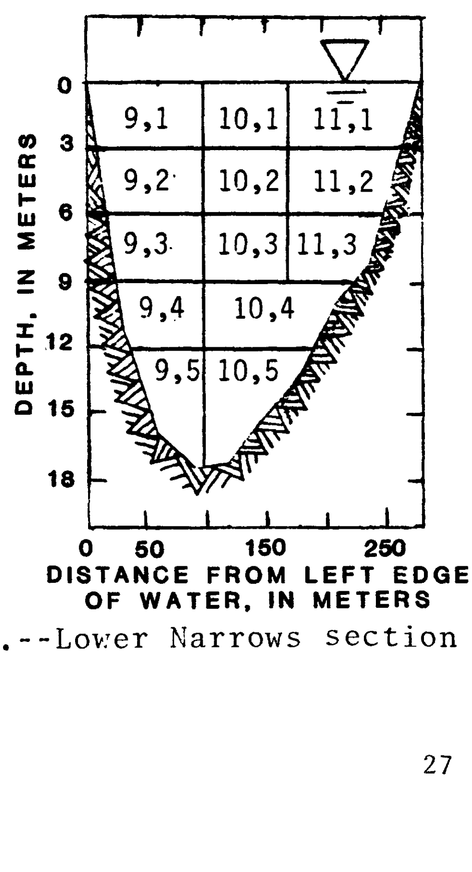

Figure 15.--Lower Narrows section showing cell division

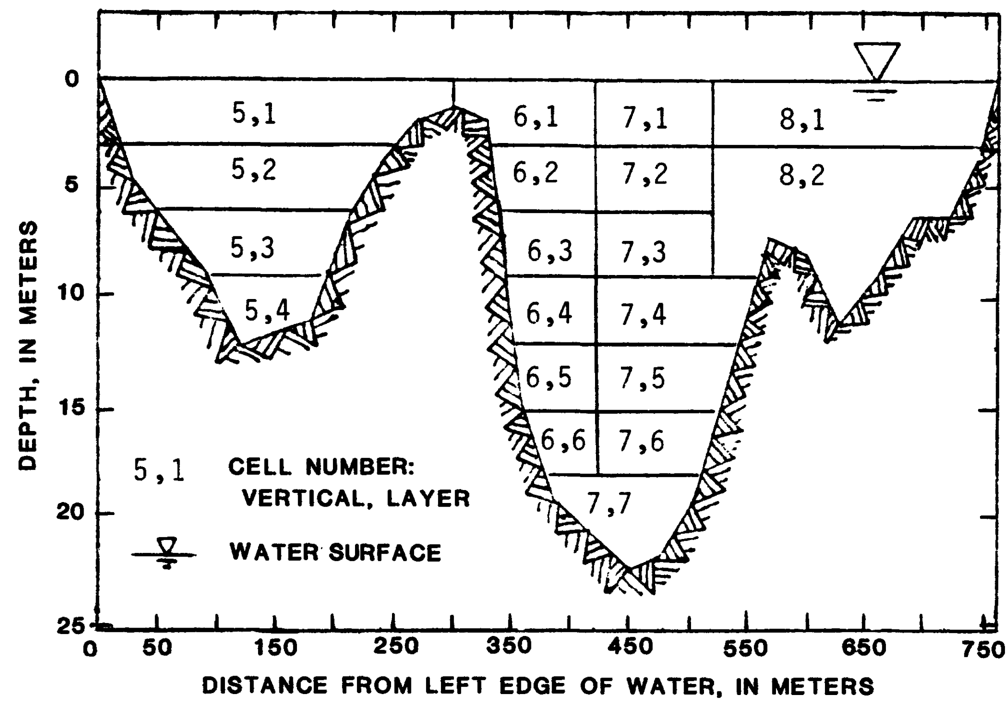

Figure 16.--Island section showing cell division

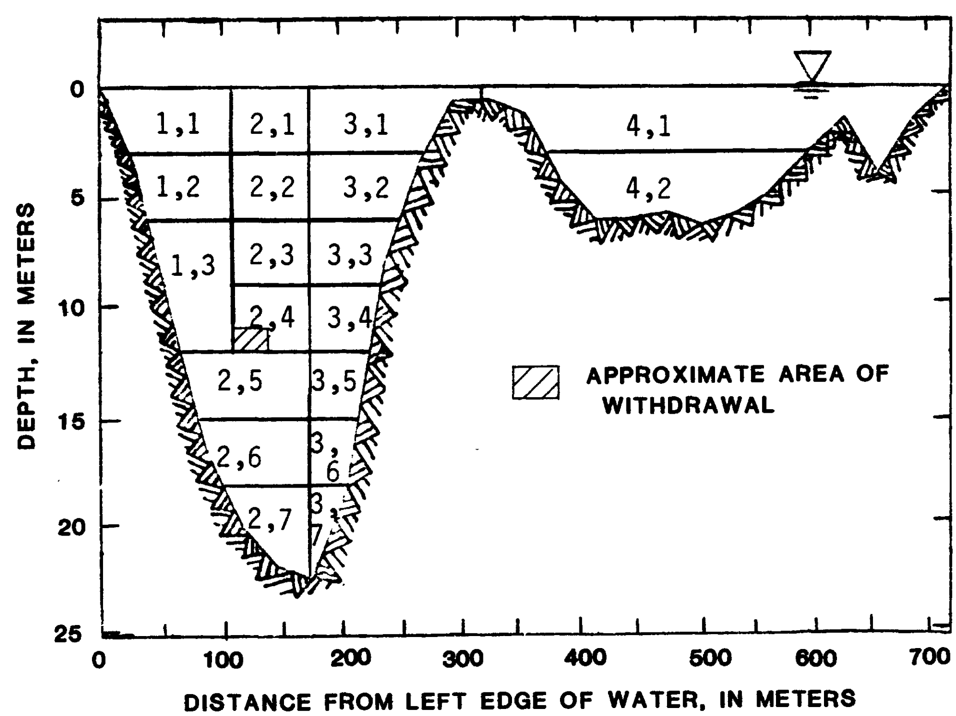

Figure 17.--Gulf Island Dam section showing cell division

Table 5 .--Times to centroid, Gulf Island Pond, June 1981

Cell (vertical, layer)	Time to centroid (h)	Cell (vertical, layer)	Time to centroid (h)	Cell (vertical, layer)	Time to centroid (h)
Upper Narrows		Island Section		Gulf Island Dam Section	
13,1	53.7	8,1	154	4,1	187
13,2	50.2	8,2	146	4,2	192
13,3	50.8	7,1	157	3,1	178
12,1	45.6	7,2	134	3,2	177
12,2	49.5	7,3	120	3,3	170
12,3	52.2	7,4	121	3,4	164
Lower Narrows		7,5	130	3,5	162
		7,6	155	3,6	171
11,1	109	7,7	186	3,7	219
11,2	100	6,1	154	2,1	177
11,3	103	6,2	143	2,2	169
10,1	108	6,3	131	2,3	155
10,2	101	6,4	132	2,4	151
10,3	98.3	6,5	139	2,5	155
10,4	116	6,6	155	2,6	167
10,5	144	5,1	160	2,7	206
9,1	108	5,2	161	1,1	177
9,2	103	5,3	145	1,2	172
9,3	104	5,4	133	1,3	173
9,4	112				
9,5	138				

Gulf Island Dam section

This section has an island to the west of the main channel and is only 150 m upstream from Gulf Island Pond (fig. 17). Referring to table 5, the centroid arrives earliest in cell 2,4 (151 h) which is about 4 hours earlier than the centroid arrival time at Gulf Island Dam outfall site (table 4) for the same study run. The longest centroid traveltime was in cell 3,7 (219 h) near the bottom. The centroid arrival times in the cells to the west of the island (4,1 and 4,2) are 10 and 15 hours slower than those at the same levels in the cells east of the island.

Selective withdrawal is said to have occurred when water withdrawn from a stratified impoundment comes only from the layer at the level of the intakes. According to Harleman (1982), selective withdrawal should occur at the level of the outlet of a reservoir when the densimetric Froude number (F_D) is less than the inverse of pi (0.318). The densimetric Froude number is defined as:

$$F_D = \frac{LQ}{HV}(g\varepsilon)^{-1/2} \tag{10}$$

where:
- L = reservoir length;
- Q = discharge;
- H = mean depth;
- V = volume;
- g = acceleration of gravity = 9.806 m/s^2; and
- ε = average normalized vertical density gradient.

For Gulf Island Pond during June 1981, Q was equal to 117 m^3/s and ε ranged from 4.8×10^{-5} /m to 1.6×10^{-5} /m. Accordingly F_D ranged from 0.28 to 0.45, indicating selective withdrawal may have occurred. In the case of Gulf Island Dam, withdrawal occurs at the turbine intakes in the east-center of the dam at a depth of 10-12 meters. The earliest centroid arrival time occurs at cell 2,4 corresponding to the location of the turbine intakes. The time-of-travel data for this cross section supports the theory that selective withdrawal did occur.

Summary

Reviewing the figures in appendix A confirms this pattern of mixing at each of the sites indicated. In addition, the cell and area of earliest centroid arrival time matches the cells observed to clear of dye the earliest. Referring to figures in appendix B, these areas also agree most closely with the 19.5°C cloud temperature observed passing Turner Bridge and Upper Narrows, again confirming the stratification-mixing patterns expected.

Mixing In Gulf Island Pond During September 1981 Study

In September 1981, complete clouds were observed at Upper Narrows and Lower Narrows before storm flows flushed the cloud from the impoundment. Centroid-time calculations for these two sections were conducted as before with the following results:

Upper Narrows

The mixing patterns are very similar to those observed in the June 1981 study run. Referring to table 6, the earliest arrival time is in cell 13,1 (67.4 h) and the latest is cell 12,3 (72.9 h), a difference of 5.5 hours. This again indicates near complete mixing at this site with the faster times for the elements near the surface.

Lower Narrows

Unlike the June 1981 study, the cloud does not seem to be well mixed laterally in the September 1981 study run. See table 6. The fastest times to centroid are in cells 10,3 and 10,4 (106 and 106 h) in the 6- to 12-m layers. The slowest time is in cell 9,1 (121 h). The centroid arrival times are consistently earlier in the center cells than in either of the side cells.

Summary

Dye concentration isopleths in appendix C show the mixing and stratification at Upper and Lower Narrows. The dye-tagged water passed through Upper Narrows fairly completely mixed. In passing through Lower Narrows section, it flowed through a stratified portion of the pond, moving first into the 6- to 12-m layers (figs. C-7 through C-10, appendix C) then going to the 9- to 15-m level at Island section. The cloud moved back into the 9- to 12-m level at Gulf Island Dam section. As discussed earlier, the dye cloud was washed out at this time and a complete picture of mixing patterns was unavailable. Comparison of appendixes C and D also confirms the mixing patterns due to temperature stratification as the cloud moved through the areas of the impoundment having a temperature near 19.0°C.

Subreach C

The most significant hydrologic characteristic of this 45-km subreach is the unsteady discharge from Gulf Island Dam. As the hydrographic information in appendix E (figs. E-7 through E-12) indicates, fluctuations of plus or minus 50 m^3/s commonly occur. The impact of discharge irregularity on traveltimes is considerable. In the case of leading-edge, peak, and trailing-edge times, irregularity in dye concentration due to fluctuating discharge makes the development of smoothed CVT curves difficult. Under these conditions, the CVT curve cannot be used to determine arrival time for these three cloud features.

MVT curves were used to determine centroid time. As the examples in appendix E demonstrate, the centroid of a MVT curve can be different from that of a CVT curve. Integrating the MVT curve to determine the centroid yields a more meaningful and correct value of traveltime. However, other uncertainties in the QVT relation arise from changes in sampler location, equipment failure, and problems in determining the discharge most representative of a dye cloud centroid.

Table 6. --Times to centroid, Gulf Island Pond, September 1981

Cell (vertical, layer)	Time to centroid (h)	Cell (vertical, layer)	Time to centroid (h)
Upper Narrows		Lower Narrows	
13,1	67.4	11,1	119
13,2	69.6	11,2	112
13,3	72.4	11,3	111
12,1	70.0	10,1	113
12,2	70.7	10,2	109
12,3	72.9	10,3	106
		10,4	106
		10,5	109
		9,1	121
		9,2	114
		9,3	113
		9,4	115
		9,5	117

Following the 1980 field season, several changes were made in the subreach C sampling design. The two 1980 dye studies, which included subreach C, began at Livermore Falls and tracked the dye cloud beyond Gulf Island Dam to Brunswick. These studies focused on subreach B, and they were designed to provide overlap into subreach C for subsequent studies. For 1981 three dye runs were planned to include subreach C. To further subdivide the 45 km of subreach C into more hydrologically homogeneous subreaches, two new sampling sites were added: the Geological Survey gage near Auburn (01059000), just downstream of the Lewiston-Auburn wastewater treatment facility and the mouth of the Little Androscoggin River; and Pejepscot Dam downstream of the discharge from the Lisbon Falls wastewater treatment facility at the head of the impoundment to be created by the new dam at Brunswick. In addition, the sampling location at Lisbon Falls was shifted upstream to ensure a more consistent water level and reliable record.

The 1981 sampling plan resulted in improved traveltime information. Time-of-travel data for the April 1981 study run, originating at Gulf Island Dam under steady-flow conditions, is summarized in table 7.

The two other 1981 study runs made in June and September started at Livermore Falls and were tracked after passing through subreach B. As mentioned previously, the September 1981 study was washed out by a flood wave passing through the study reach after the dye injection had been made. Only Deer Rips Dam and Lisbon Falls had more than two valid data sets, due to these problems and changes.

The summary of subreach C centroid traveltime data is presented in table 8. Because the subreach begins below Gulf Island Dam, all elapsed times in table 8 are referenced to that point. Thus, data for three of the four study runs had to be adjusted by subtracting elapsed times from Livermore Falls, the injection site, to Gulf Island Dam. Cumulative elapsed times from Livermore Falls are presented in table 4 for those study runs when the dye cloud was tracked through subreaches B and C. Traveltime for leading edge, peak, and trailing edge are not included in table 8 because these measurements from a CVT curve were difficult to interpret for unsteady discharges except for the April 1981 run. For this run, dye injection was at Gulf Island Dam under high discharge conditions which remained steady during the 2 days required for dye passage. The hydrologic characteristics and discharge regulation of this subreach, which made the interpretation of CVT lines more complex, also greatly influenced the QVT lines. When dye was injected at Livermore Falls, the cloud arriving at Gulf Island Dam was extended more than 11 days at an average discharge of 115 m^3/s. At 60 m^3/s, the cloud passage time exceeded 3 weeks. Even without the discharge fluctuations associated with regulation, it would be unlikely to have constant discharge over such an extended passage time. These flow conditions render meaningless the use of mean discharge values in association with leading edge, peak, and trailing edge traveltimes. Thus, only centroid arrival times determined from MVT equations are useful for QVT analysis, which are presented in figures 18 through 21. The scatter of data in figure 18 is due to differences in the degree of mixing of the dye clouds measured at Deer Rips Dam. For three of the data points, the dye clouds had traveled through Gulf Island Pond with adequate time for complete mixing. In the fourth case, however, the dye was injected at Gulf Island Dam and the short distance to Deer Rips Dam (2.1 km) precluded complete mixing at the site.

Table 7 .--Summary of traveltime data from the Gulf Island Dam injection site

Sampling Site	River distance[a] (Km)	Discharge (m^3/s)	Elapsed time from injection to: Leading edge (h)	Peak (h)	Centroid (h)	Trailing Edge (h)	Percent recovery	Variance (h^2)	Skewness
April 1981									
Deer Rips Dam	42.8	167[b]	2.0	2.7	3.8	8.0	74	1.5	1.0
Auburn Gage	34.3	190[b]	8.3	11.1	12.6	19.6	56	5.8	.8
Lisbon Falls	13.2	189[b]	20.2	25.2	26.5	35.2	58	8.8	.5
Pejepscot Dam	7.7	191[b]	24.2	30.2	31.7	42.3	60	11.7	.6
Brunswick	0.1	193[b]	28.2	34.8	36.6	48.4	59	14.0	.7

[a] River distance above tide effect.
[b] Estimated based on intervening drainage area.

Table 8.--Summary of centroid traveltime from Gulf Island Dam for subreach C

Sampling Site	River distance[a] (Km)	August 1980 Dis-charge (m^3/s)	August 1980 Cen-troid (h)	May 1980 Dis-charge (m^3/s)	May 1980 Cen-troid (h)	June 1981 Dis-charge (m^3/s)	June 1981 Cen-troid (h)	April 1981 Dis-charge (m^3/s)	April 1981 Cen-troid (h)
Deep Rips Dam	42.8	58[b]	17	93[b]	16	115[b]	13	167[b]	3.8
Auburn Gage	34.3					123	20	190	12.6
Lisbon Falls	13.2	69[b]	78	92[b]	64	119[b]	38	189[b]	26.5
Pejepscot Dam	7.7					122[b]	49	191[b]	31.7
Brunswick	.1					122	54	193	36.6

[a] River distance above tide effect

[b] Estimated based on intervening drainage area

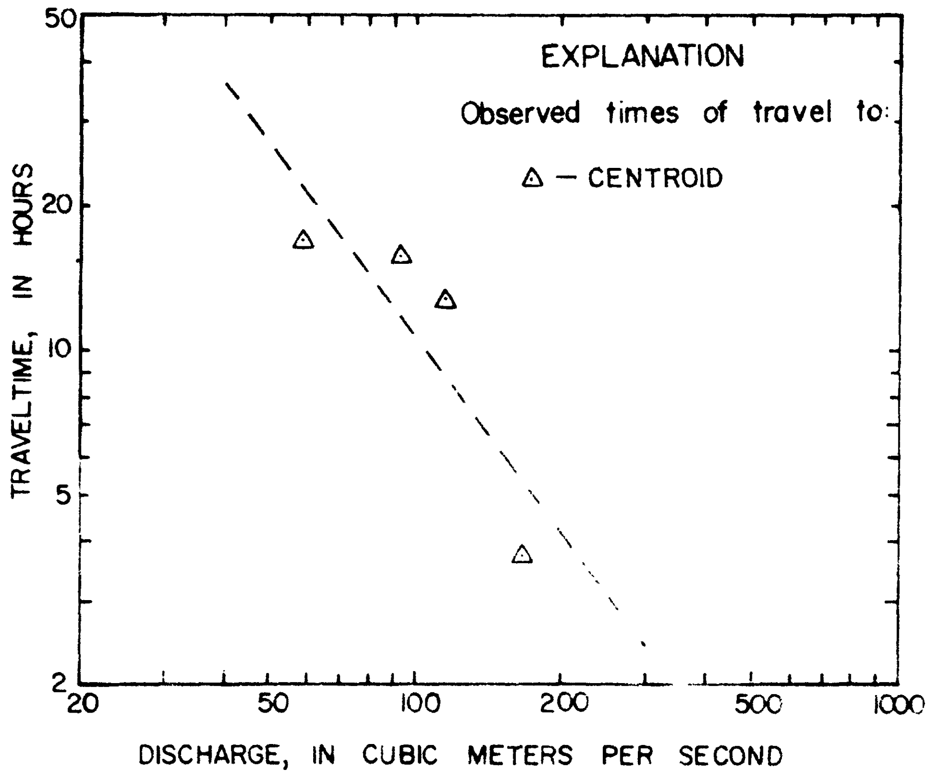

Figure 18.--Traveltime versus discharge for Gulf Island Dam to Deer Rips Dam, Maine

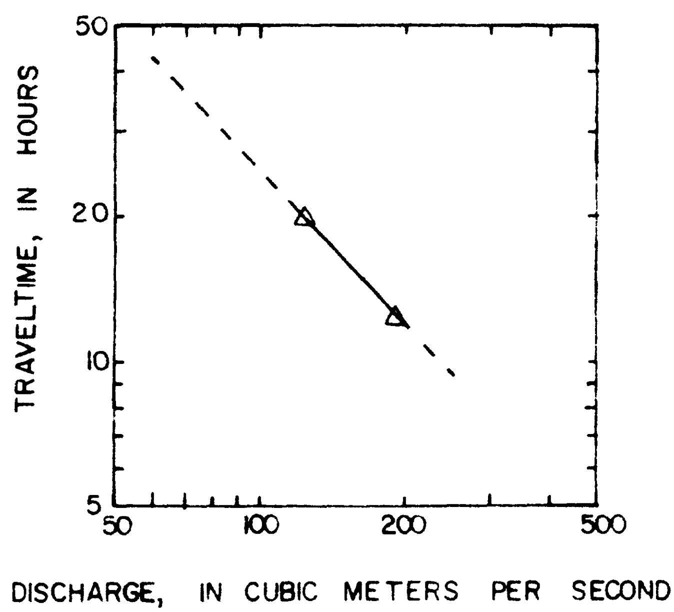

Figure 19.--Traveltime versus discharge for Gulf Island Dam to survey gage near Auburn, Maine

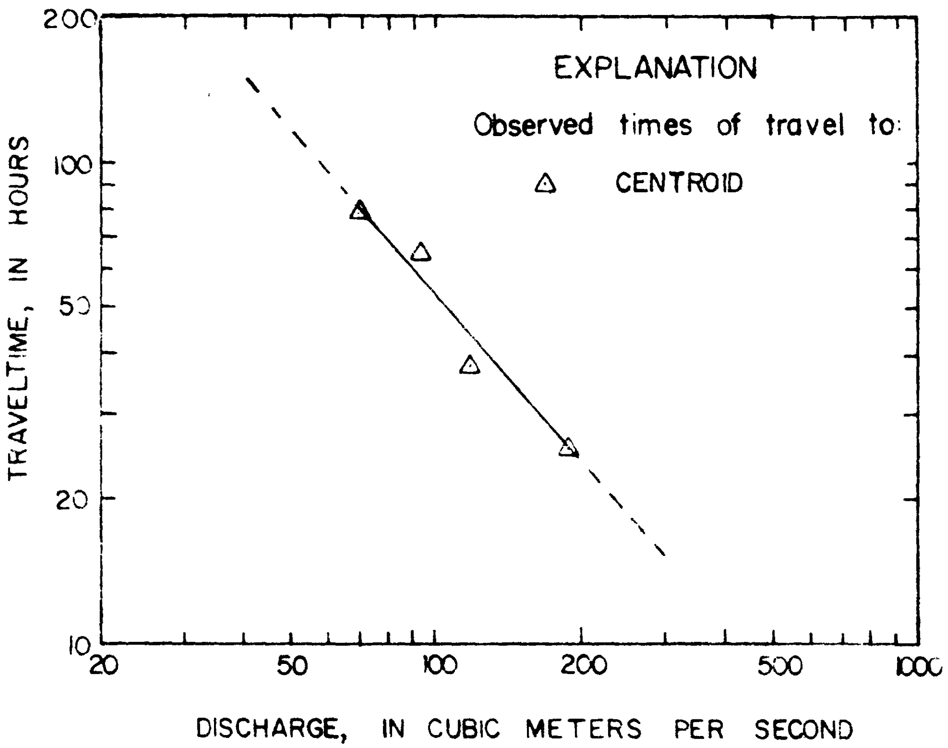

Figure 20.--Traveltime versus discharge for
Gulf Island Dam to Lisbon Falls, Maine

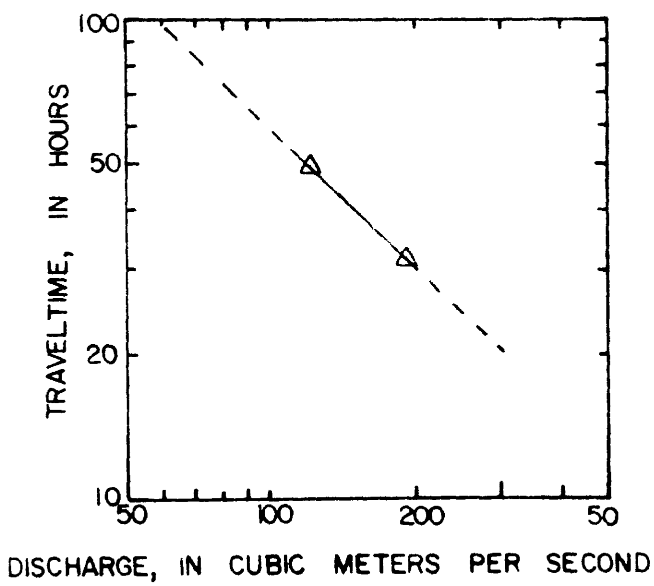

Figure 21.--Traveltime versus discharge for
Gulf Island Dam to Pejepscot Dam , Maine

Distance Versus Time

A summary of time-of-travel data is given in figure 22 by plotting centroid traveltime versus distance between sampling points and injection site. The centroid traveltimes are determined from the appropriate QVT curve at each of the sites. Discharges shown in figure 22 are based at an appropriate index gage in the reach. Above Gulf Island Dam, the survey gage at Rumford was used as the index, and below Gulf Island Dam the survey gage near Auburn was used. From the relationships illustrated in figure 22, centroid traveltime can be estimated to any point in the reach. Centroid velocity can also be estimated by determining the inverse of the line's slope for the desired discharge level wanted. Dashed lines illustrate the centroid traveltime through the lower reach of Gulf Island Pond and are an approximation of traveltime versus distance. The velocity of a dye cloud in the pond is highly variable depending upon stratification and mixing patterns. Because of uncertainties in traveltime through the pond, the data are shown as a dashed line in figure 22.

The movement of dissolved waste materials would be very similar to that of a dye cloud. It would be expected that materials would move swiftly from Rumford to Twin Bridges. Its velocity would slow between Twin Bridges and Turner Bridge and would slow even more dramatically between Turner Bridge and Gulf Island Dam. Once through Gulf Island Pond, waste materials would move rapidly downstream to Pejepscot Dam though not as swiftly as upstream of the Twin Bridges. The larger the discharge, the smaller the impact the eight run-of-the-river impoundments have on centroid traveltimes. Pollutants may spend about as much time in Gulf Island Pond as in the rest of the study reach.

Longitudinal Dispersion

Longitudinal dispersion was determined from equation 9 (Tsai and Holley, 1979). For this study, the mean velocity in each subreach was calculated from the centroid traveltime of CVT curves. Likewise, variance was determined from CVT curves.

Dispersion coefficients were calculated for subreaches A and C. Subreach B was omitted because of the limited number of sampling locations and lack of complete mixing in Gulf Island Pond. Three complete dye runs through subreach A were observed: June and September 1980 and April 1981. In subreach C there were two complete dye runs: April and June 1981. A third run in September 1981 was lost due to heavy rains and flood-stage discharge. Plots of $V^3\sigma_t^2/2$ against distance below injection are shown in figures 23 through 26. Dispersion coefficients were determined from the slope of the least-squared regression line. Results are summarized in table 9. No dispersion is reported for the subreach C dye cloud of June, 1981 because of the low correlation coefficient. Inconsistencies in variance data were observed during the run, possibly due to problems in defining the dye cloud's leading and trailing edges. Correlation coefficients ranging from 0.9279 to 0.9857 were observed for the other four runs.

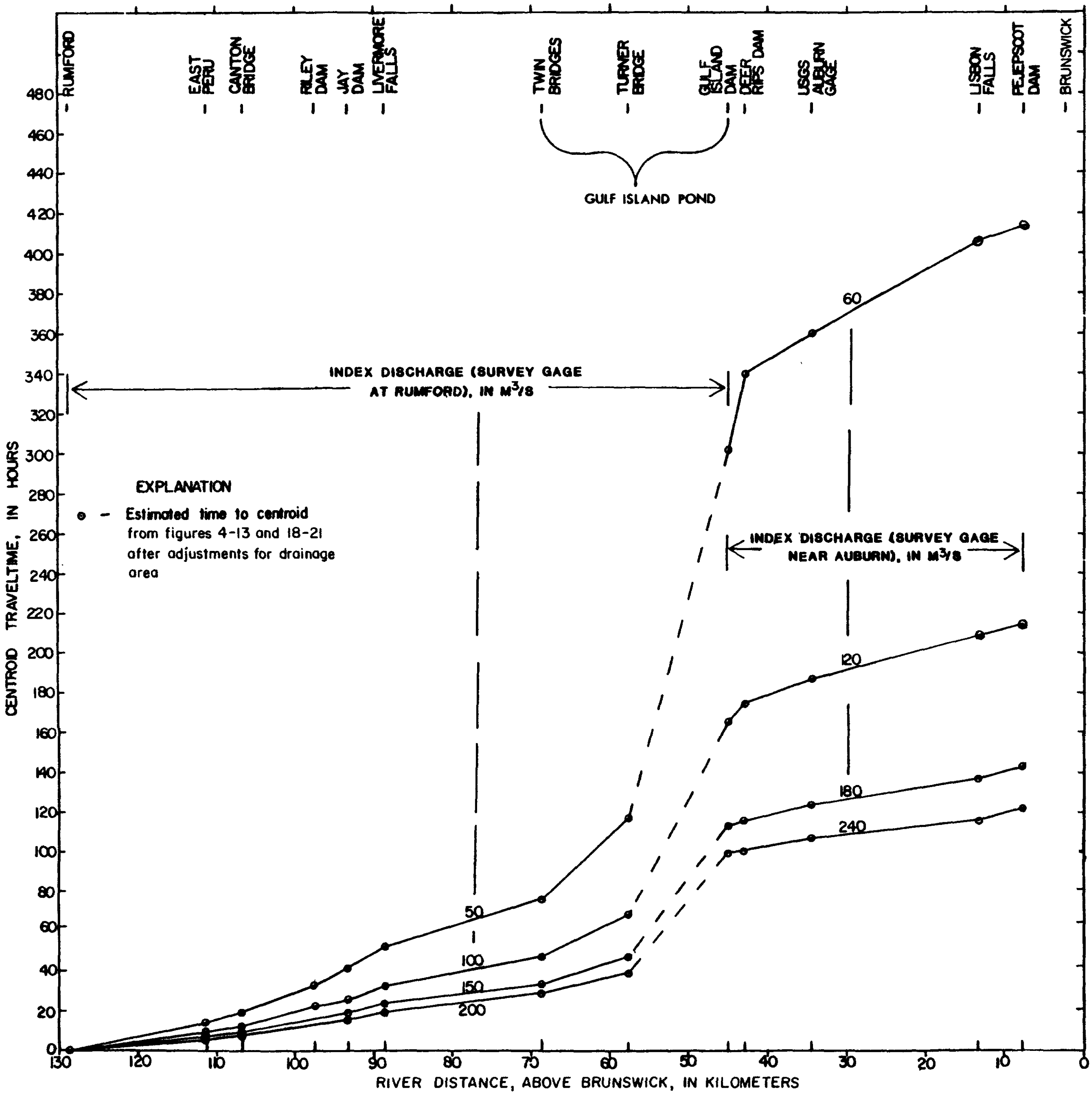

Figure 22.--Centroid traveltime versus distance above Brunswick, Maine

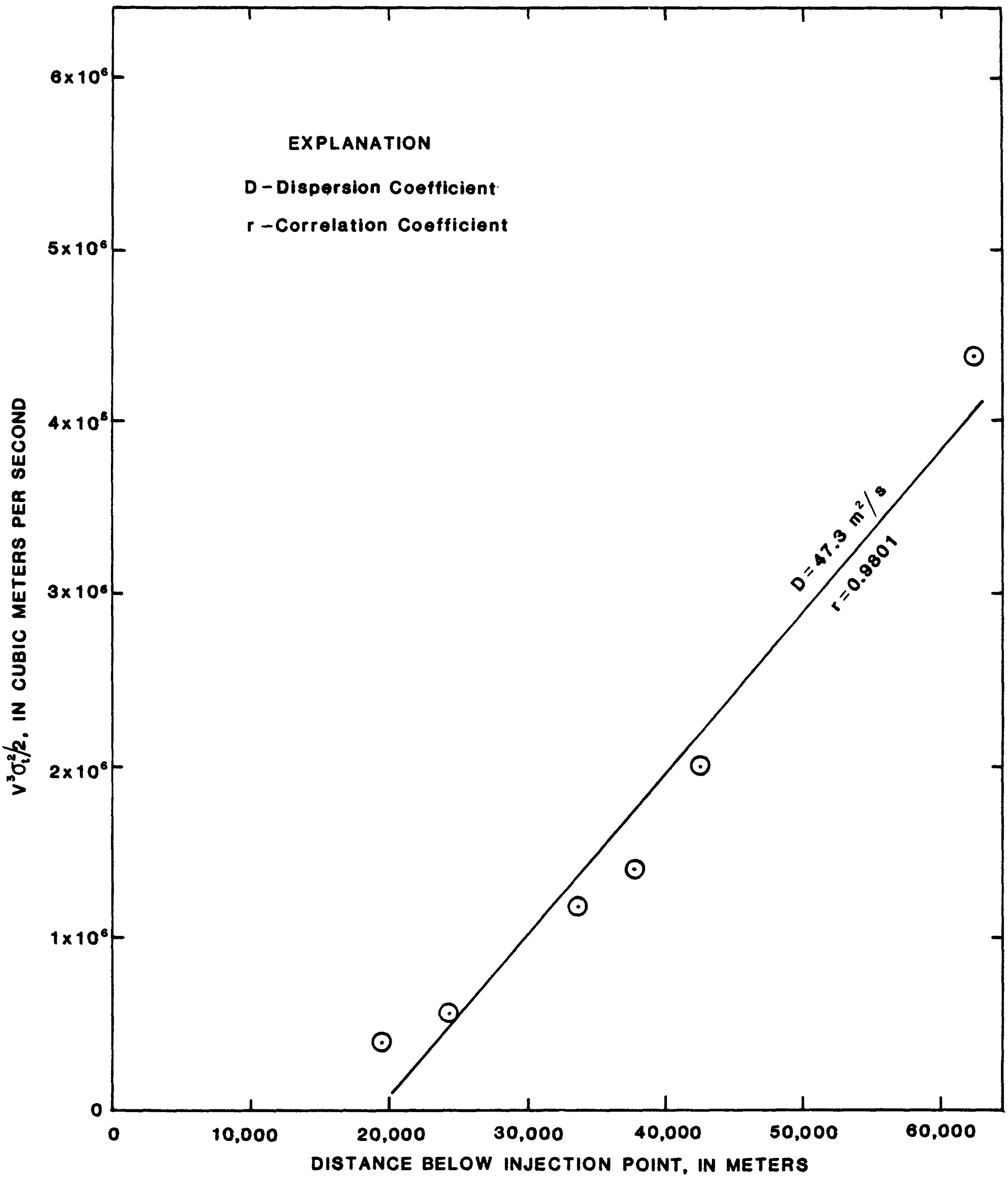

Figure 23.--Determination of the longitudinal dispersion coefficient in subreach A, June 1980

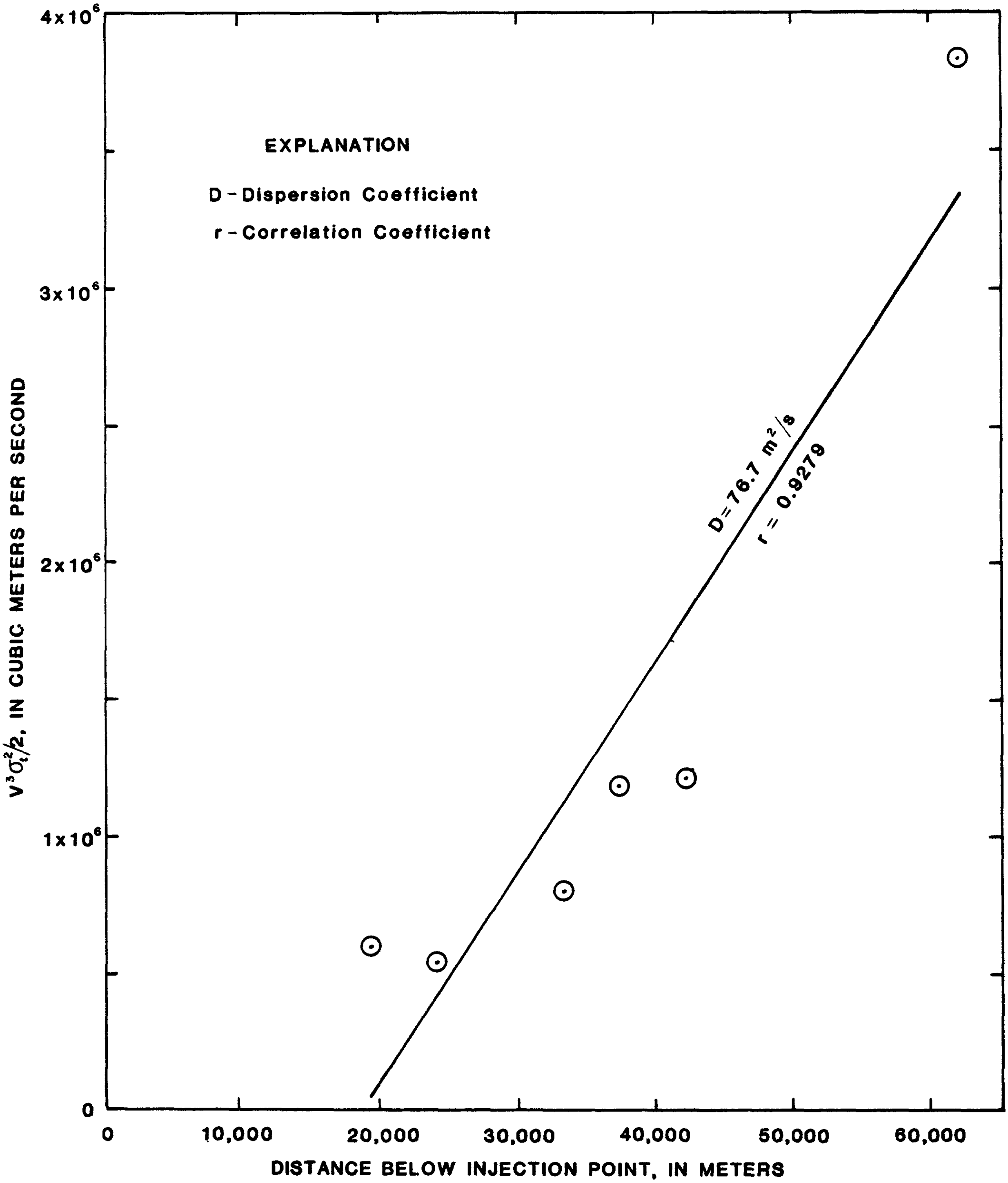

Figure 24.--Determination of the longitudinal dispersion coefficient in subreach A, September 1980

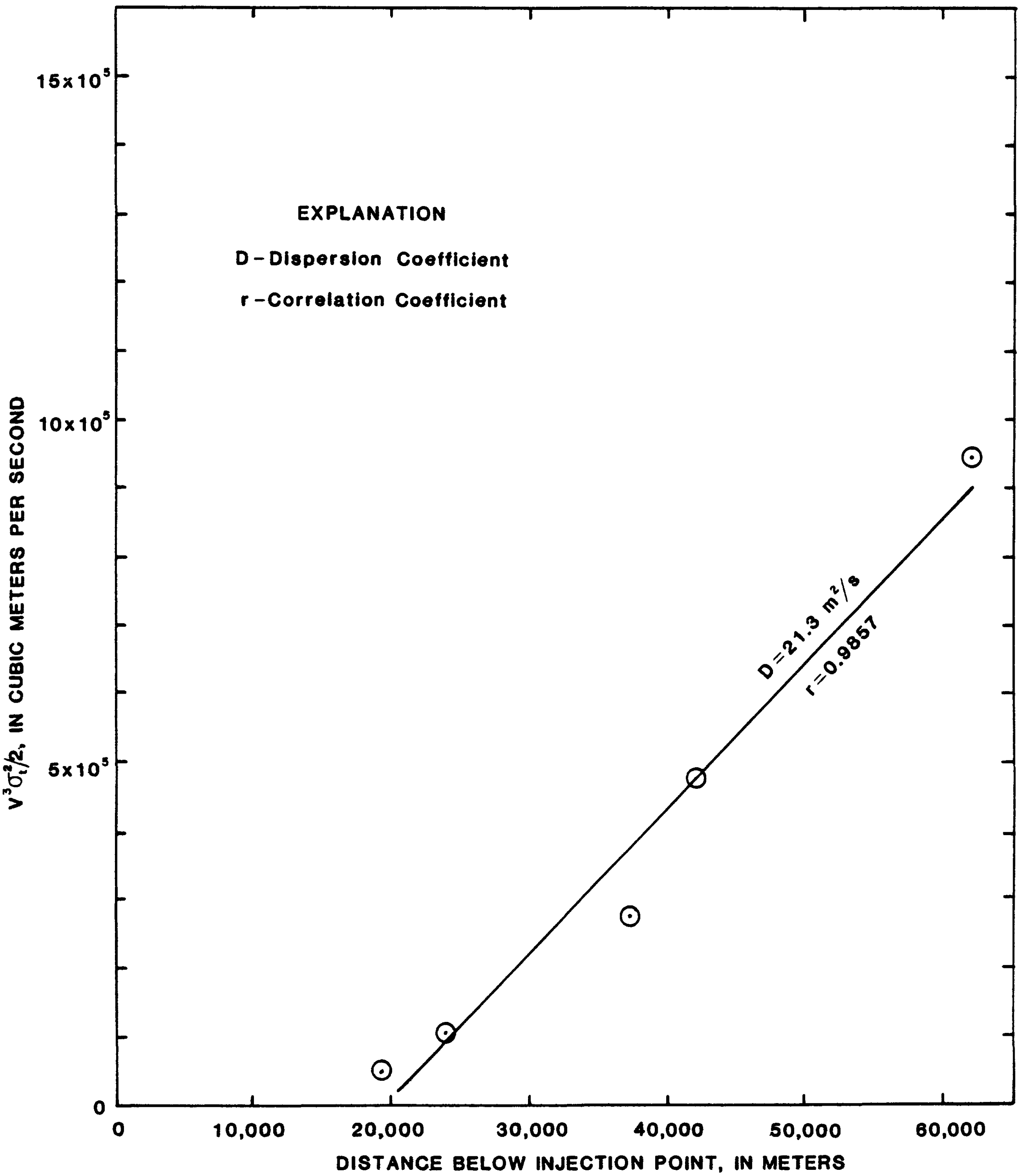

Figure 25.--Determination of the longitudinal dispersion coefficient in subreach A, April 1981

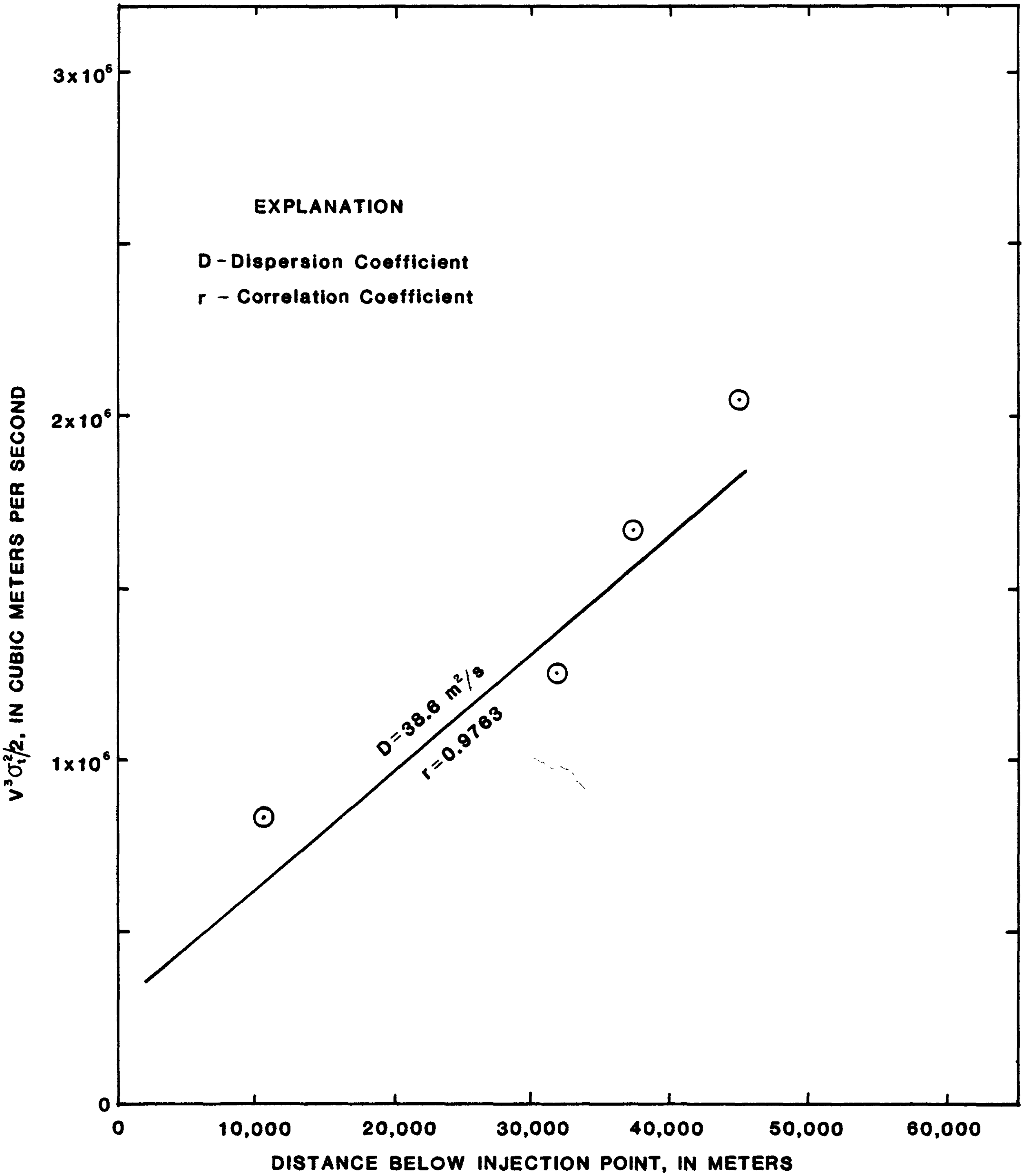

Figure 26.--Determination of the longitudinal dispersion coefficient in subreach C, April 1981

Table 9.--Longitudinal dispersion coefficient data

Subreach	Subreach length (km)	Date of study (month, year)	Mid-subreach discharge (m /s)	Longitudinal dispersion coefficient (m /s)	Correlation coefficient
A	60.1	June, 1980	74	47.3	0.9801
		Sept., 1980	45	76.7	.9279
		Apr., 1981	204	21.3	.9857
C	37.2	Apr., 1981	190	38.6	.9763
		June, 1981	Varied (123)	--	.0761

Taylor (1954) states that the dispersion coefficient may be independent of discharge within certain bankfull flows. However, the data in table 9 show an inverse relation between dispersion coefficient and discharge through subreach A. Although the number of data points is limited (three), the high correlation of 0.93 suggests that the relation is a real one. More study would be necessary to determine the significance of the relation.

SUMMARY

Centroid traveltime versus distance relationships for the 123 km river reach from Rumford to Pejepscot Dam, Maine ranged from approximately 120 hours at 240 m^3/s to 410 hours at 60 m^3/s. As expected, the lowest velocities occurred in Gulf Island Pond in which traveltime estimates are only approximate. A concept of mass flow versus time, in the place of concentration versus time, was used to determine dye cloud centroid traveltime to five sites in the reach of the Androscoggin River below Gulf Island Dam having unsteady flow. In the steady flow reaches above Gulf Island Dam, mass flow versus time analyses are identical to concentration versus time methods. Traveltime versus discharge curves were developed for 12 sites in the study area. Two curves (figs. 12 and 13) were developed for a cloud passing through Gulf Island Pond and ending at Gulf Island Dam and Deer Rips Dam but they are not as reliable as other curves because the pathways through a stratified lake are variable. Longitudinal dispersion coefficients ranging from 21.3 m^2/s to 76.7 m^2/s were determined in four study runs. The dispersion coefficient in subreach A varies inversely with discharge.

Observed dye mixing patterns in Gulf Island Pond, during the 1981 study runs indicated stratification occurred when inflowing water, at 19.5°C in June and 19.0°C in September, sought its own density level. The reservoir had a temperature span (bottom to top) of 16°C to 22°C in June and 18.5°C to 20°C in September 1981. Densimetric Froude numbers ranging from 0.28 to 0.45 for Gulf Island Pond in June 1981 indicated that stratification and selective withdrawal may occur (Harleman, 1982) which was confirmed by observation. Comparison of centroid traveltimes with graphic representations of dye-concentration isopleths and isotherms over time in Gulf Island Pond indicates that the dye moved fastest at that level having a temperature nearest the temperature of the inflowing water.

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APPENDIX A.--ISOPLETHS OF DYE CONCENTRATION IN GULF ISLAND POND JUNE 1981

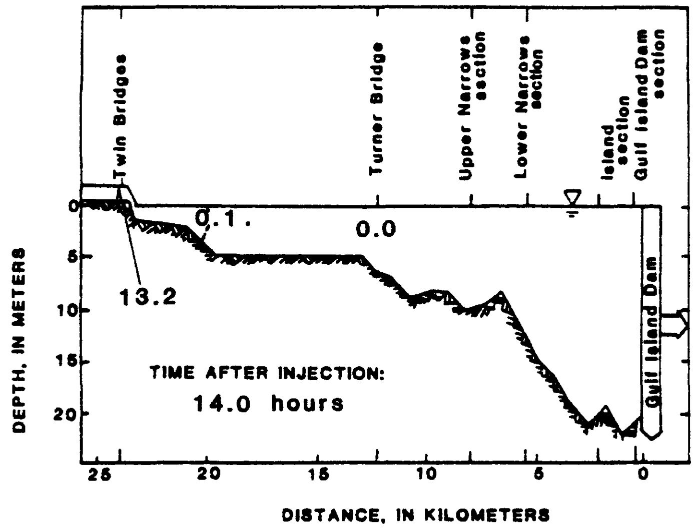


Figure A-1.--Isopleths of dye concentration in Gulf Island Pond, June 12, 1981

EXPLANATION

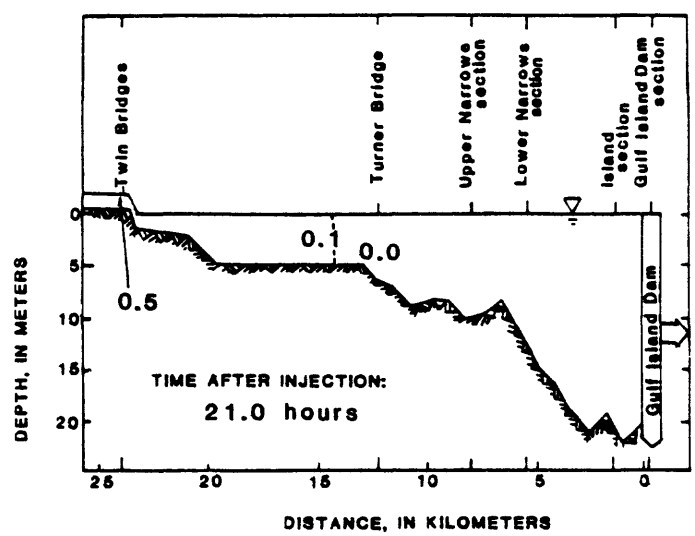
Water surface

— — Line of estimated equal dye concentration, in micrograms per liter

Streambed

Outflow dye concentration, in micrograms per liter

A single uncontoured value indicates equal dye concentration for the entire section in micrograms per liter



Note: Peak between Twin Bridges and Turner Bridge

Figure A-2.--Isopleths of dye concentration in Gulf Island Pond, June 12, 1981

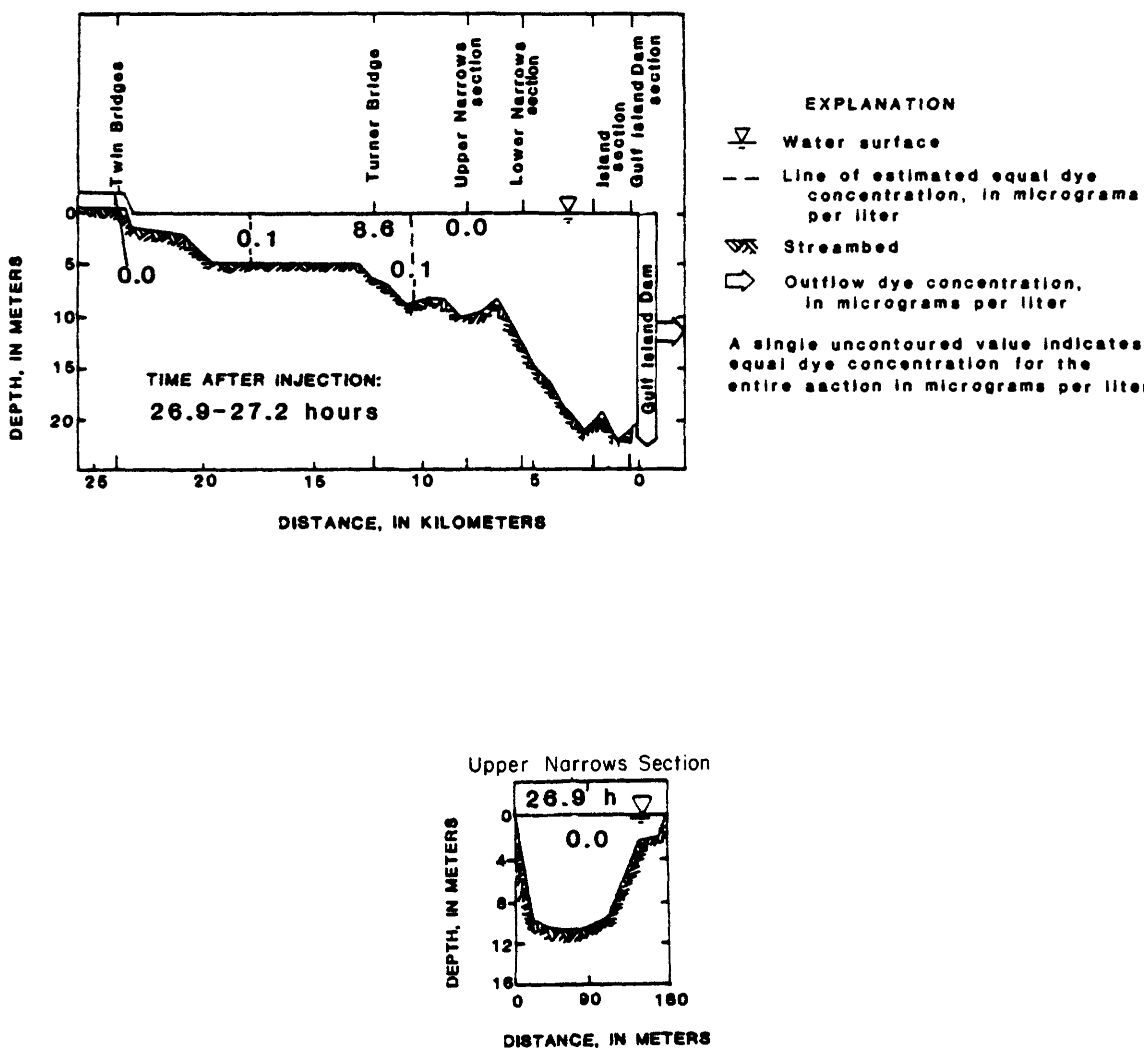
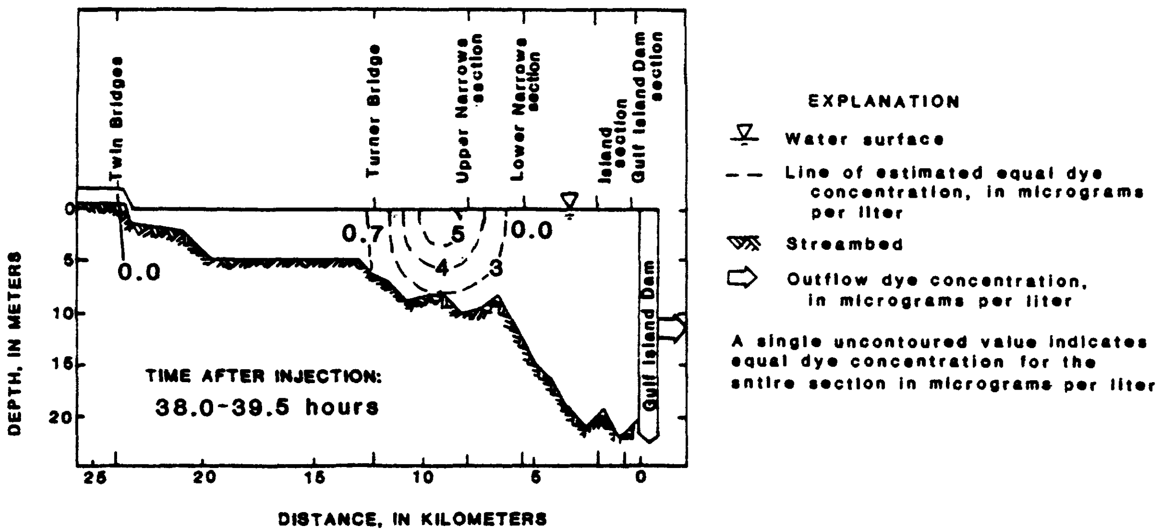


Figure A-3.--Isopleths of dye concentration in Gulf Island Pond, June 12, 1981



Note: Peak between Twin Bridges and Turner Bridge.

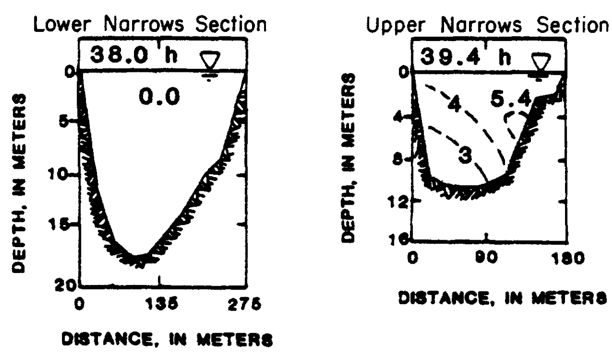


Figure A-4.--Isopleths of dye concentration in Gulf Island Pond, June 13, 1981

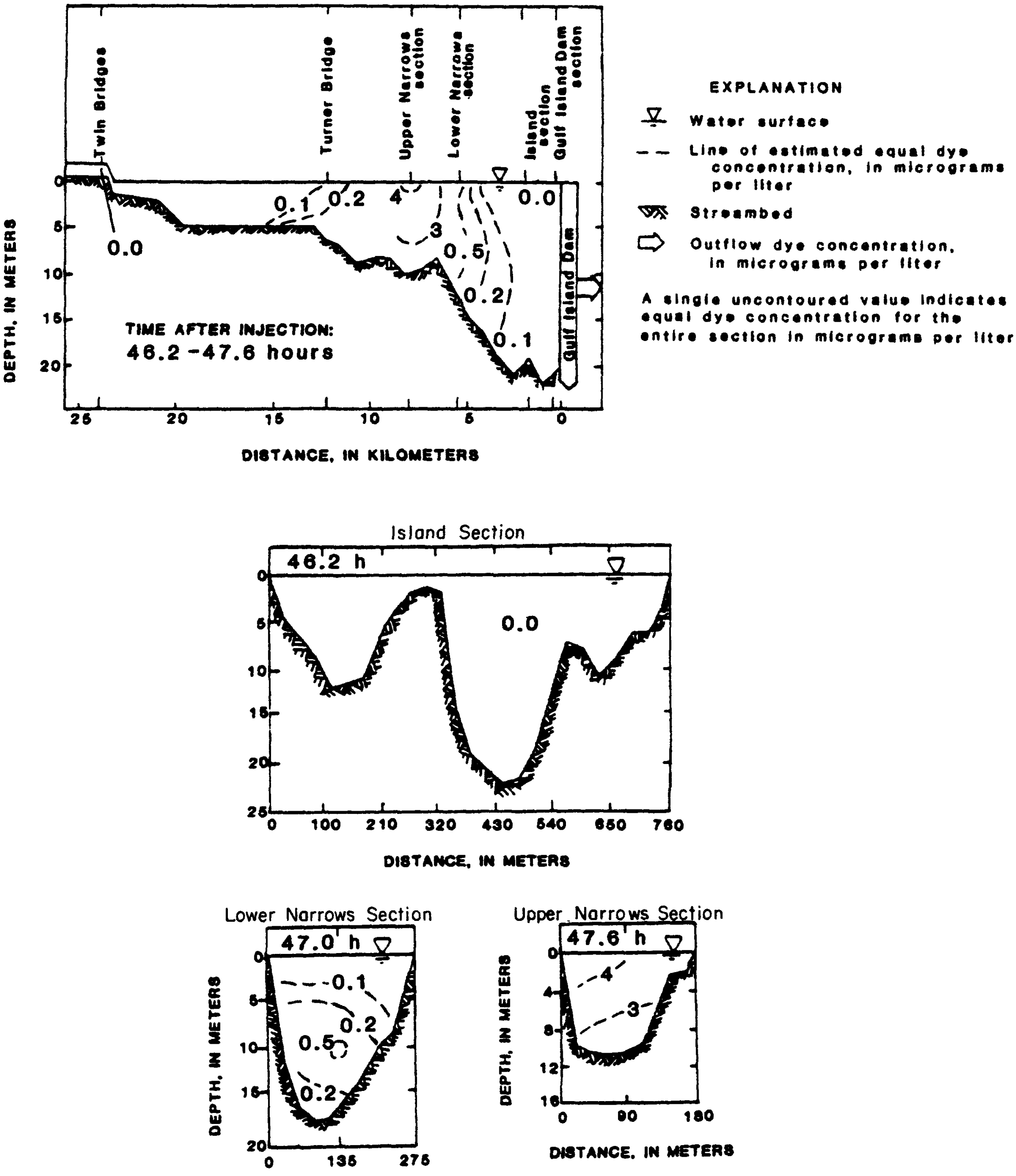


Figure A-5.--Isopleths of dye concentration in Gulf Island Pond, June 13, 1981

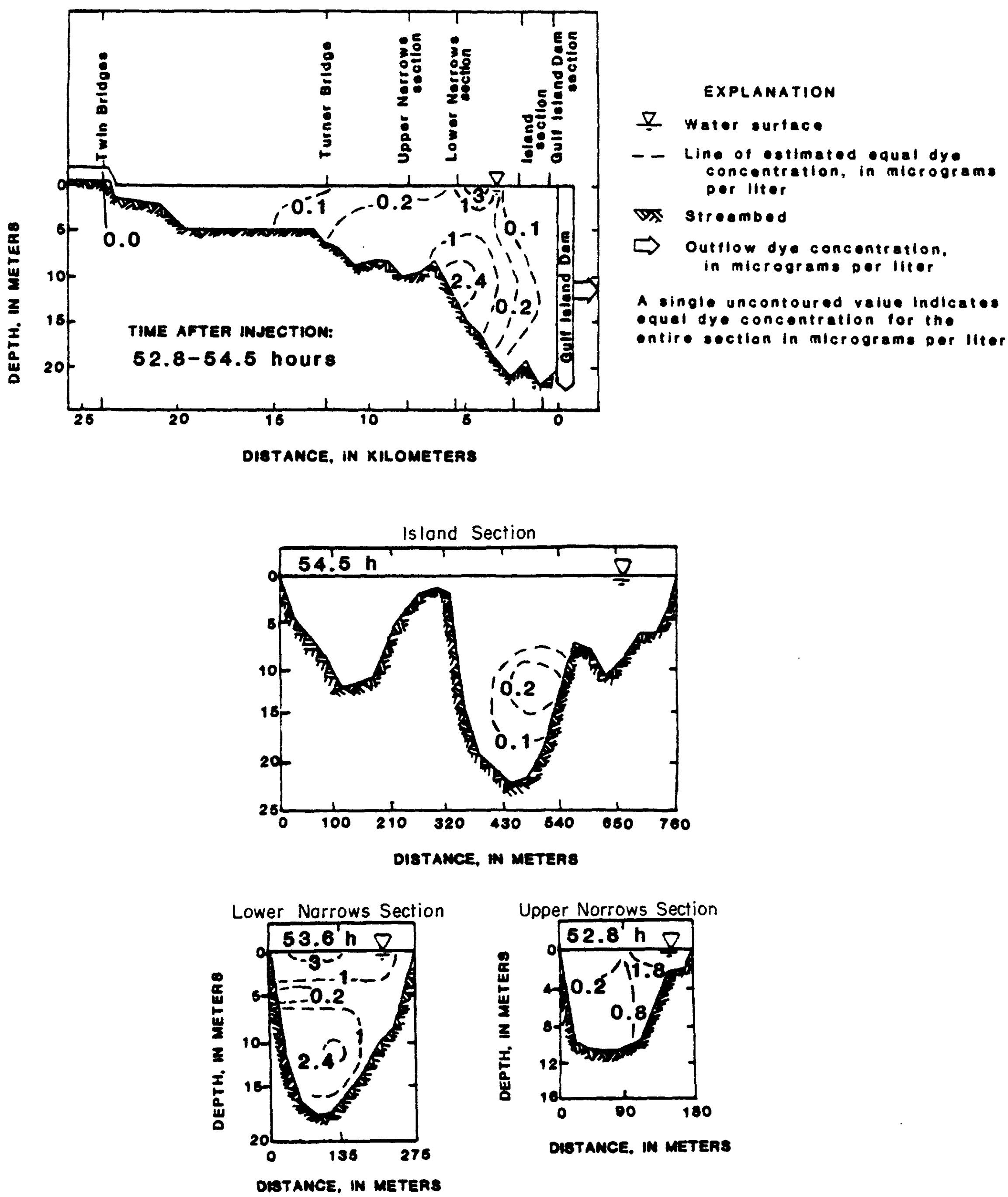


Figure A-6.--Isopleths of dye concentration in Gulf Island Pond, June 13, 1981

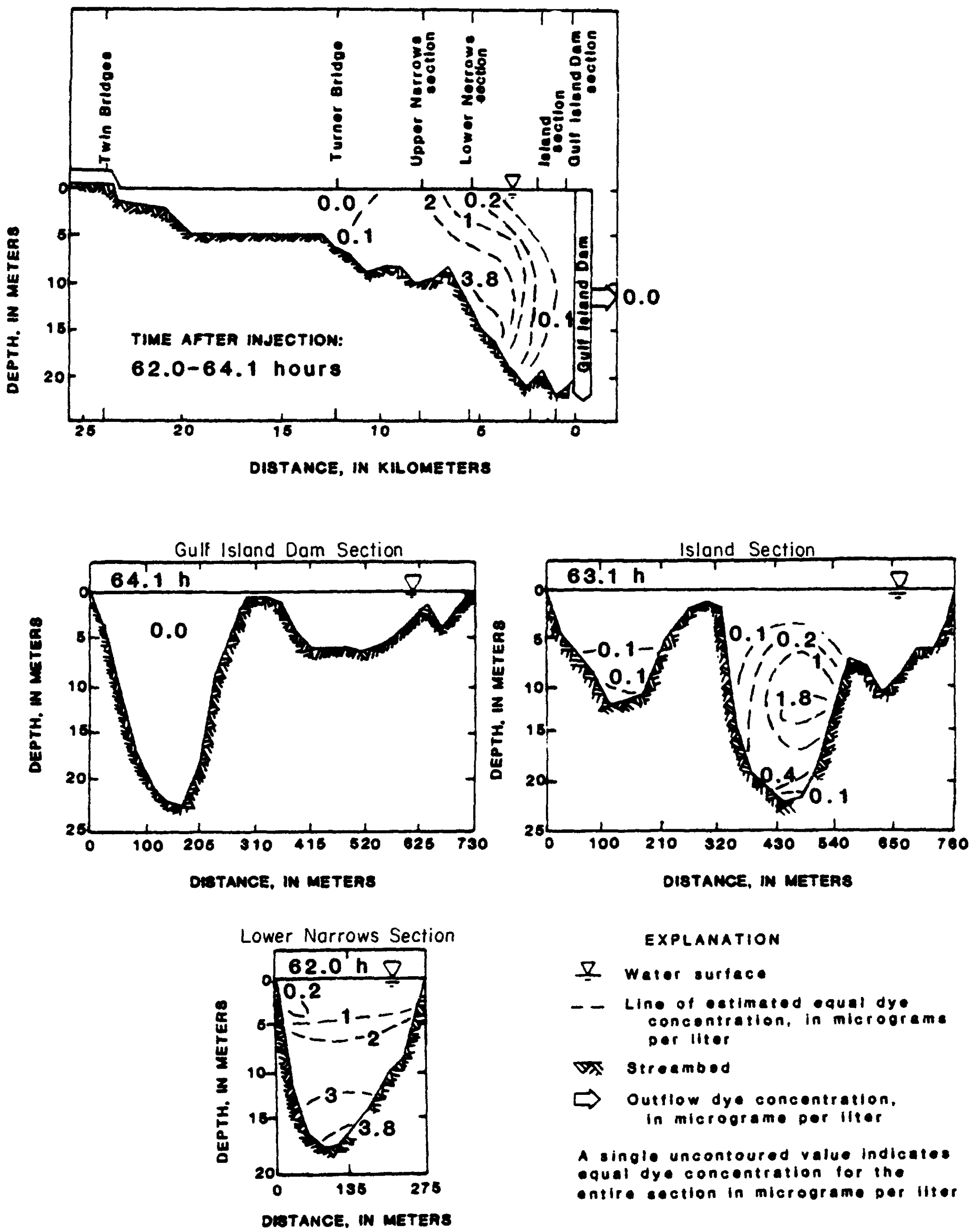


Figure A-7.--Isopleths of dye concentration in Gulf Island Pond, June 14, 1981

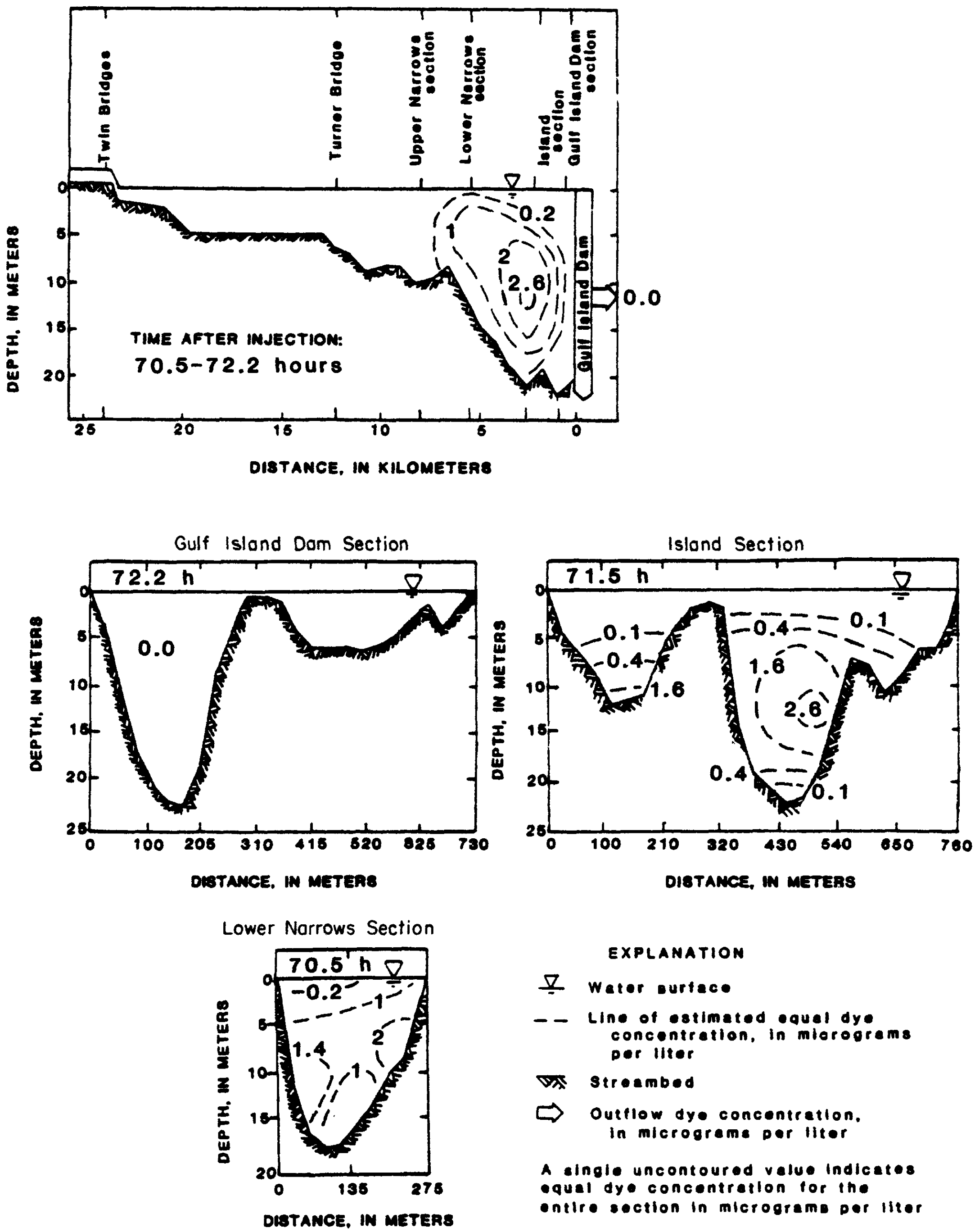


Figure A-8.--Isopleths of dye concentration in Gulf Island Pond, June 14, 1981

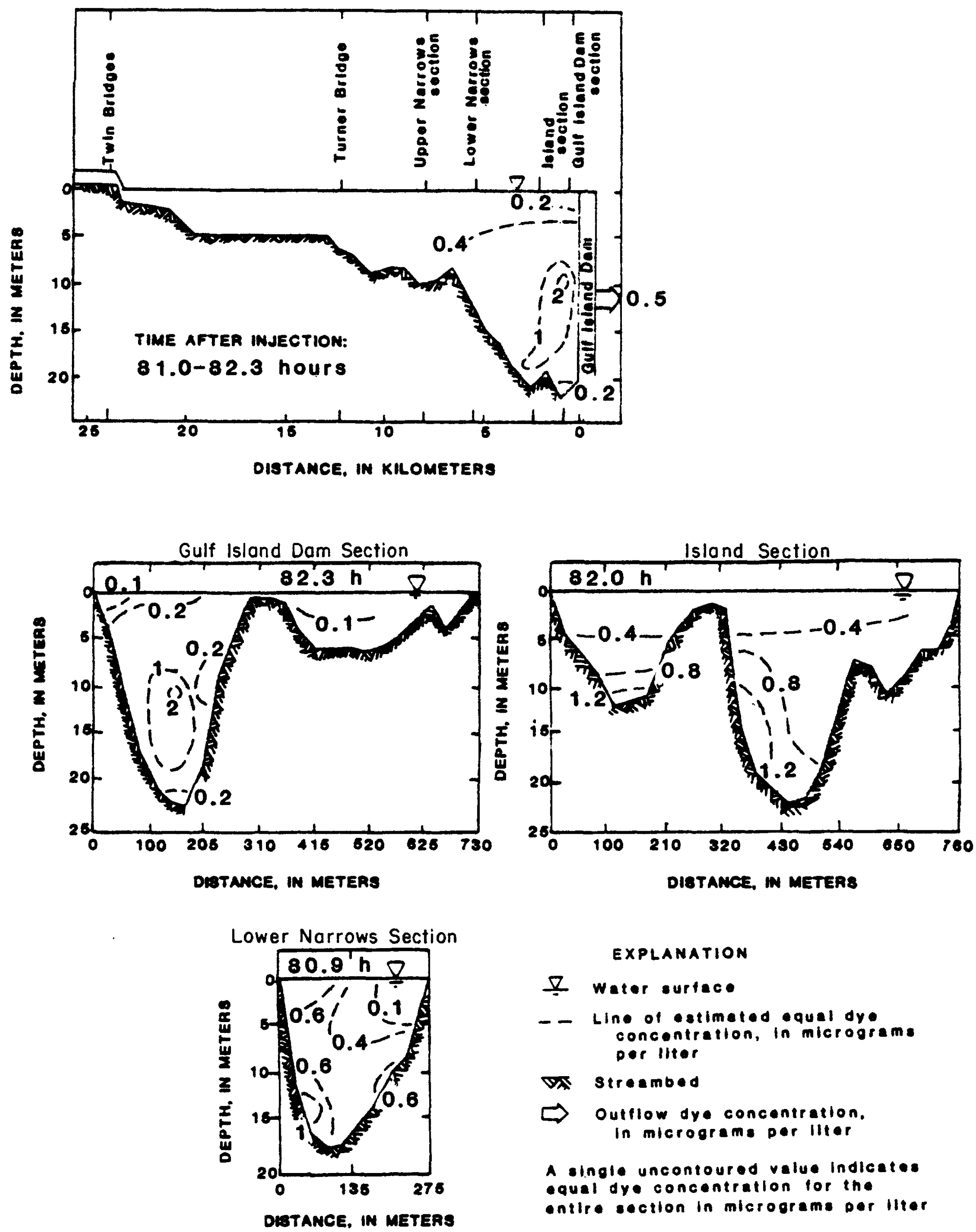


Figure A-9.--Isopleths of dye concentration in Gulf Island Pond, June 14, 1981

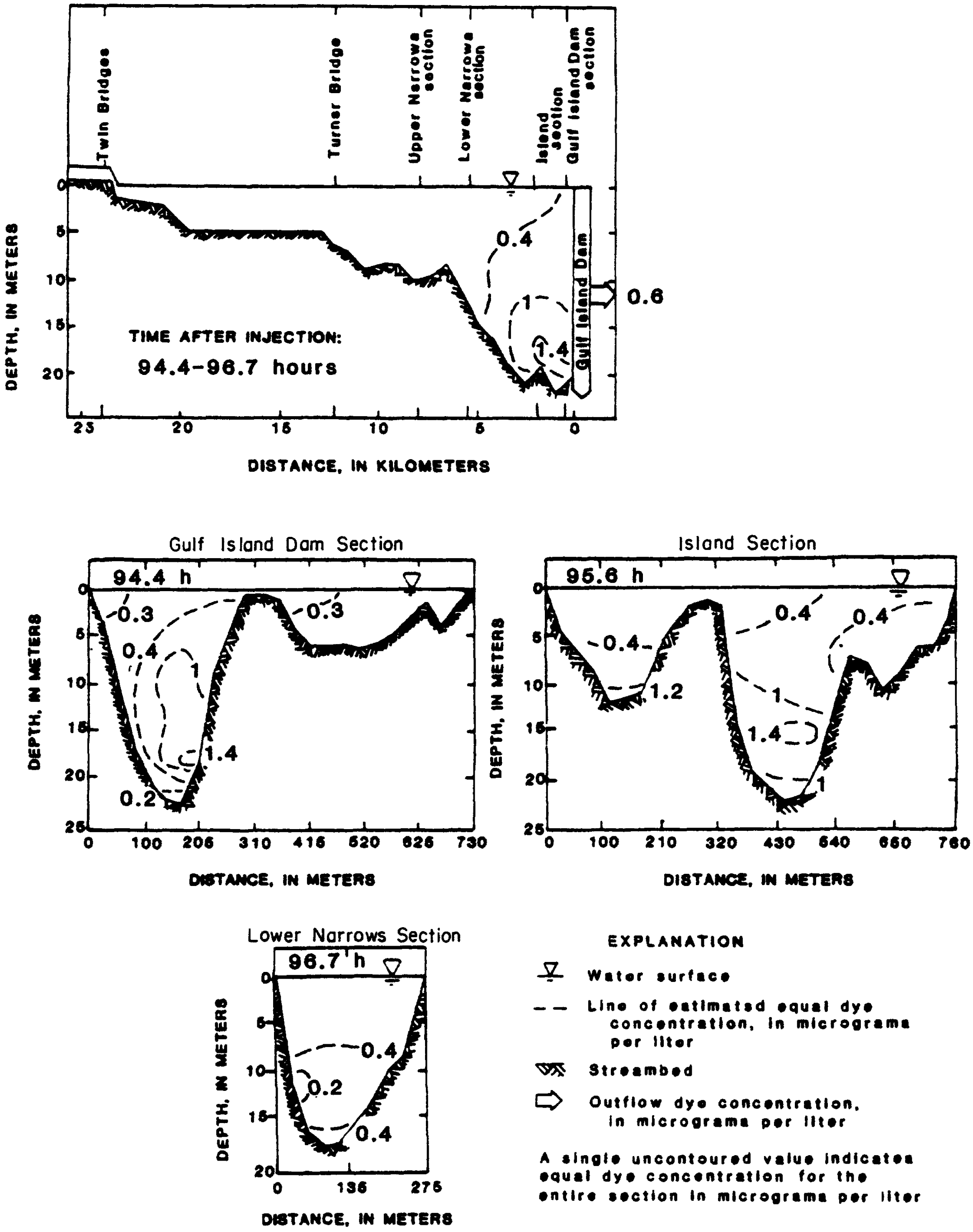


Figure A-10.--Isopleths of dye concentration in Gulf Island Pond, June 15, 1981

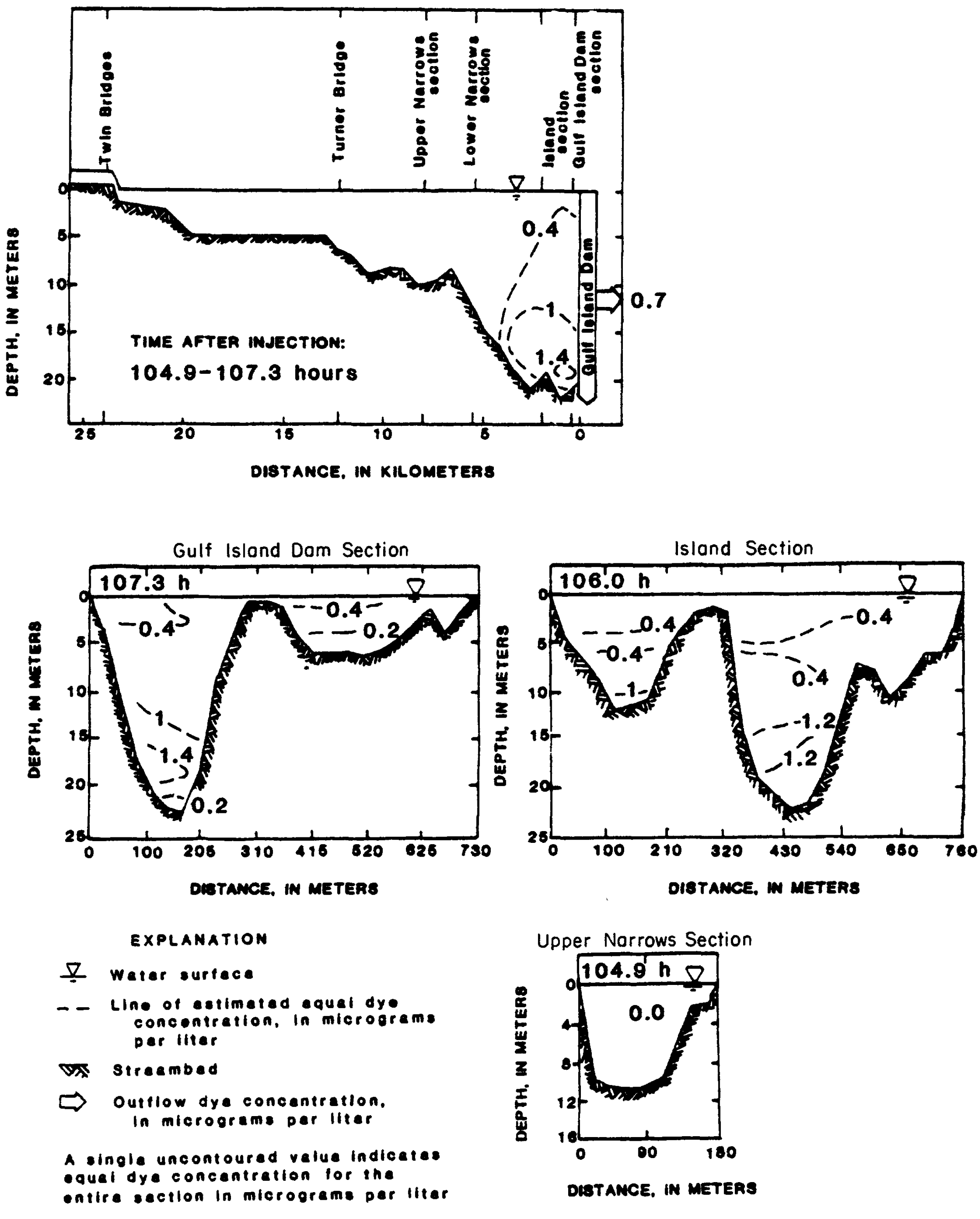


Figure A-11.--Isopleths of dye concentration in Gulf Island Pond, June 15, 1981

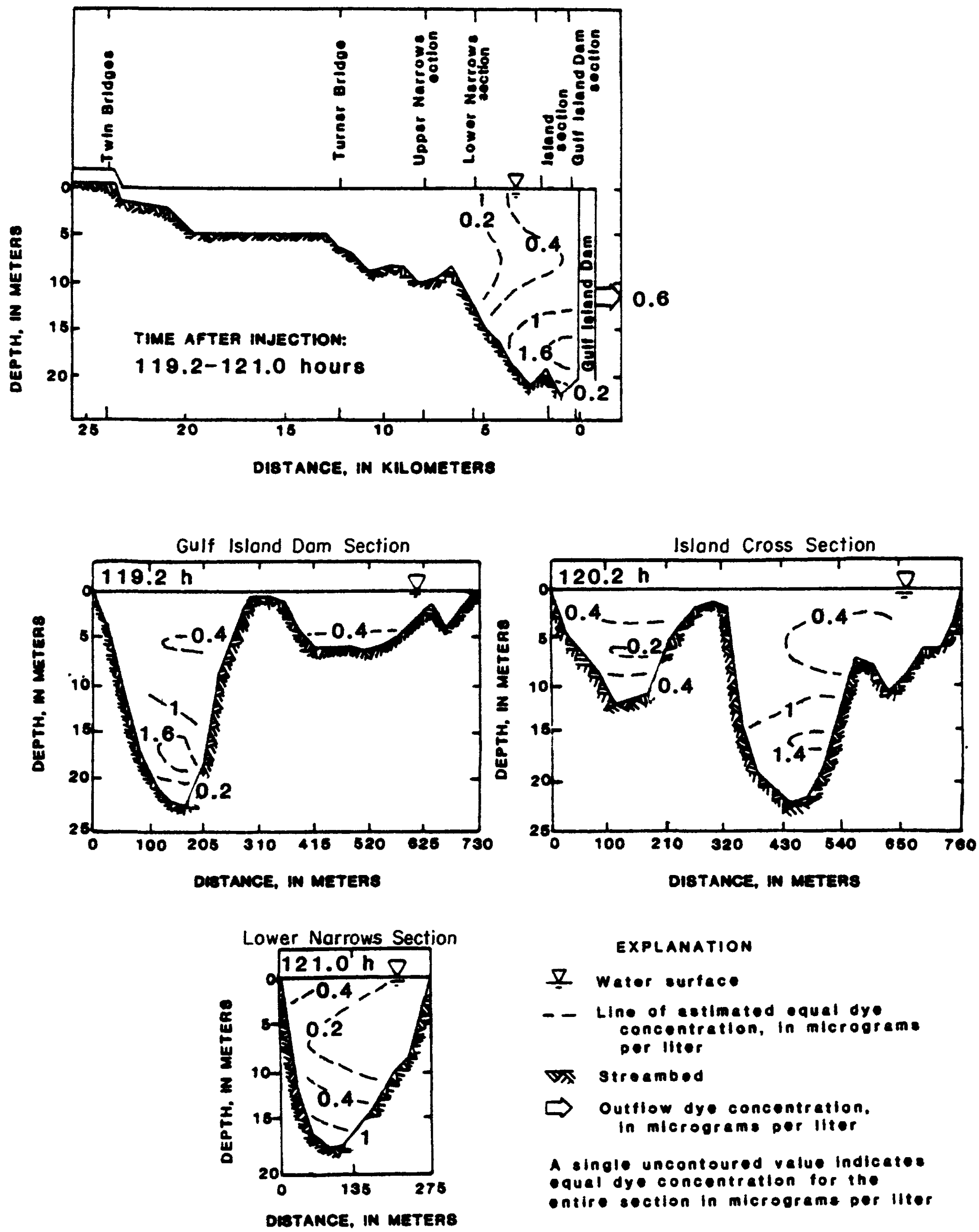


Figure A-12.--Isopleths of dye concentration in Gulf Island Pond, June 16, 1981

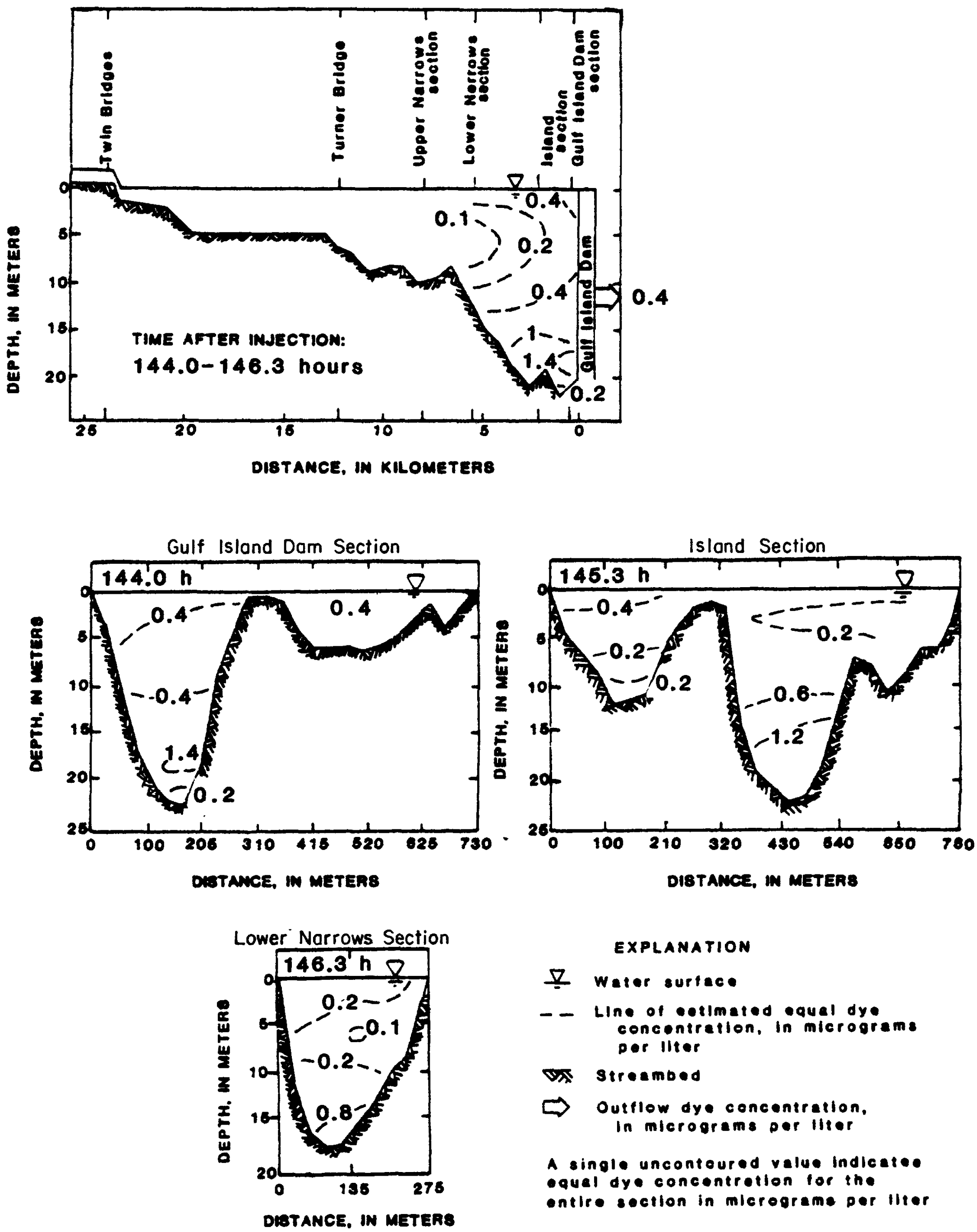


Figure A-13.--Isopleths of dye concentration in Gulf Island Pond, June 17, 1981

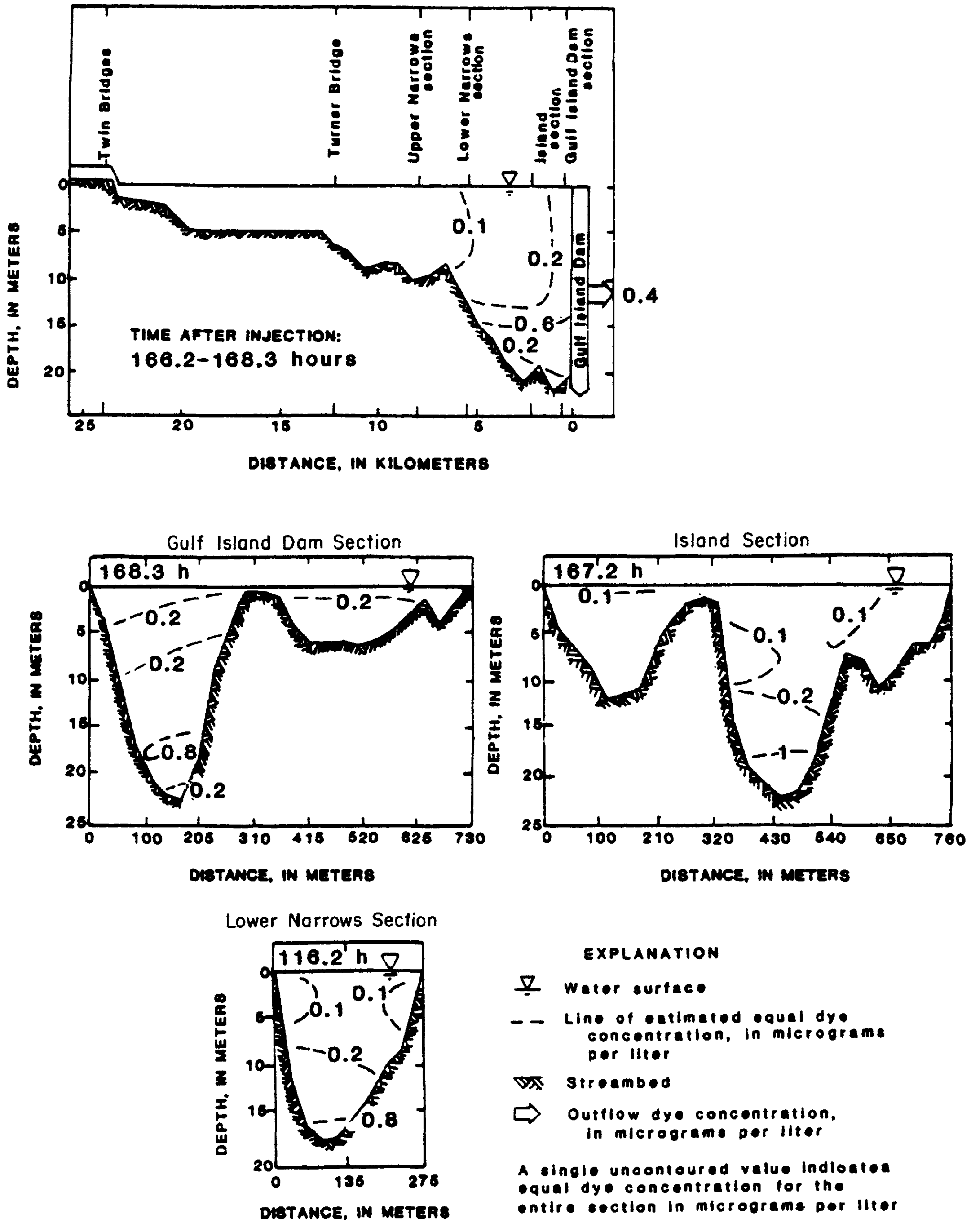


Figure A-14.--Isopleths of dye concentration in Gulf Island Pond, June 18, 1981

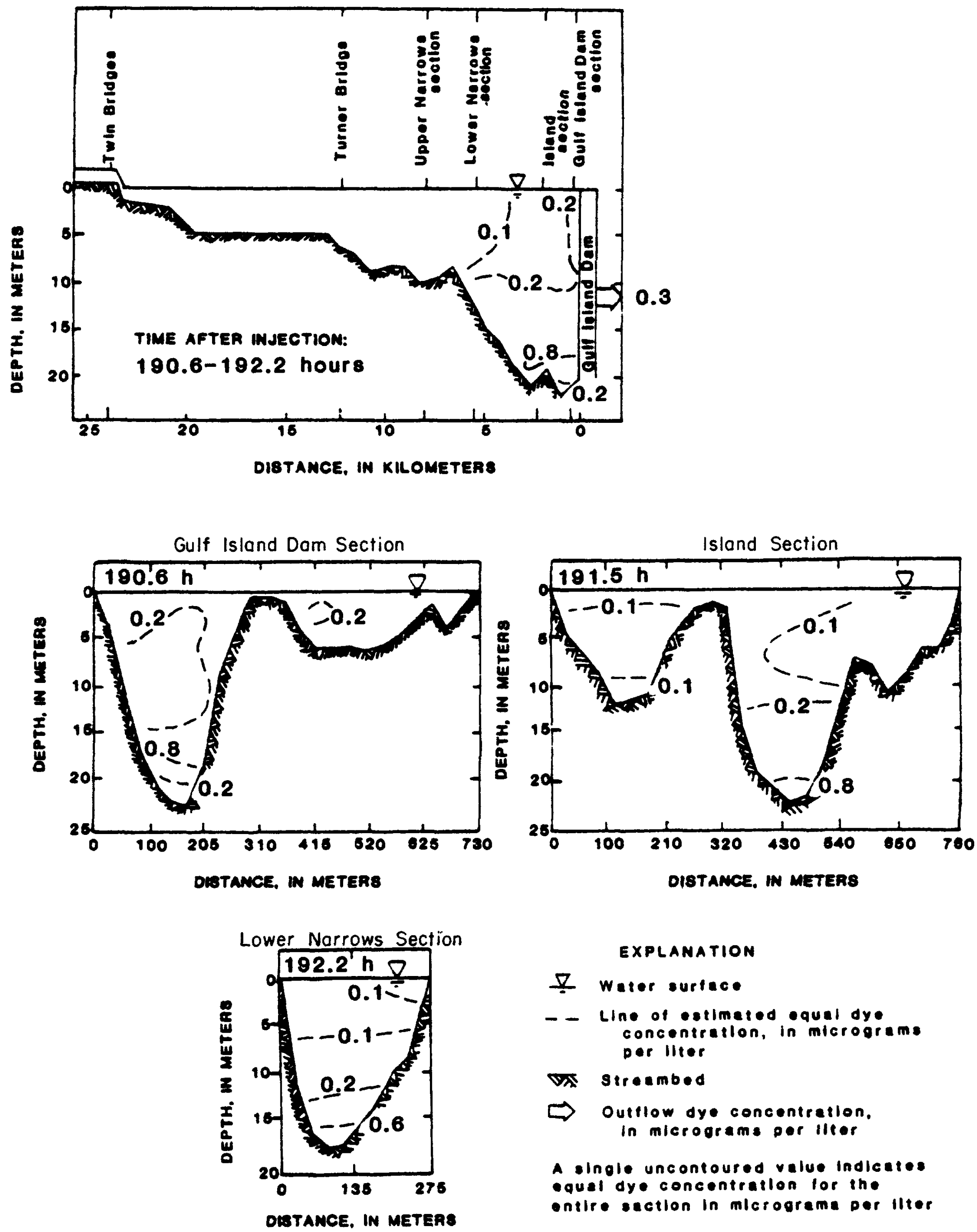


Figure A-15.--Isopleths of dye concentration in Gulf Island Pond, June 19, 1981

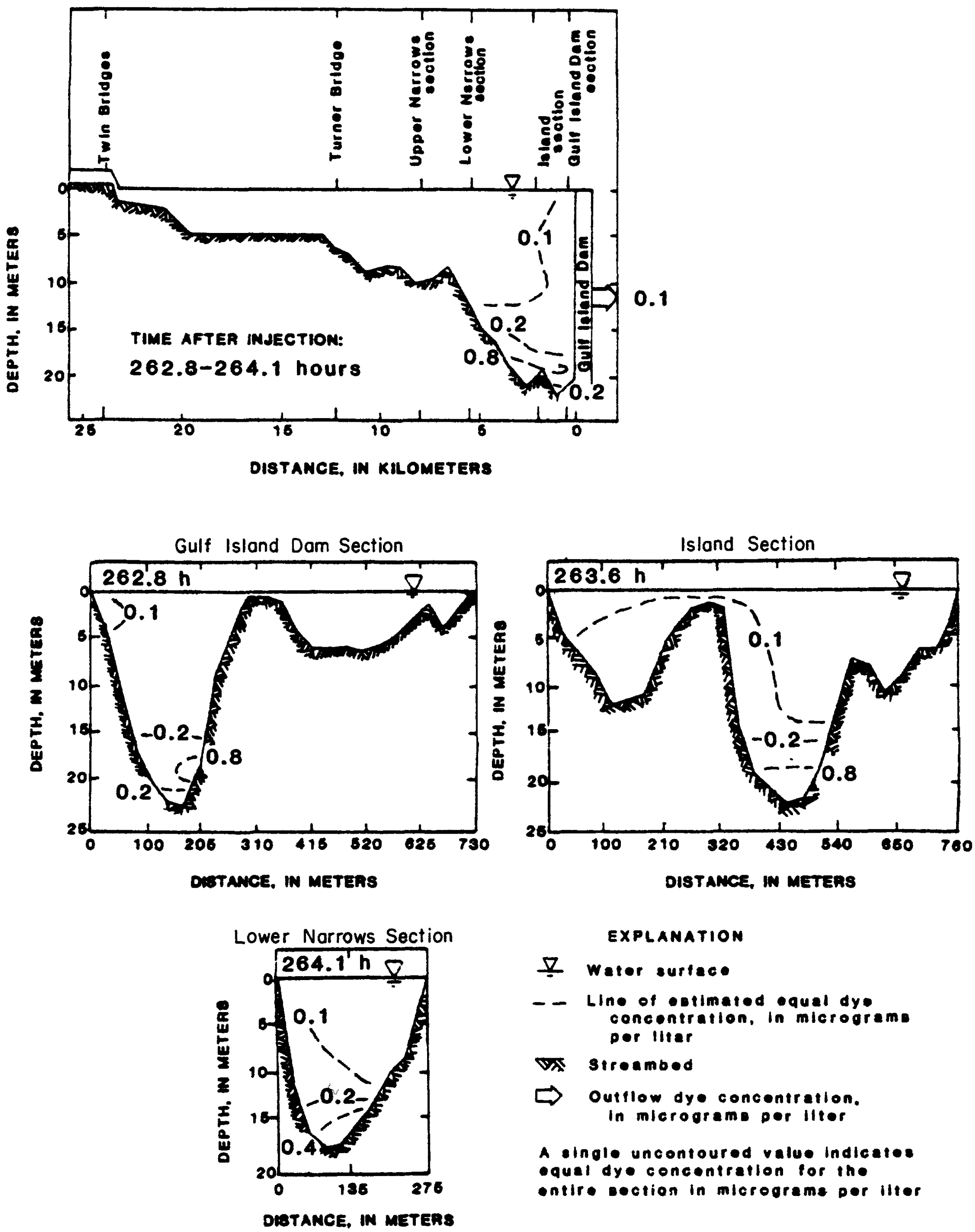


Figure A-16.--Isopleths of dye concentration in Gulf Island Pond, June 22, 1981

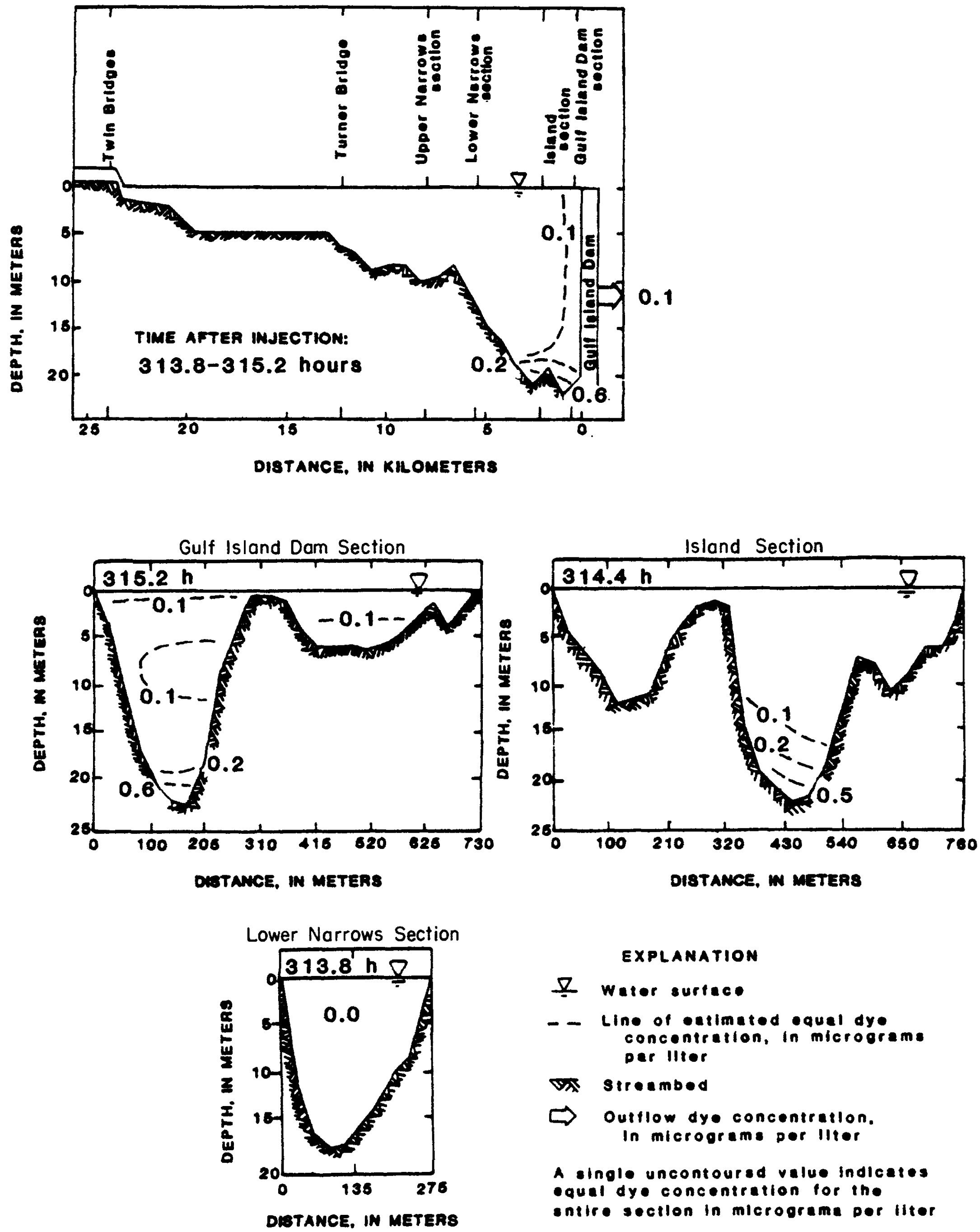


Figure A-17.--Isopleths of dye concentration in Gulf Island Pond, June 24, 1981

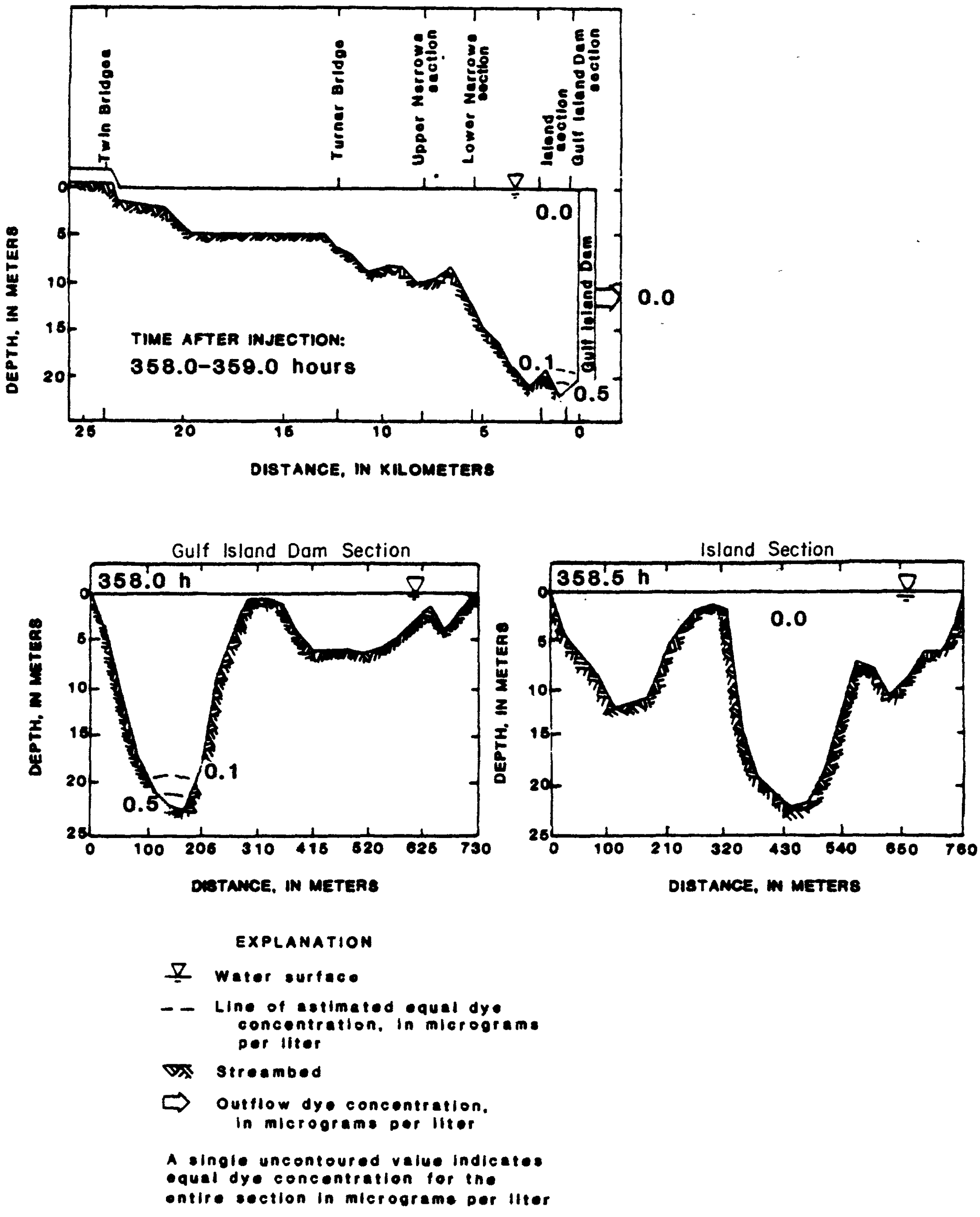


Figure A-18.--Isopleths of dye concentration in Gulf Island Pond, June 26, 1981

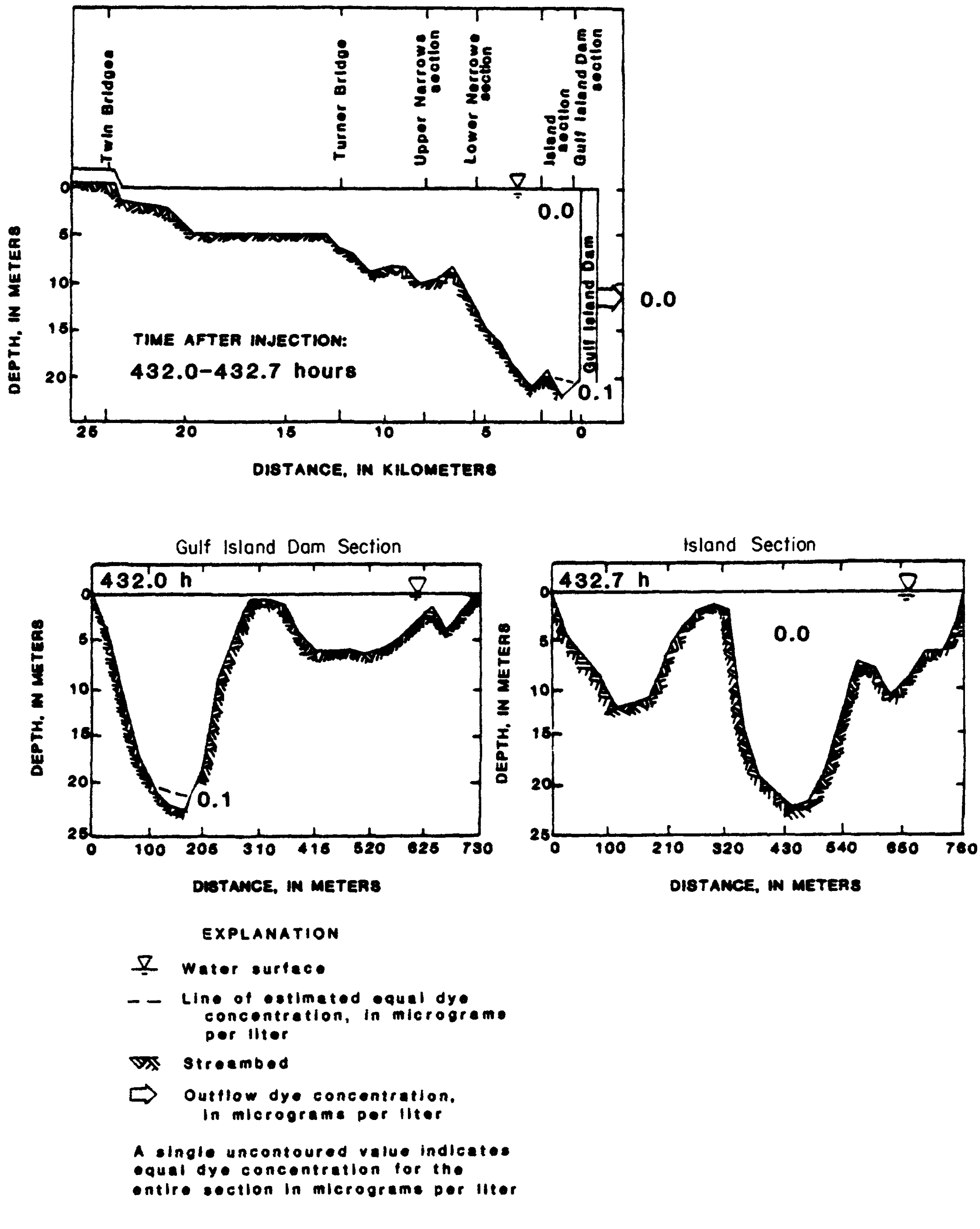
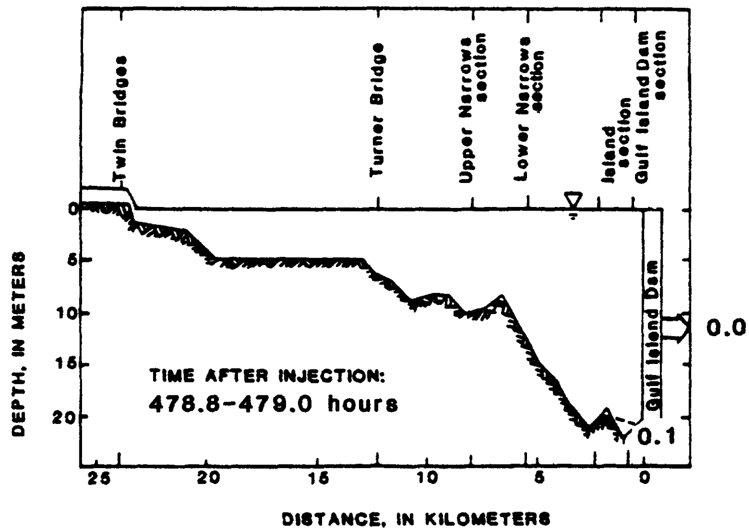
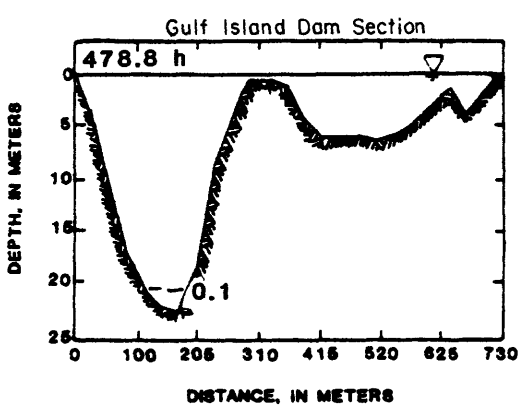


Figure A-19.--Isopleths of dye concentration in Gulf Island Pond, July 1, 1981





EXPLANATION

Water surface

Line of estimated equal dye concentration, in micrograms per liter

Streambed

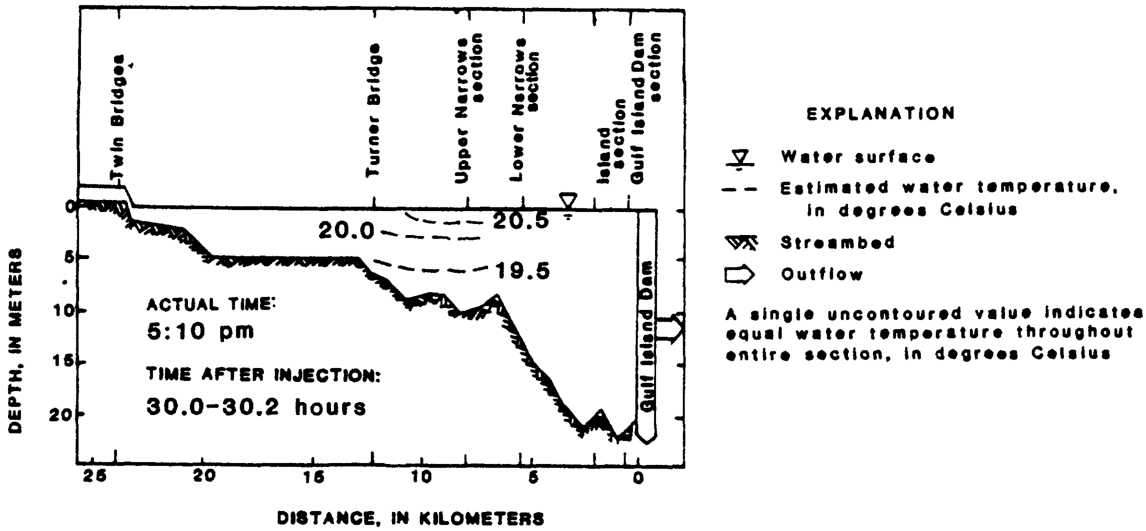
Outflow dye concentration, in micrograms per liter

A single uncontoured value indicates equal dye concentration for the entire section in micrograms per liter

Figure A-20.--Isopleths of dye concentration in Gulf Island Pond, July 1, 1981

APPENDIX B.--ISOTHERMS IN GULF ISLAND POND

JUNE 1981



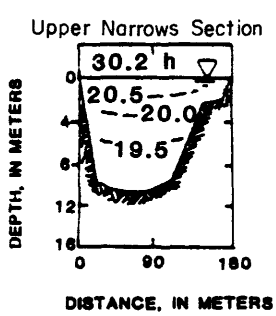
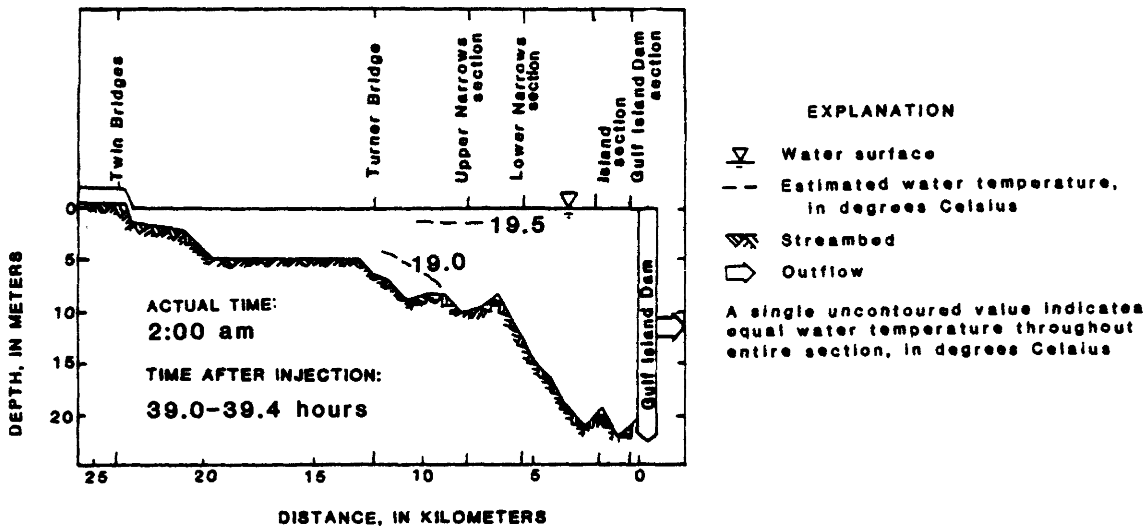


Figure B-1.--Isotherms in Gulf Island Pond, June 12, 1981



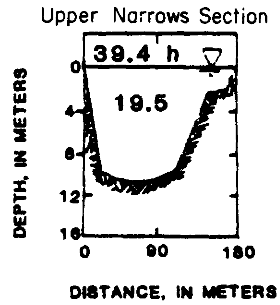


Figure B-2.--Isotherms in Gulf Island Pond, June 13, 1981

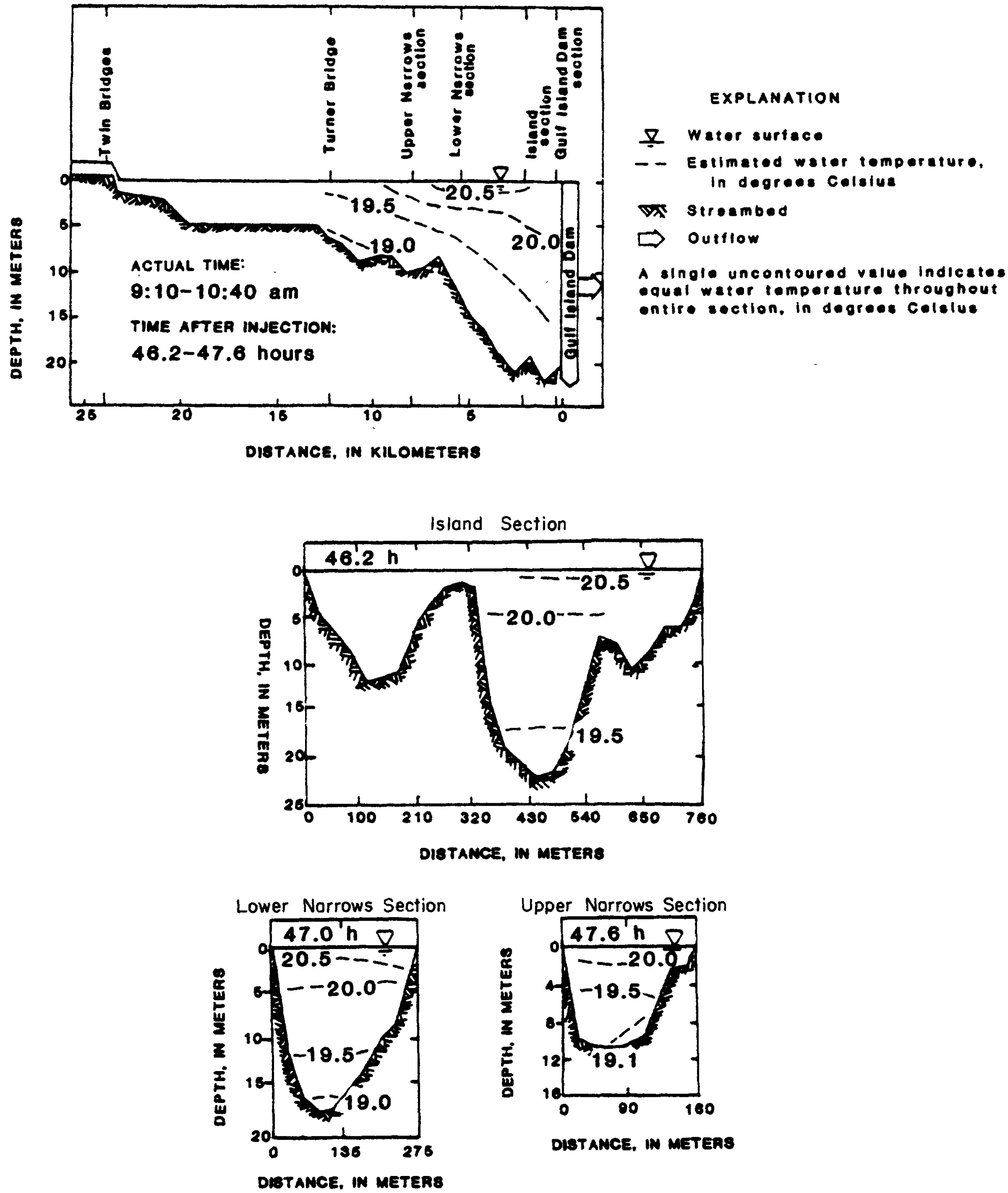


Figure B-3.--Isotherms in Gulf Island Pond, June 13, 1981

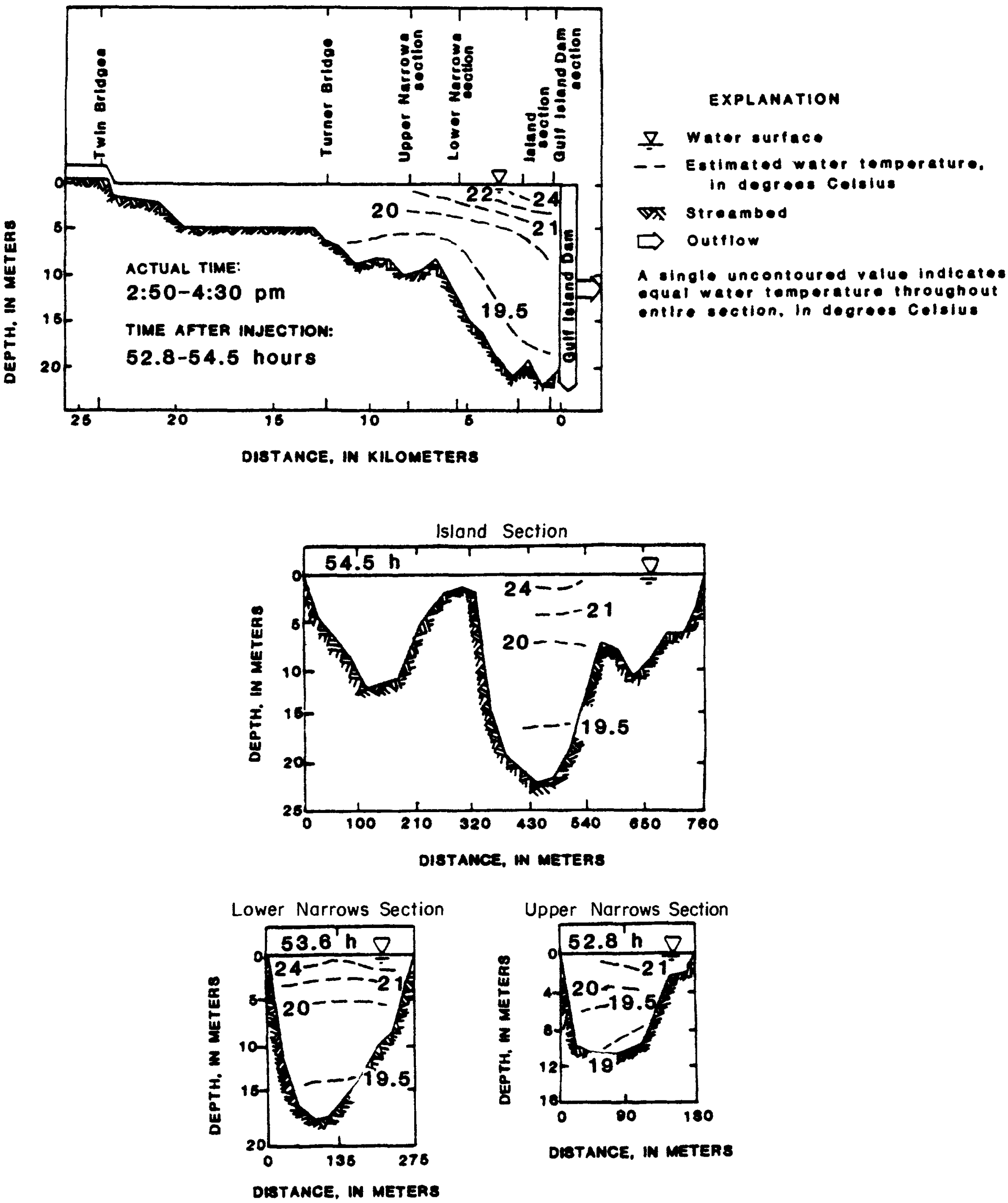


Figure B-4.--Isotherms in Gulf Island Pond, June 13, 1981

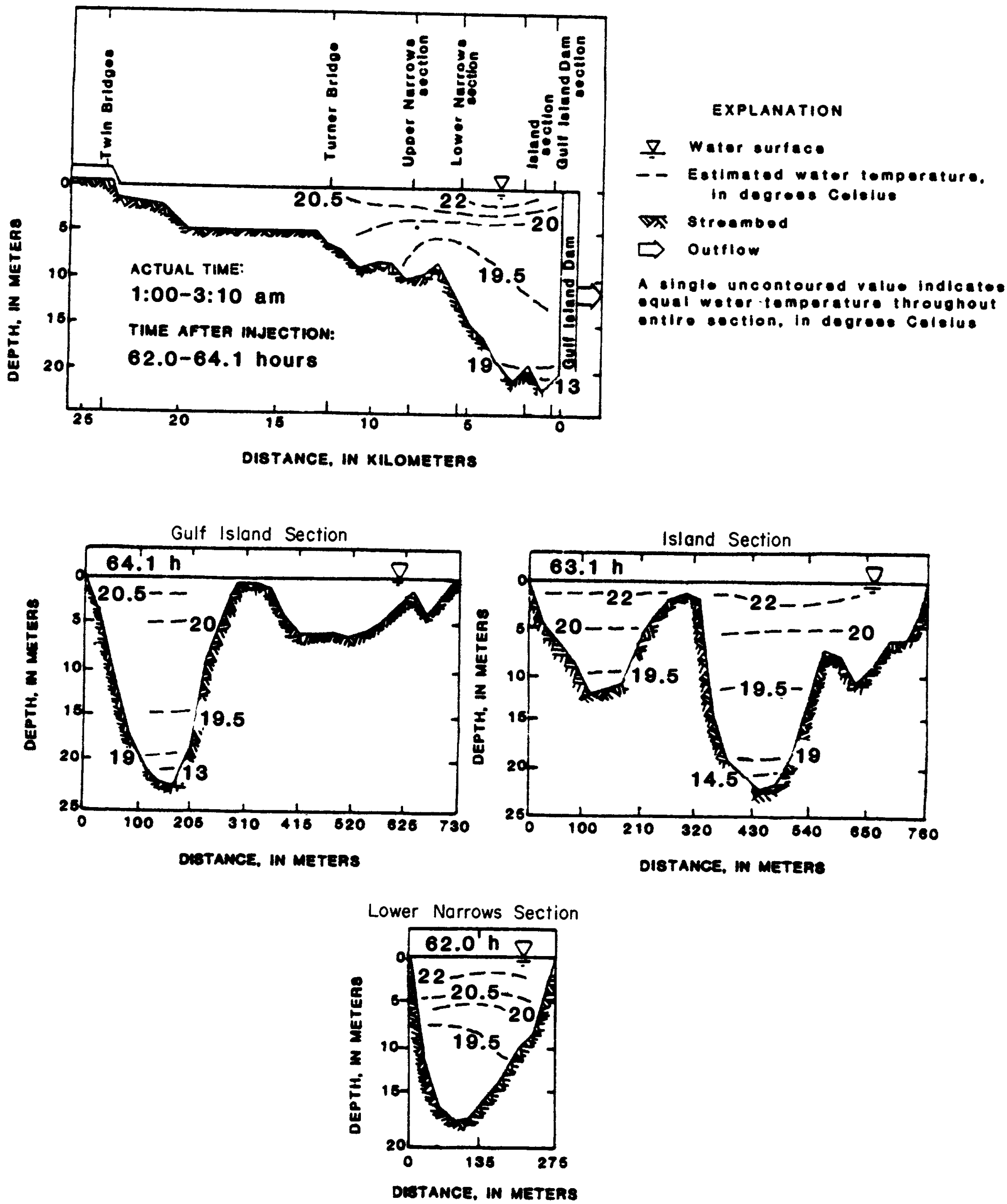


Figure B-5.--Isotherms in Gulf Island Pond, June 14, 1981

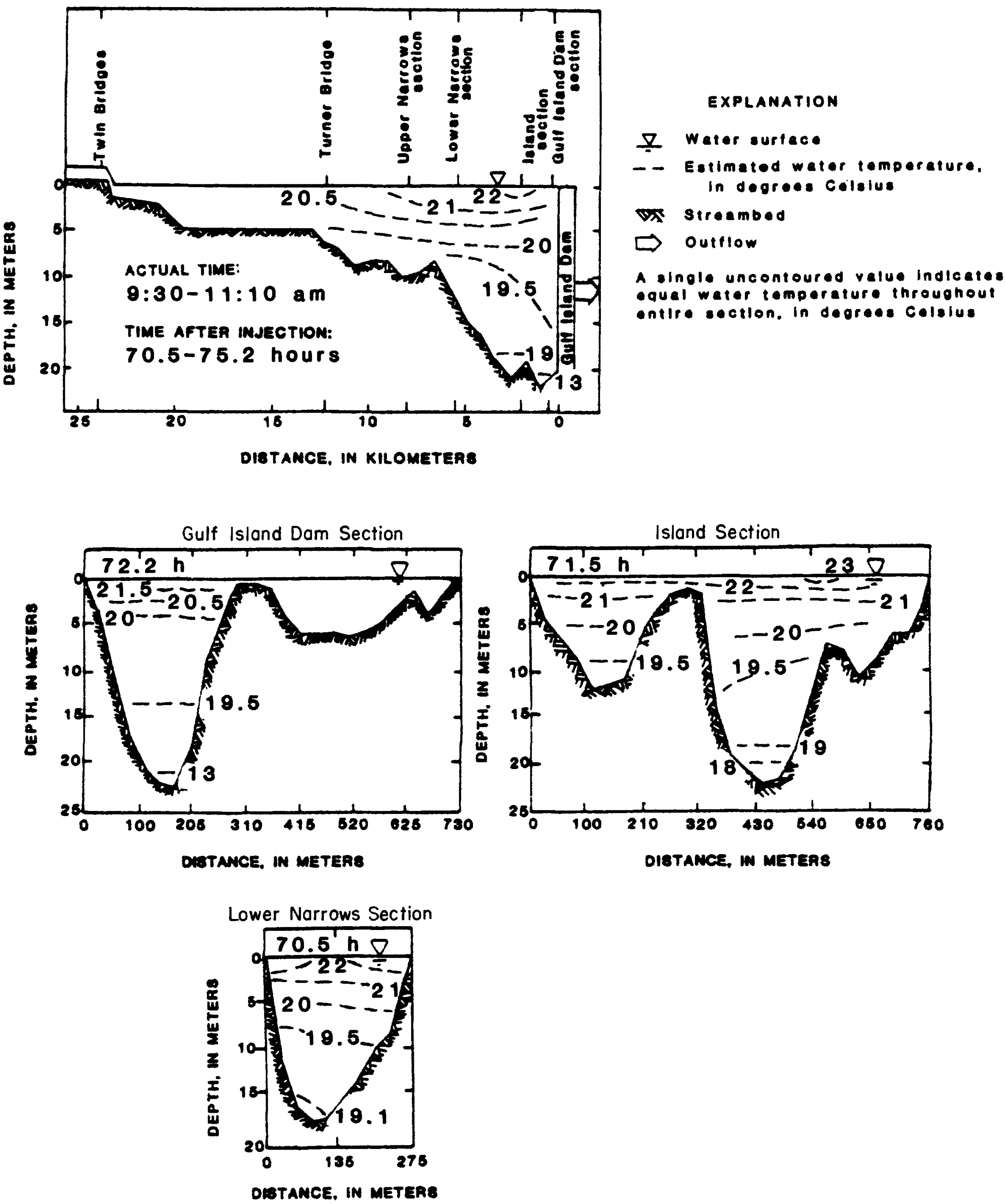


Figure B-6.--Isotherms in Gulf Island Pond, June 14, 1981

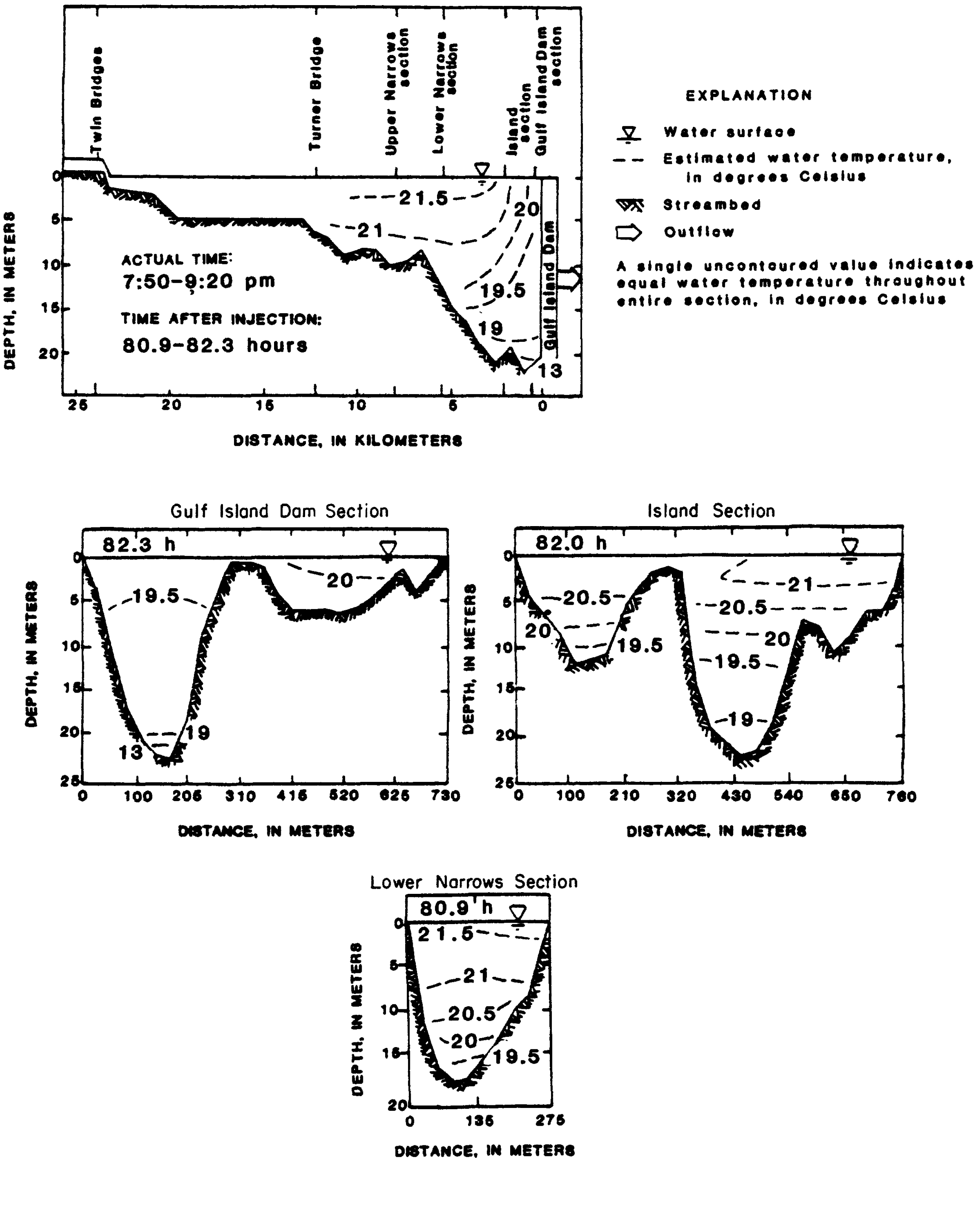


Figure B-7.--Isotherms in Gulf Island Pond, June 14, 1981

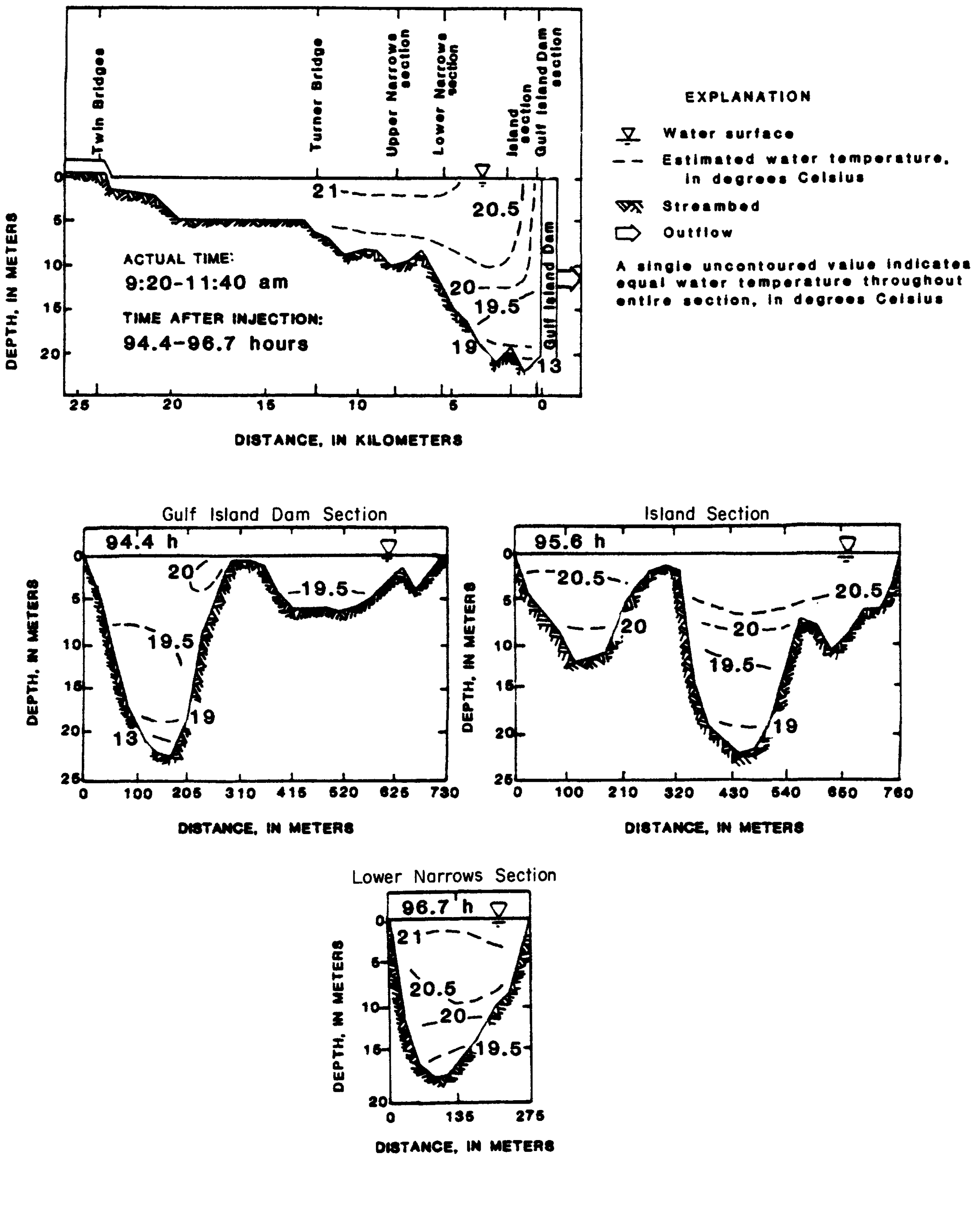


Figure B-8.--Isotherms in Gulf Island Pond, June 15, 1981

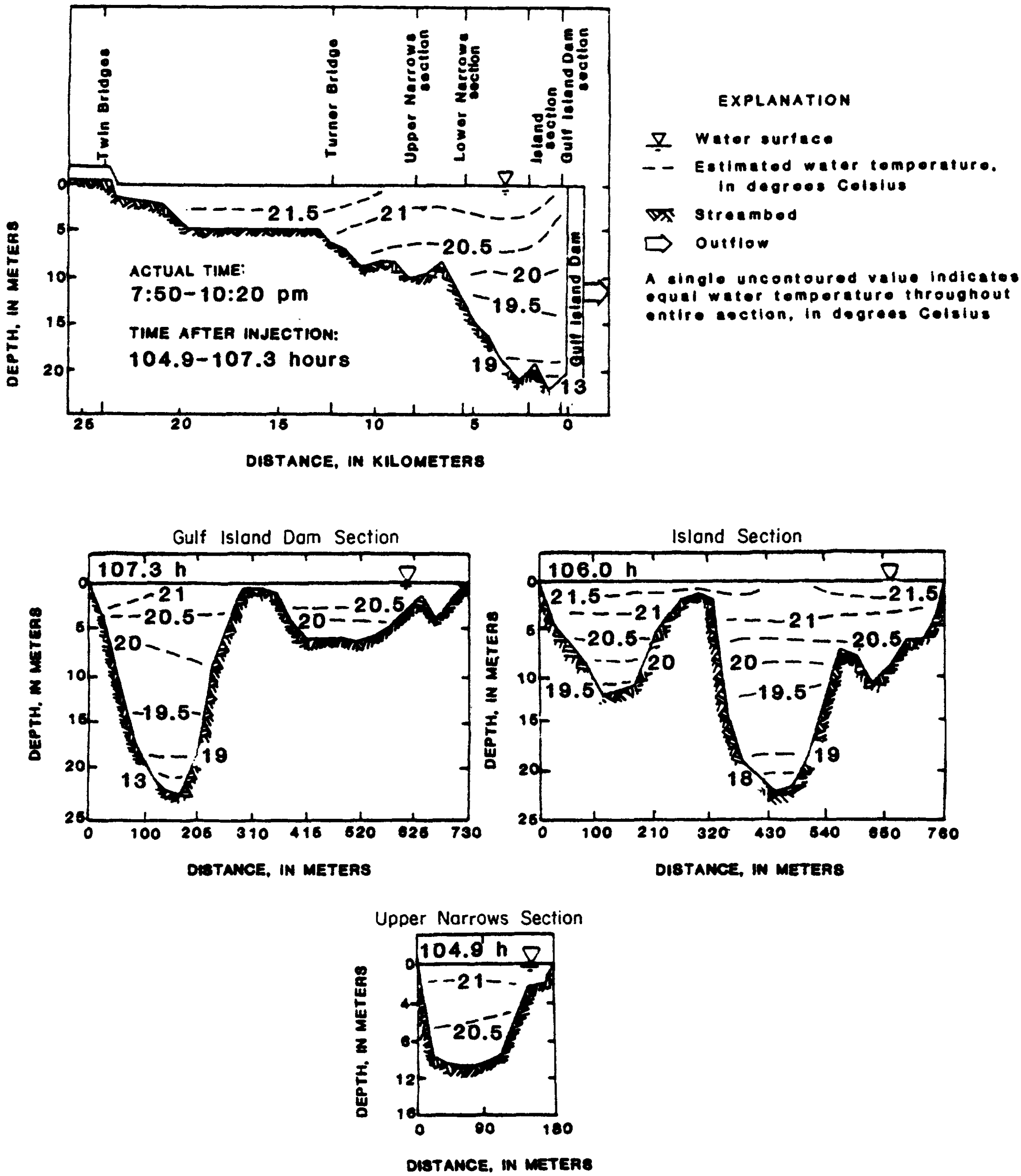


Figure B-9.--Isotherms in Gulf Island Pond, June 15, 1981

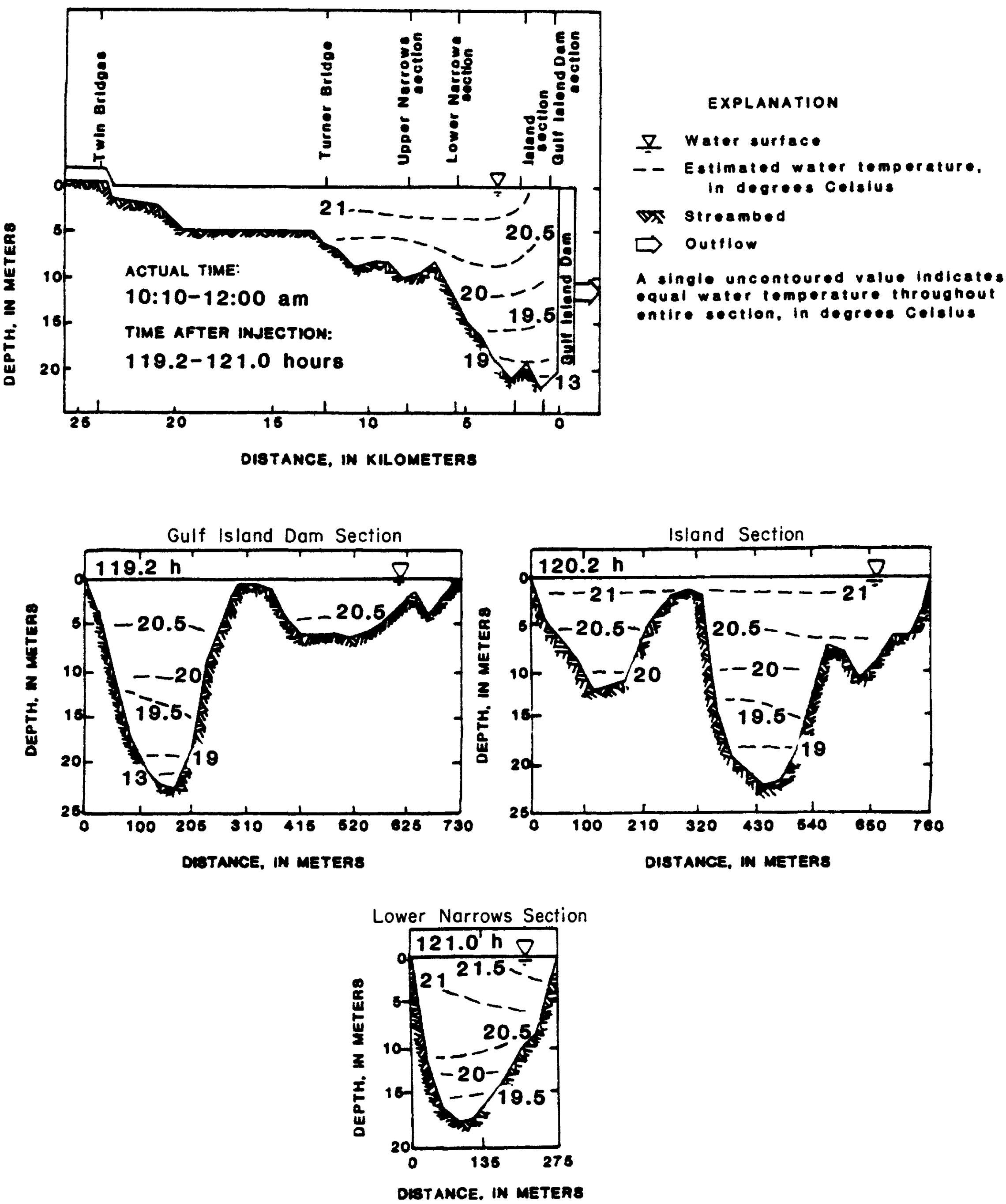


Figure B-10.--Isotherms in Gulf Island Pond, June 16, 1981

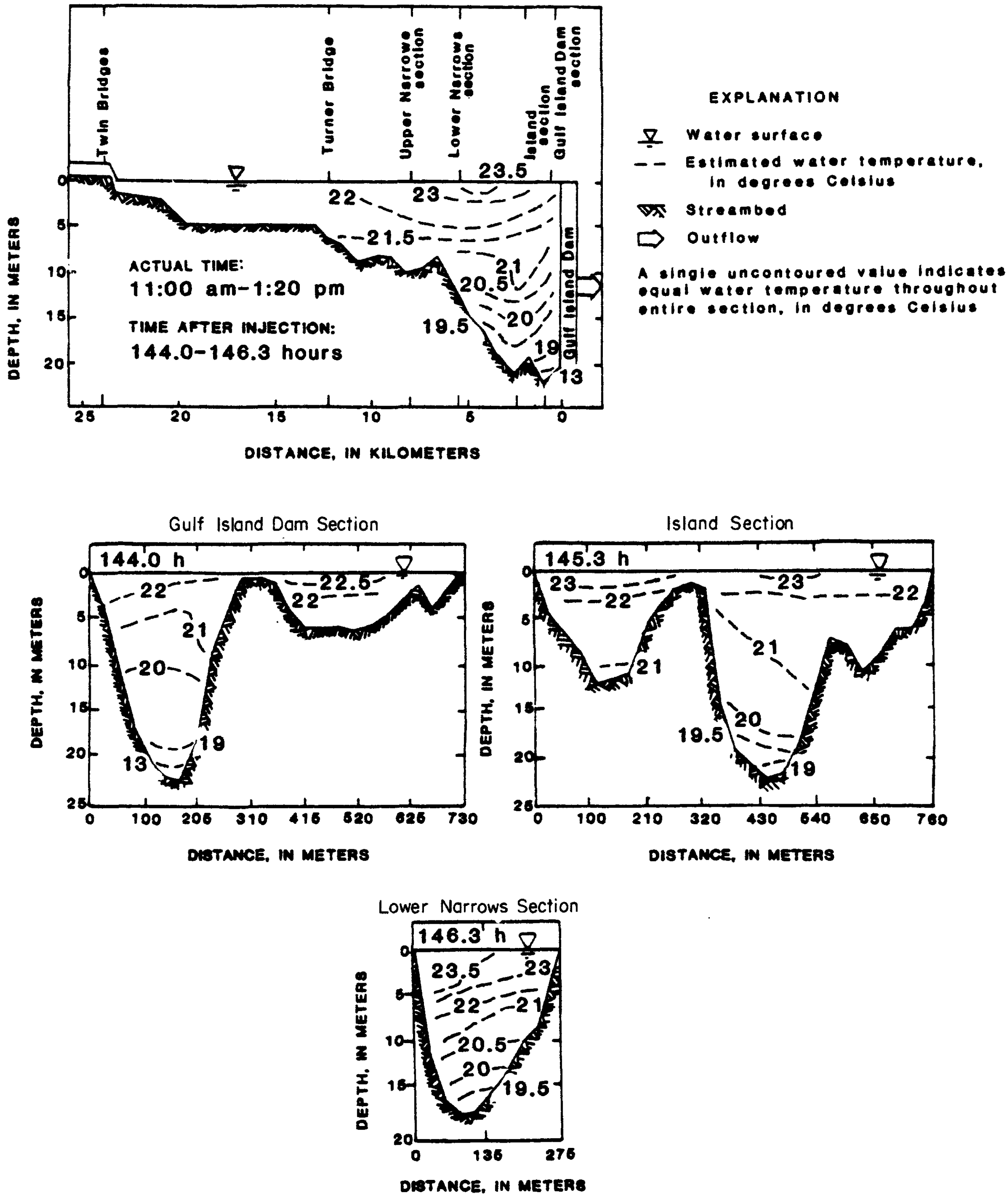


Figure B-11.--Isotherms in Gulf Island Pond, June 17, 1981

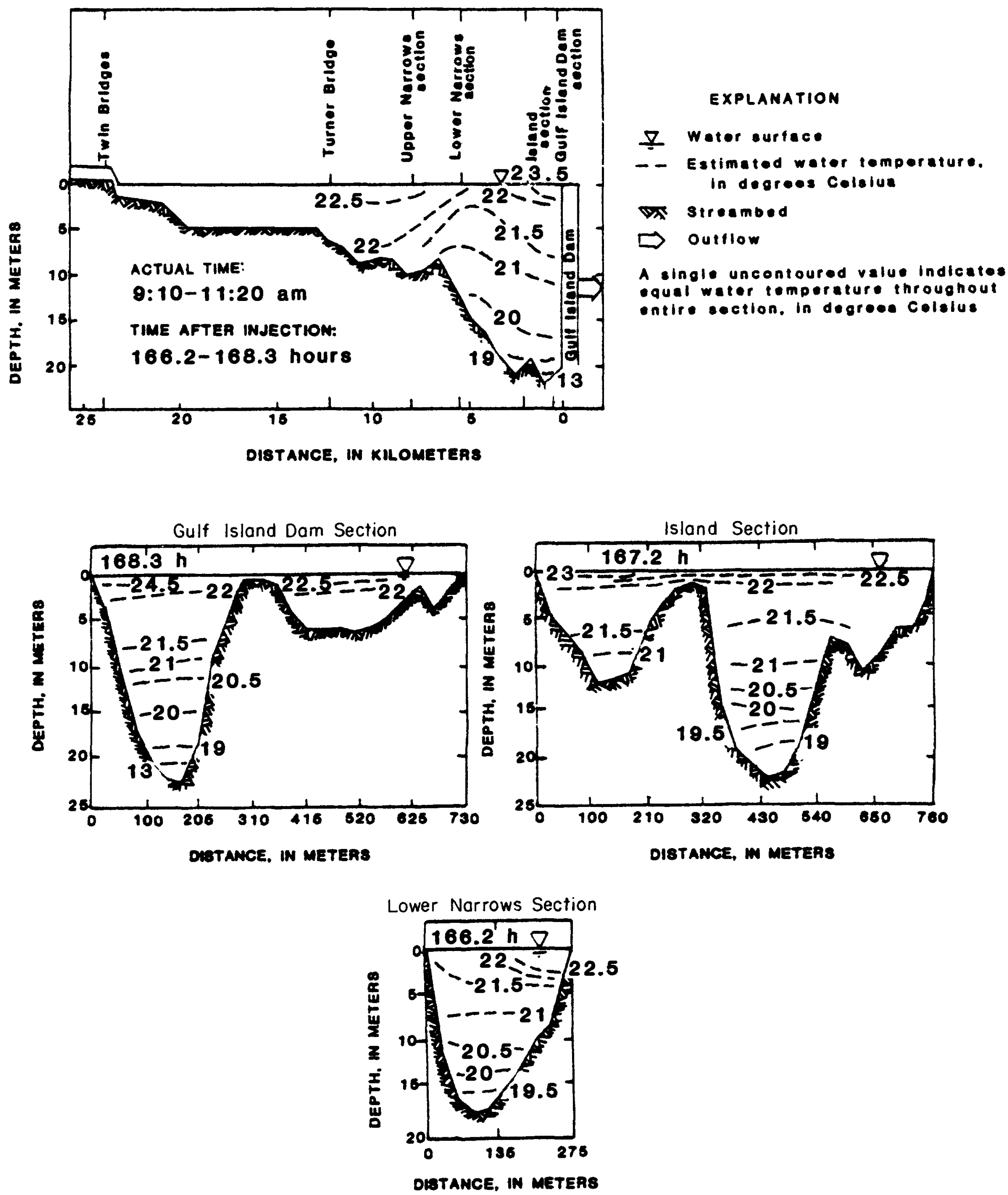


Figure B-12.--Isotherms in Gulf Island Pond, June 18, 1981

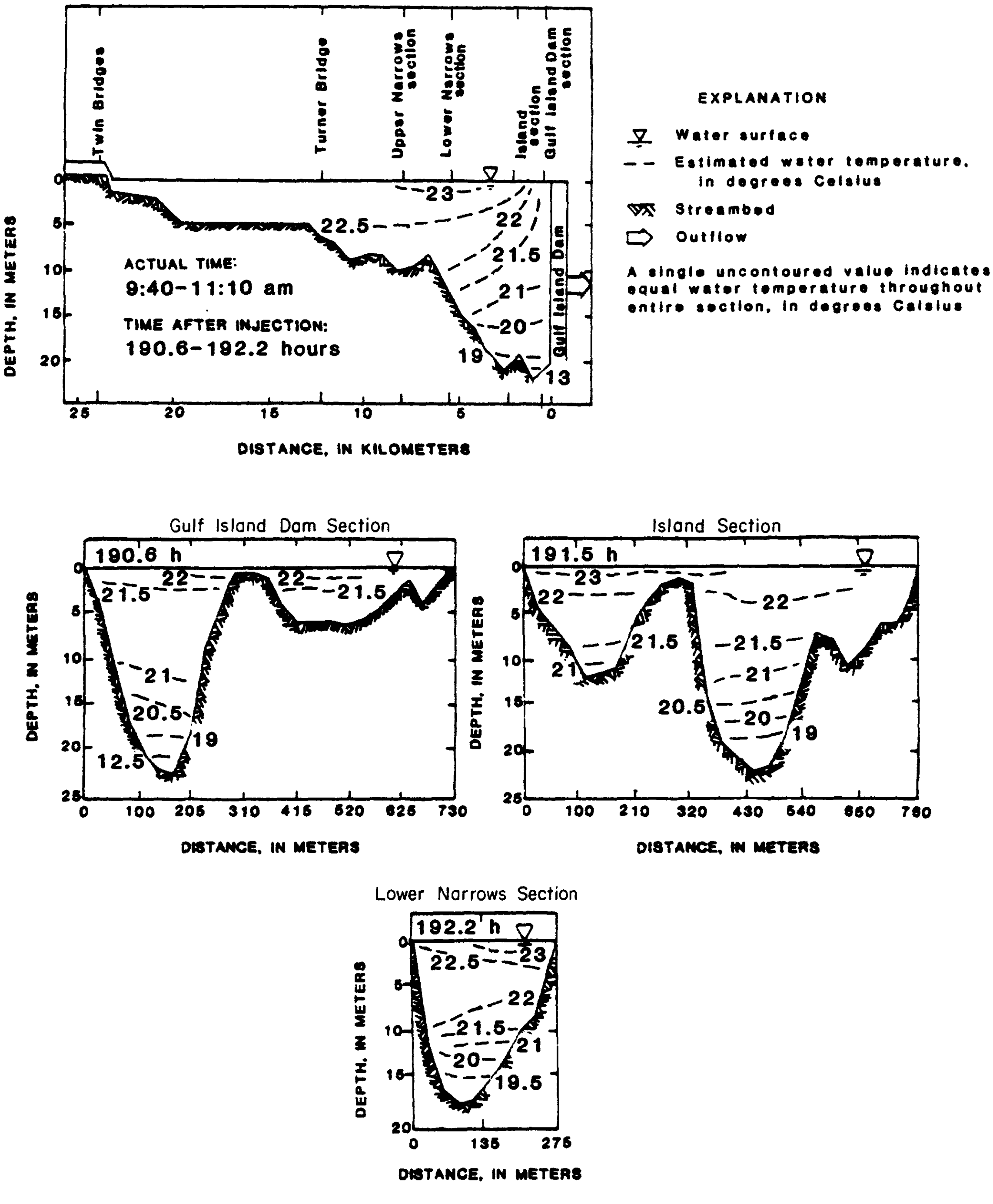


Figure B-13.--Isotherms in Gulf Island Pond, June 19, 1981

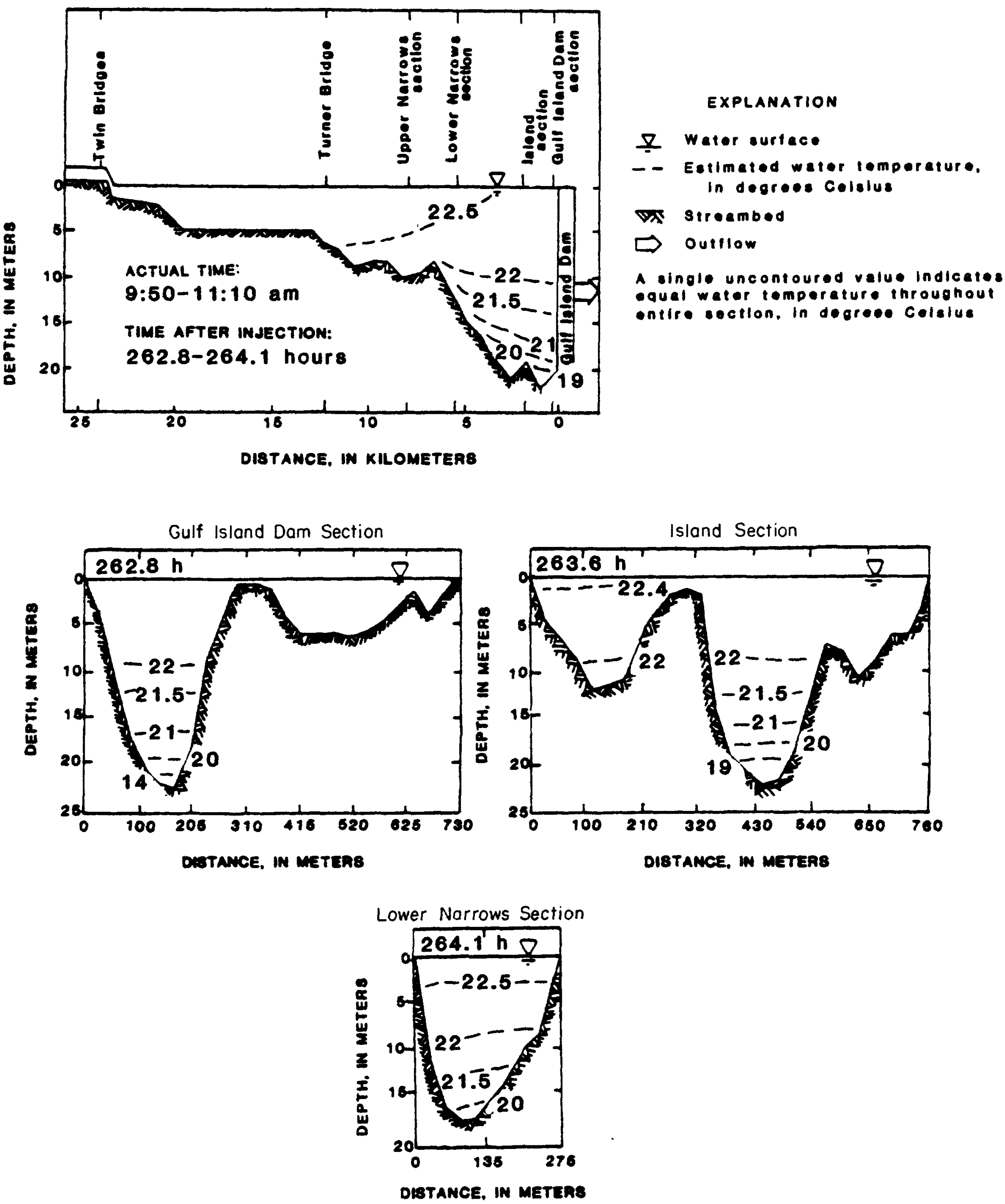


Figure B-14.--Isotherms in Gulf Island Pond, June 22, 1981

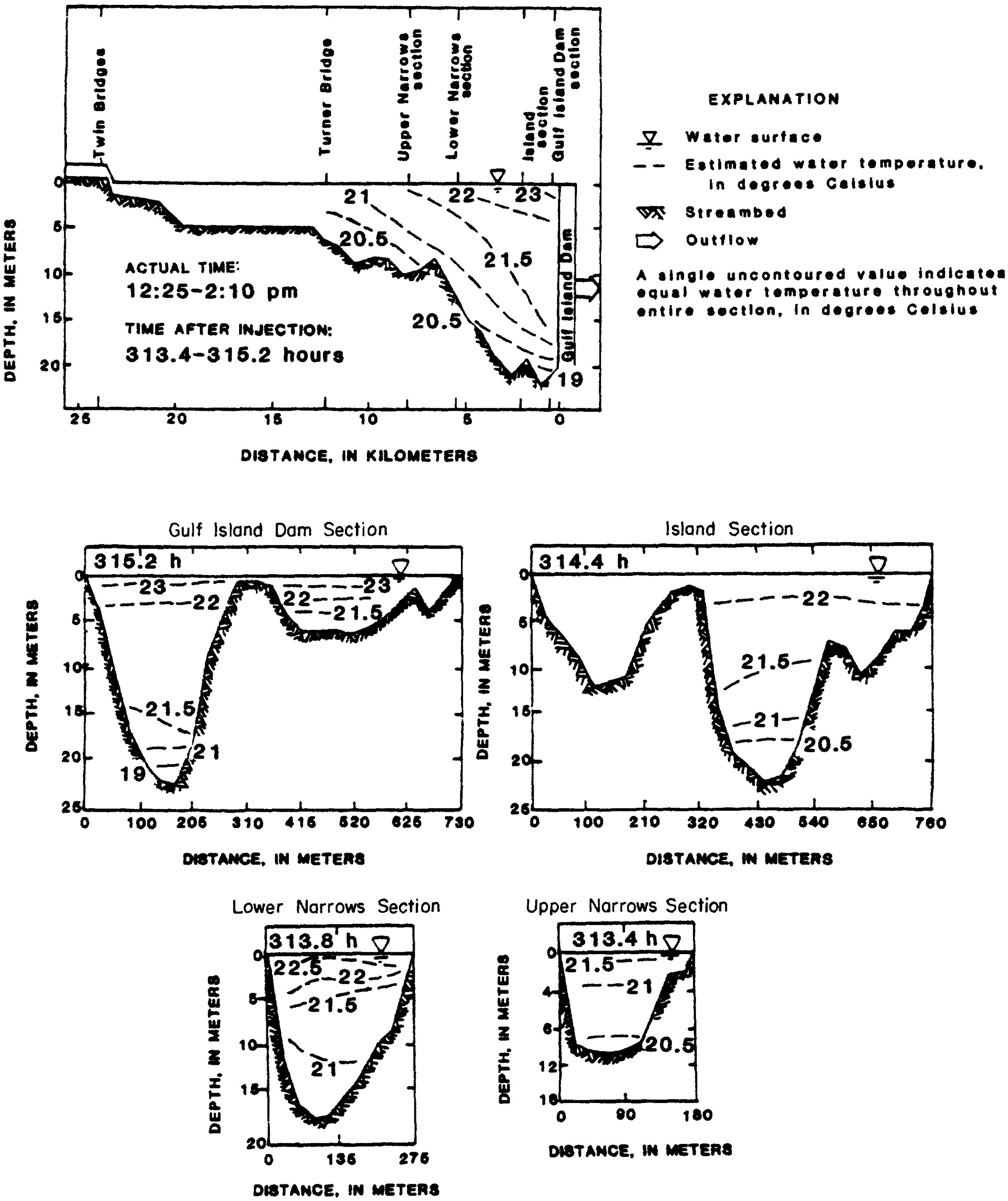


Figure B-15.--Isotherms in Gulf Island Pond, June 24, 1981

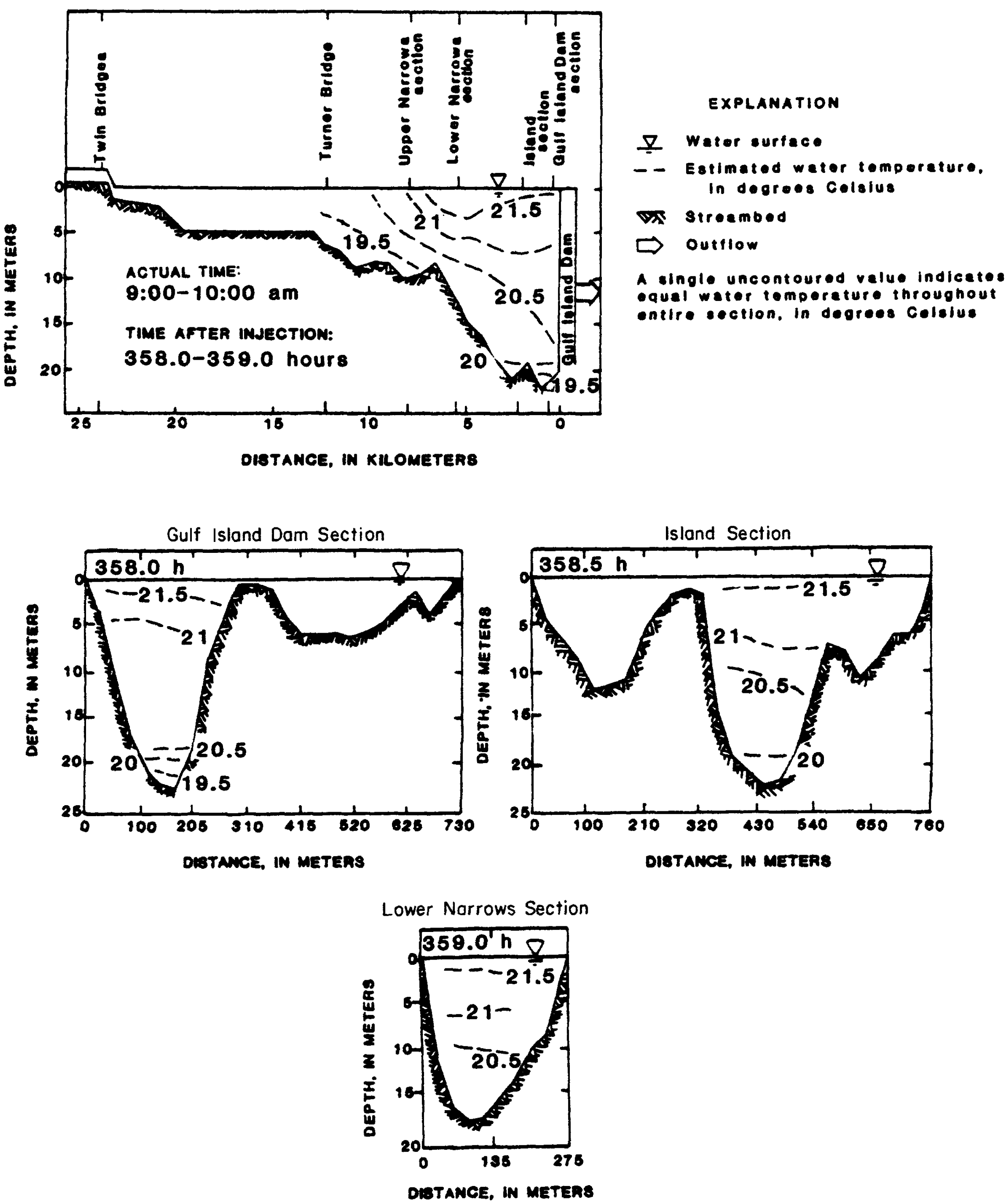


Figure B-16.--Isotherms in Gulf Island Pond, June 26, 1981

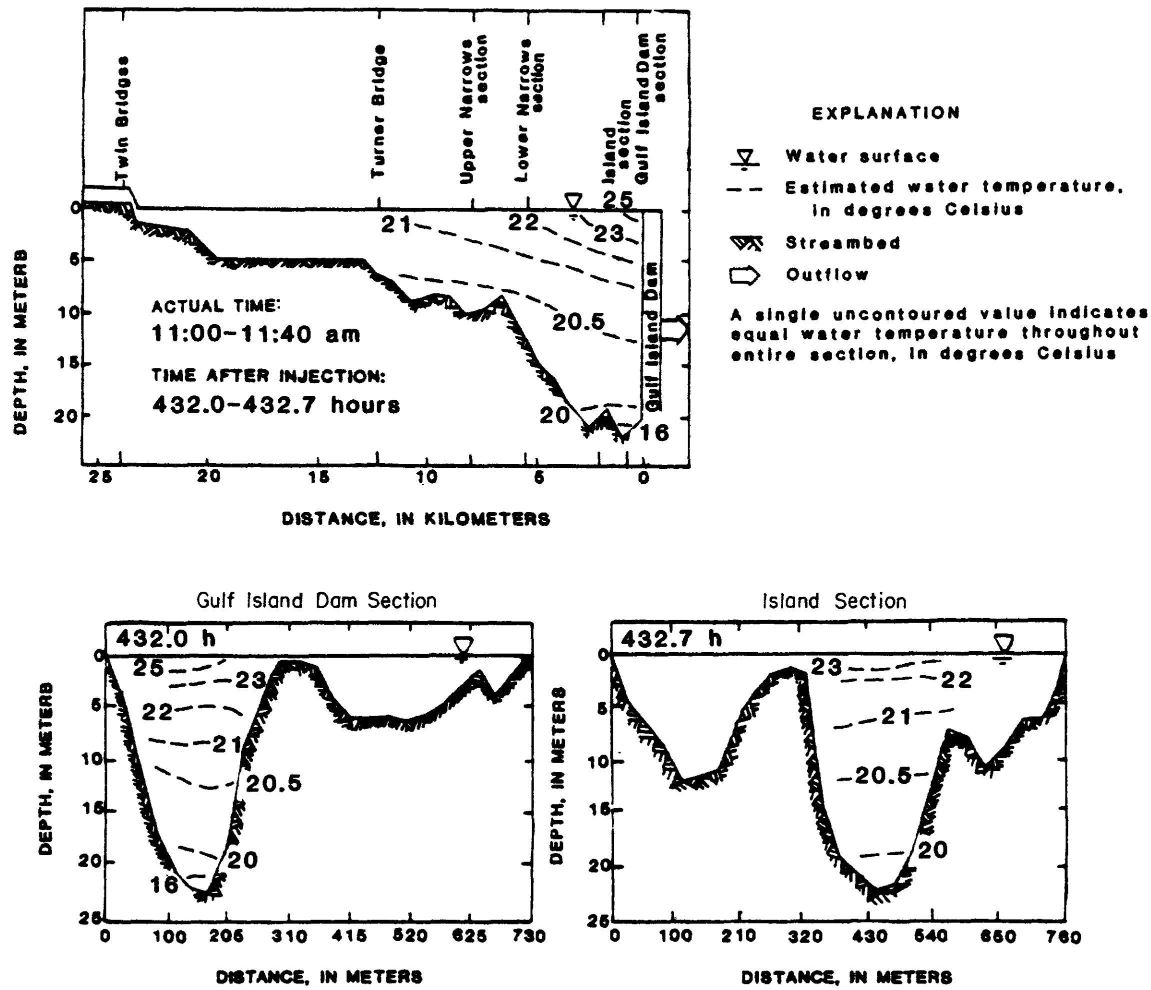


Figure B-17.--Isotherms in Gulf Island Pond, June 29, 1981

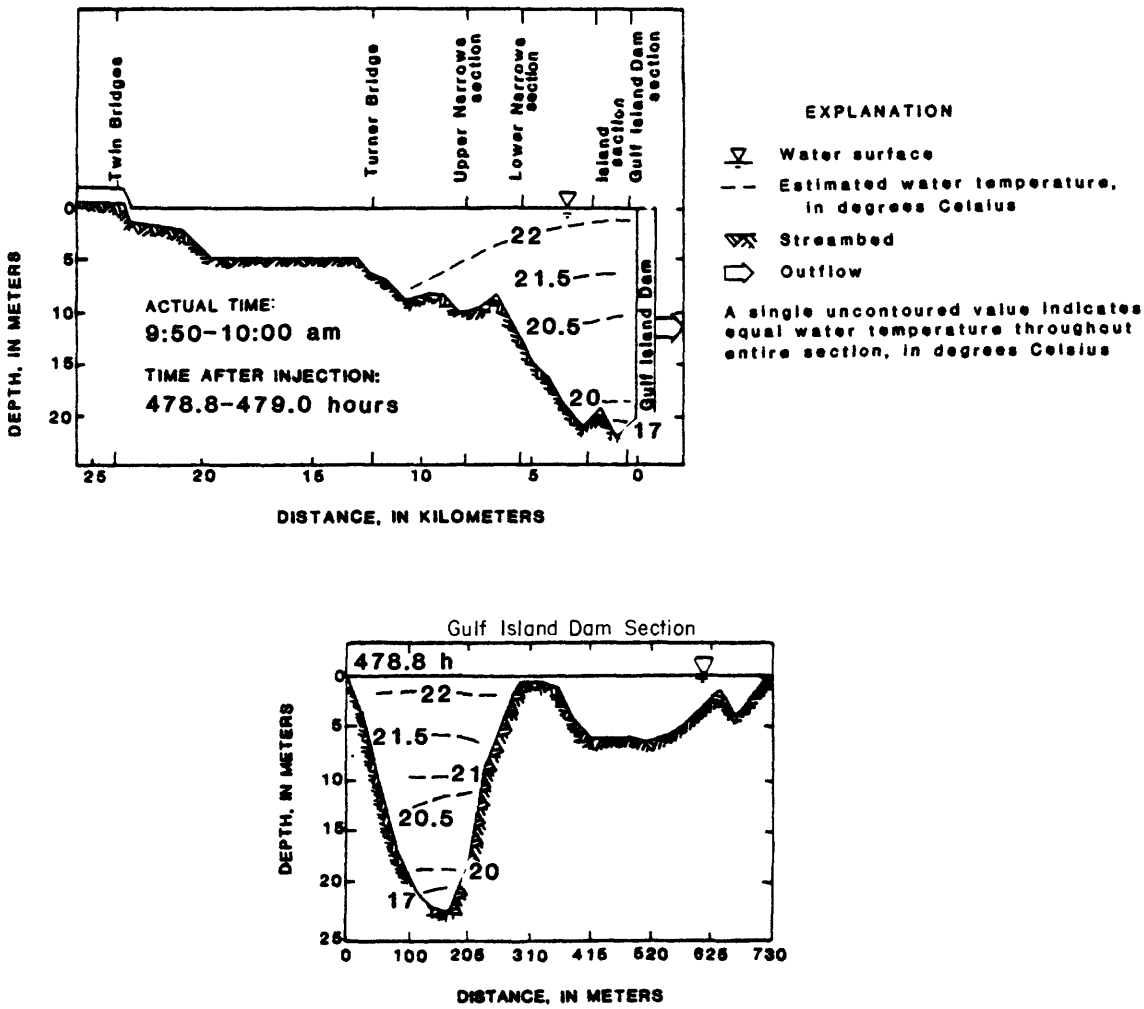


Figure B-18.--Isotherms in Gulf Island Pond, July 1, 1981

APPENDIX C.--ISOPLETHS OF DYE CONCENTRATION IN GULF ISLAND POND

SEPTEMBER 1981

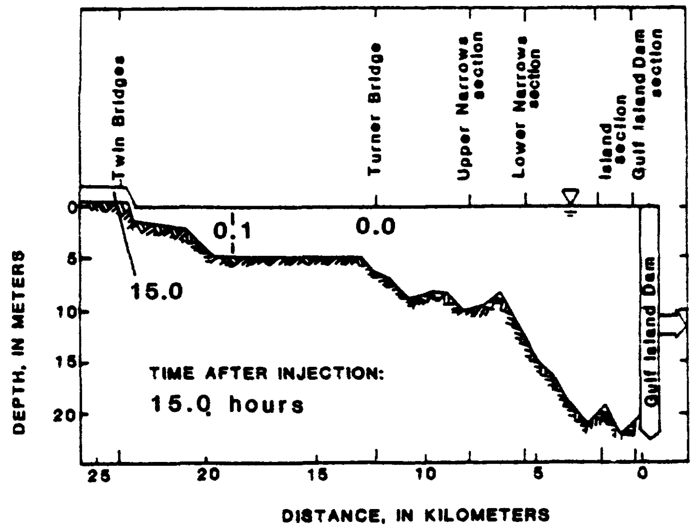


Figure C-1.--Isopleths of dye concentration in Gulf Island Pond, September 14, 1981

EXPLANATION

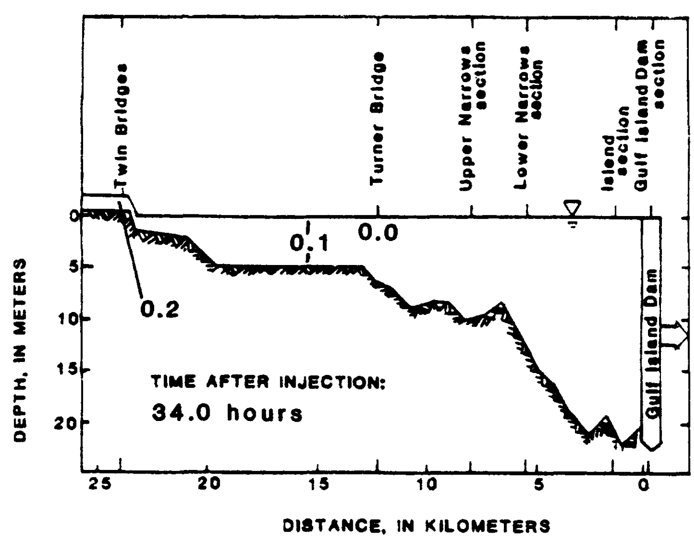
Water surface

Line of estimated equal dye concentration, in micrograms per liter

Streambed

Outflow dye concentration, in micrograms per liter

A single uncontoured value indicates equal dye concentration for the entire section in micrograms per liter



Note: Peak between Twin Bridges and Turner Bridge

Figure C-2.--Isopleths of dye concentration in Gulf Island Pond, September 14, 1981

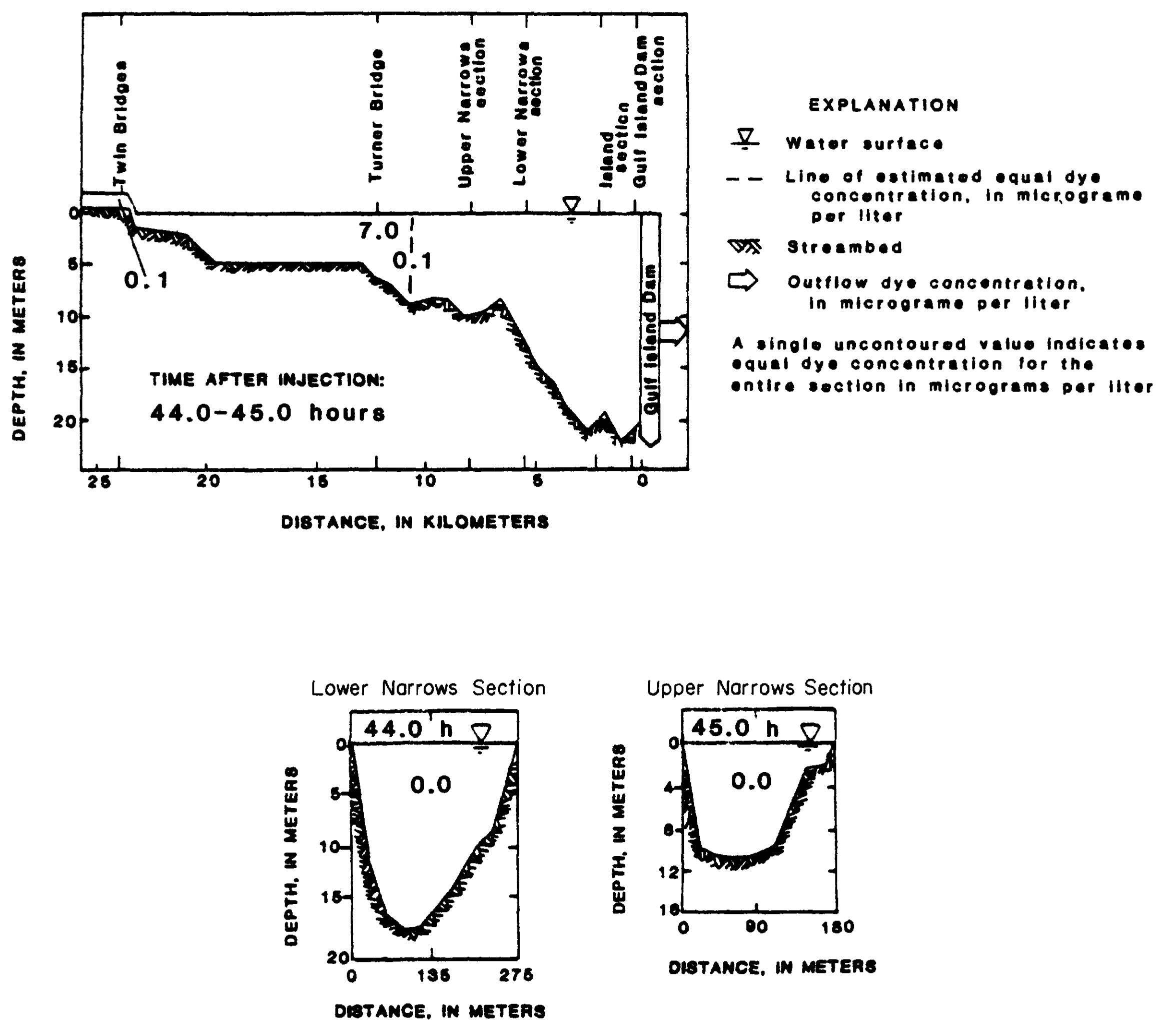


Figure C-3.--Isopleths of dye concentration in Gulf Island Pond, September 15, 1981

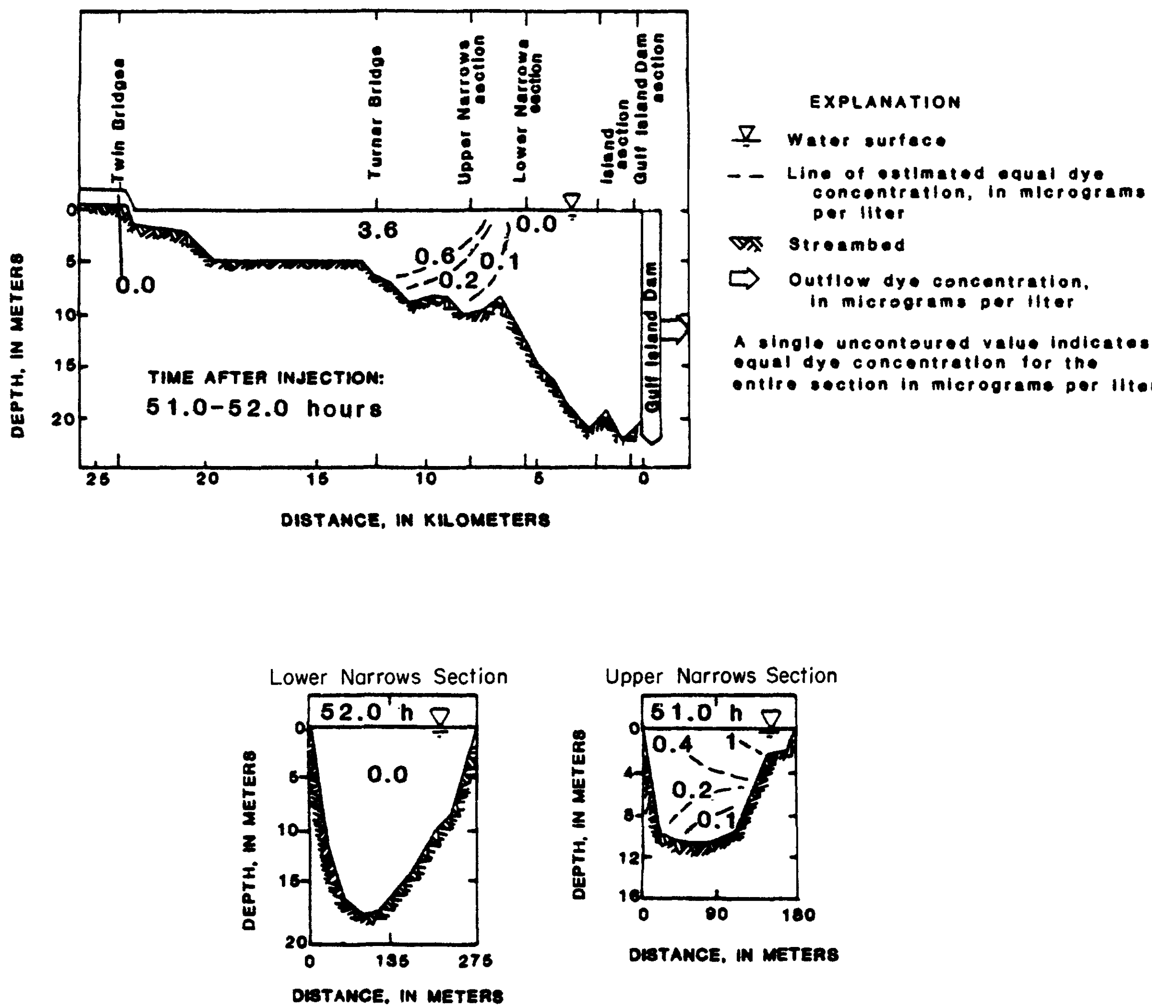


Figure C-4.--Isopleths of dye concentration in Gulf Island Pond, September 15, 1981

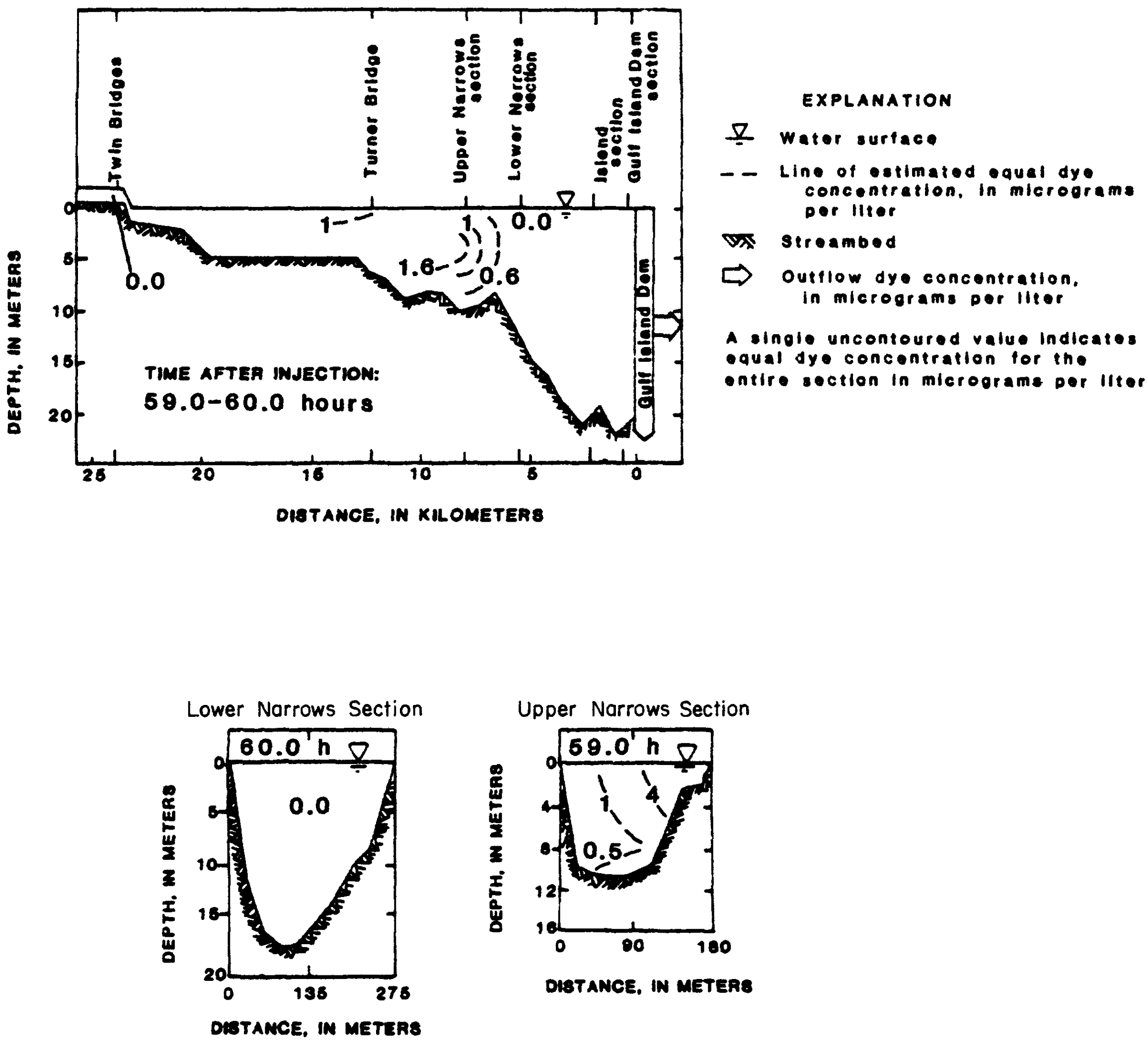


Figure C-5.--Isopleths of dye concentration in Gulf Island Pond, September 16, 1981

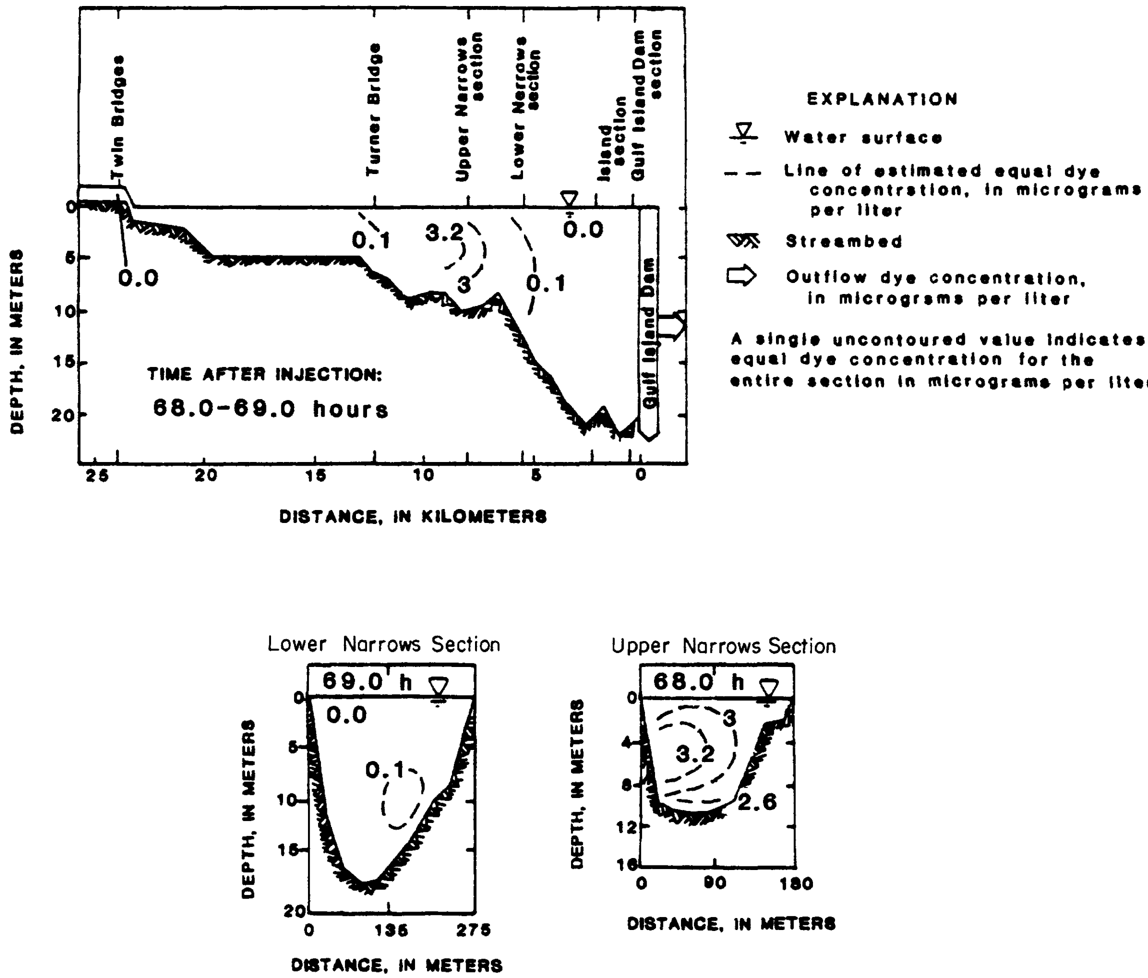


Figure C-6.--Isopleths of dye concentration in Gulf Island Pond, September 16, 1981

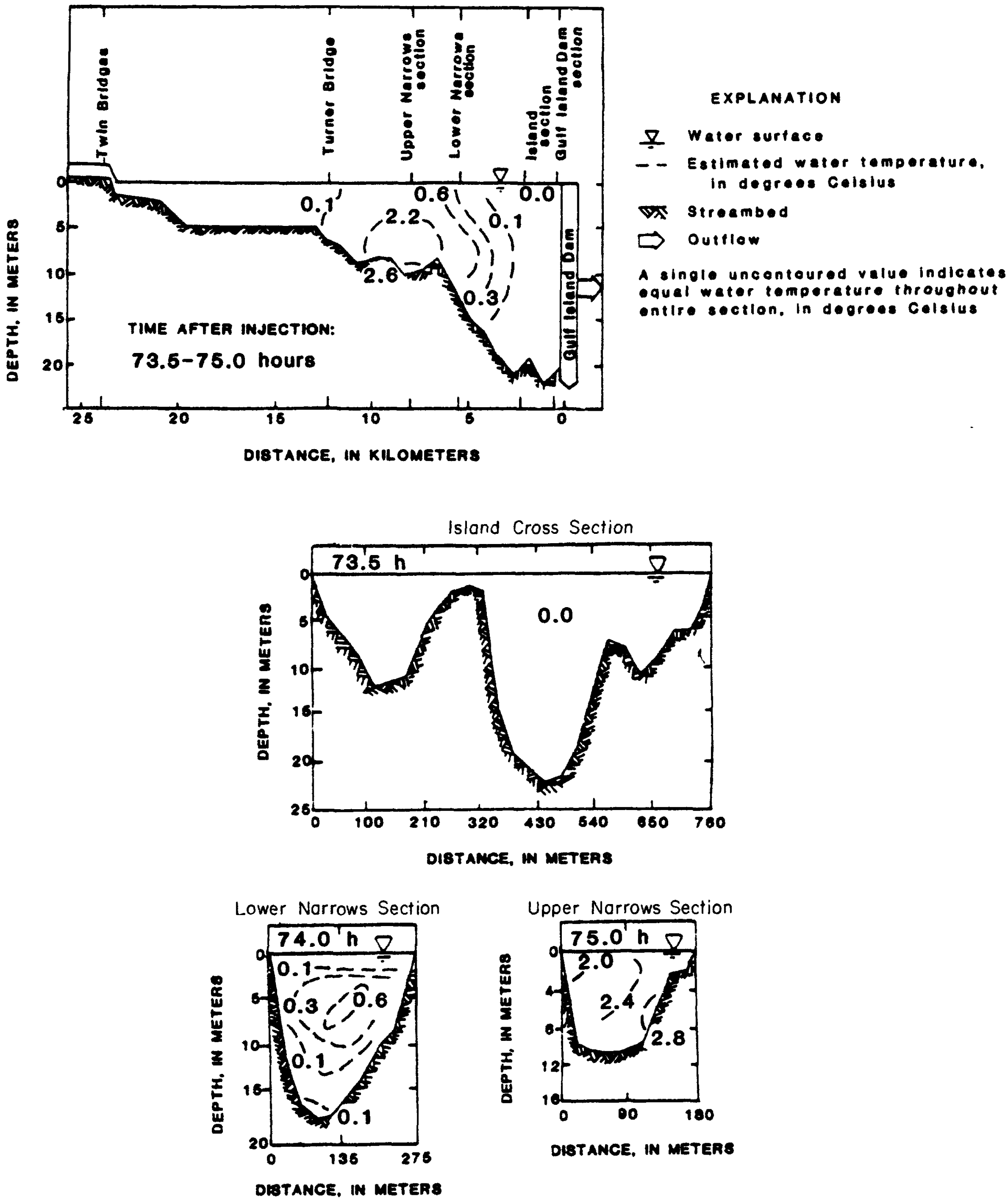


Figure C-7.--Isopleths of dye concentration in Gulf Island Pond, September 16, 1981

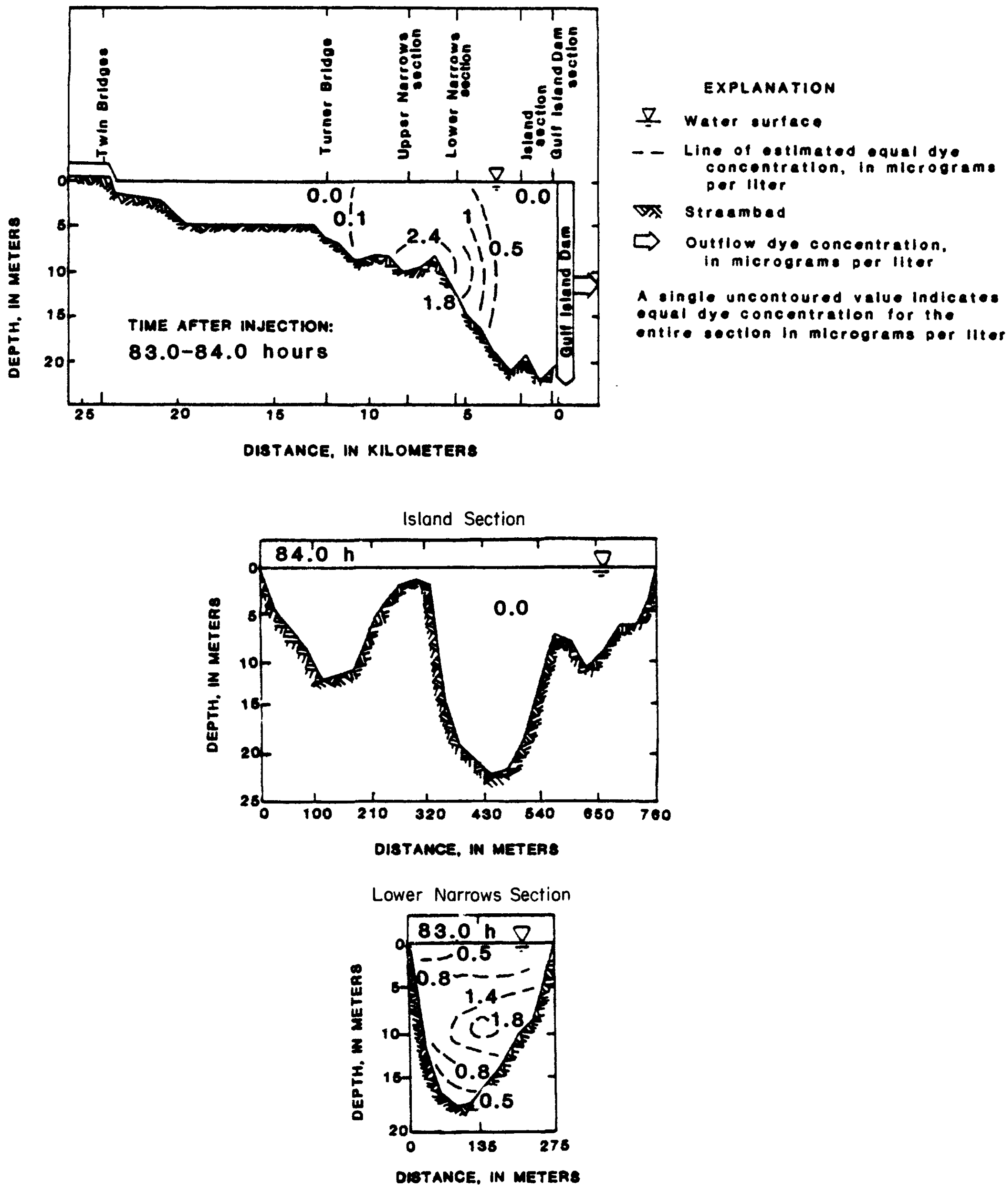


Figure C-8.--Isopleths of dye concentration in Gulf Island Pond, September 17, 1981

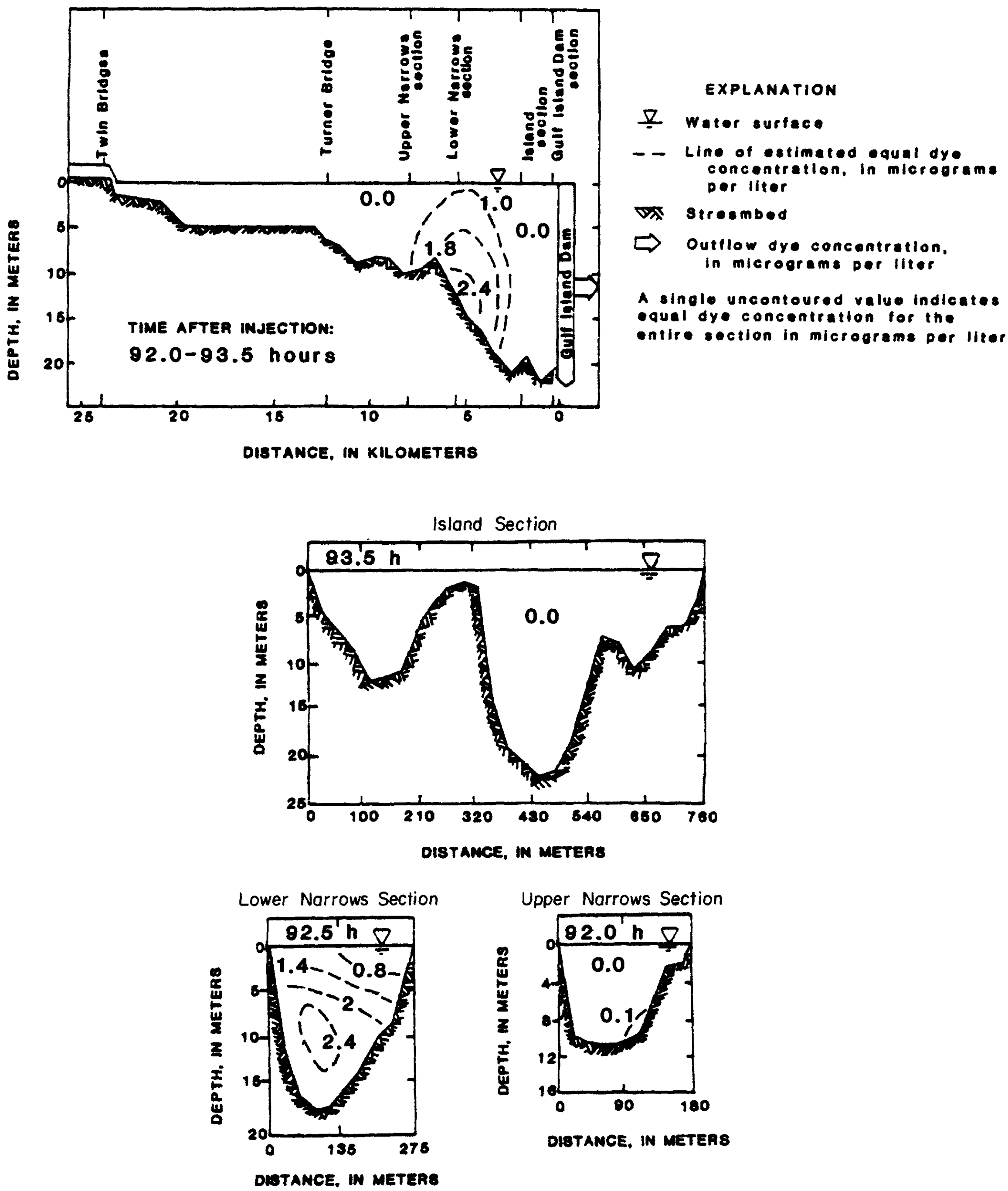


Figure C-9.--Isopleths of dye concentration in Gulf Island Pond, September 17, 1981

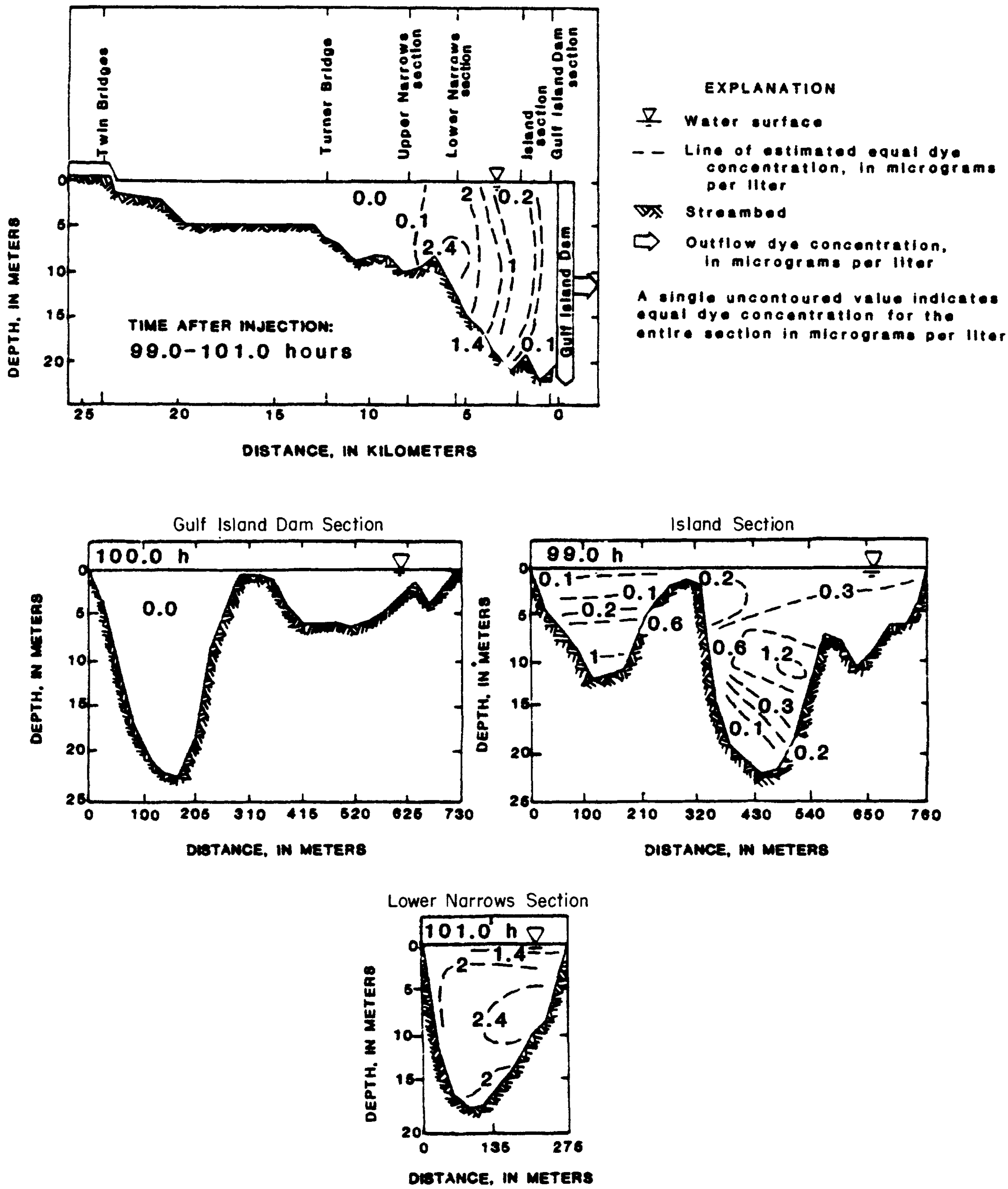


Figure C-10.--Isopleths of dye concentration in Gulf Island Pond, September 17, 1981

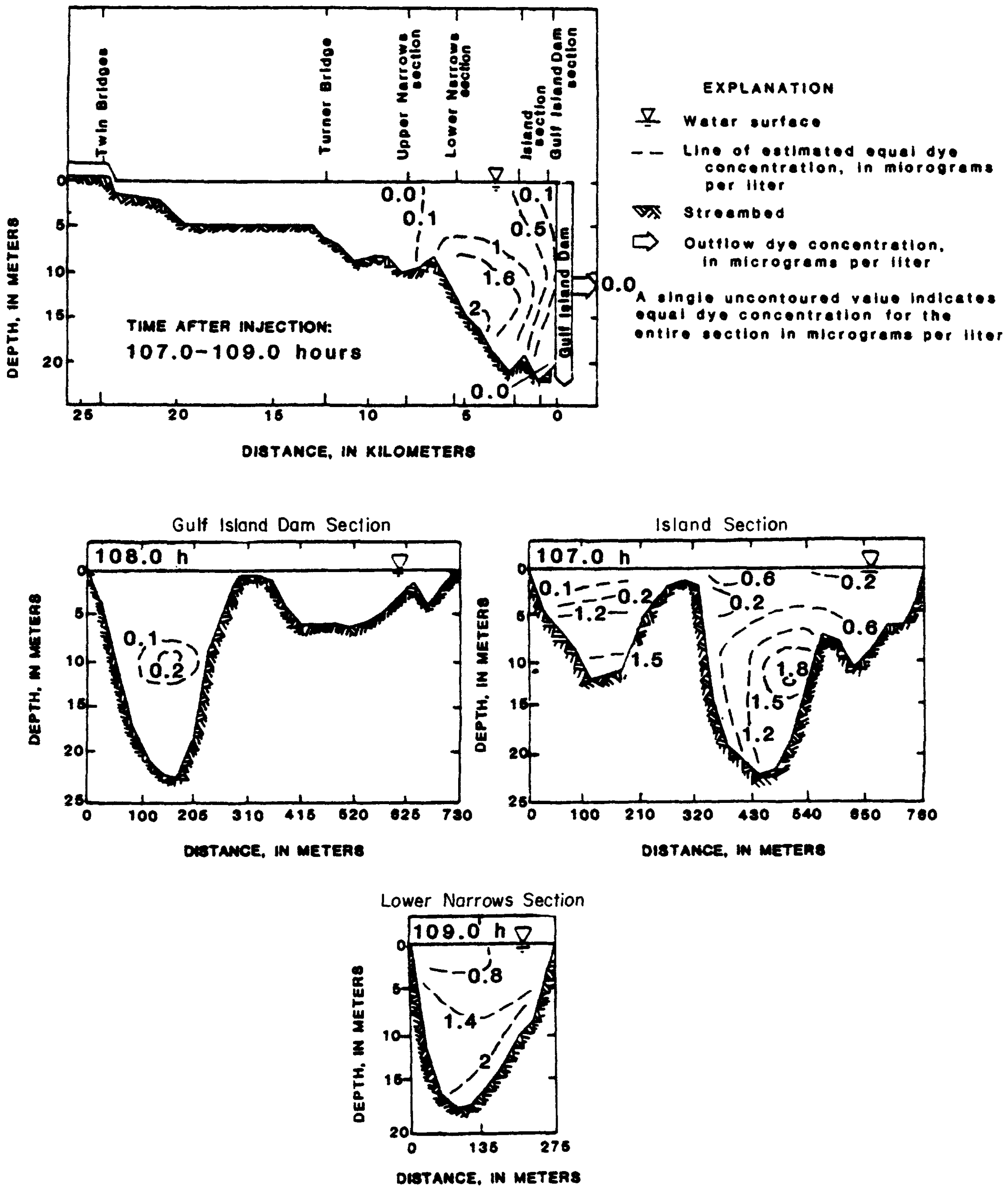


Figure C-11.--Isopleths of dye concentration in Gulf Island Pond, September 18, 1981

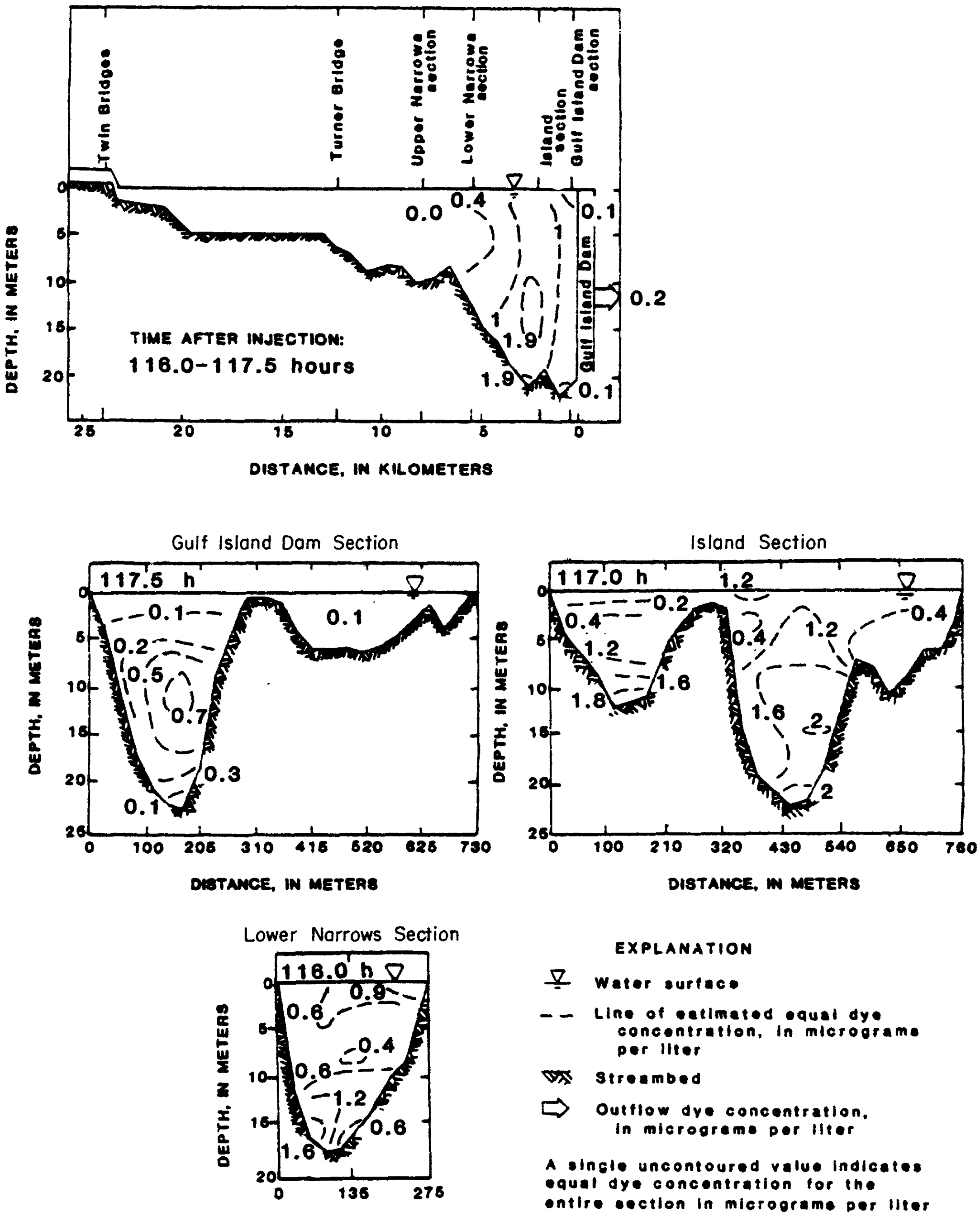


Figure C-12.--Isopleths of dye concentration in Gulf Island Pond, September 18, 1981

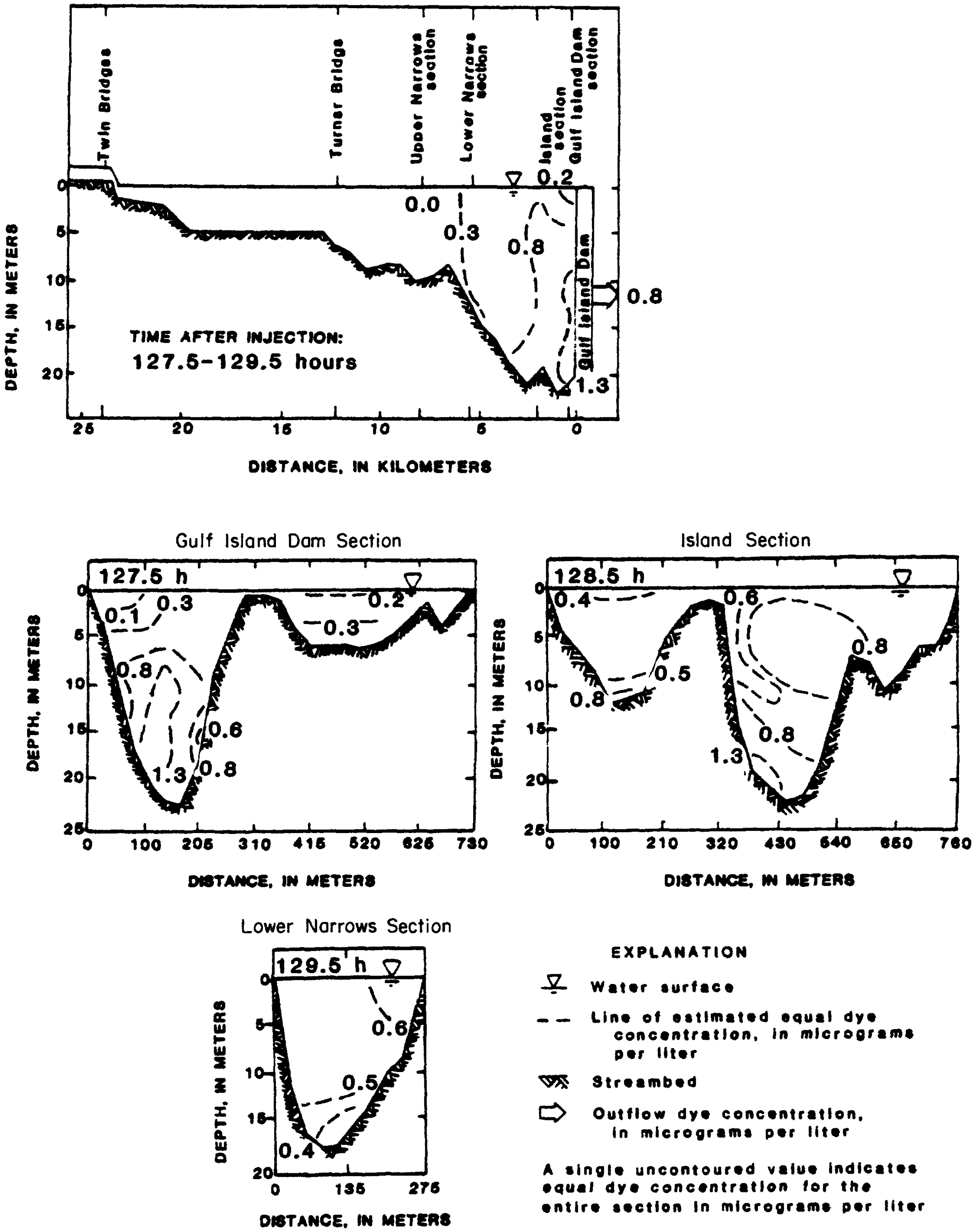


Figure C-13.--Isopleths of dye concentration in Gulf Island Pond, September 18, 1981

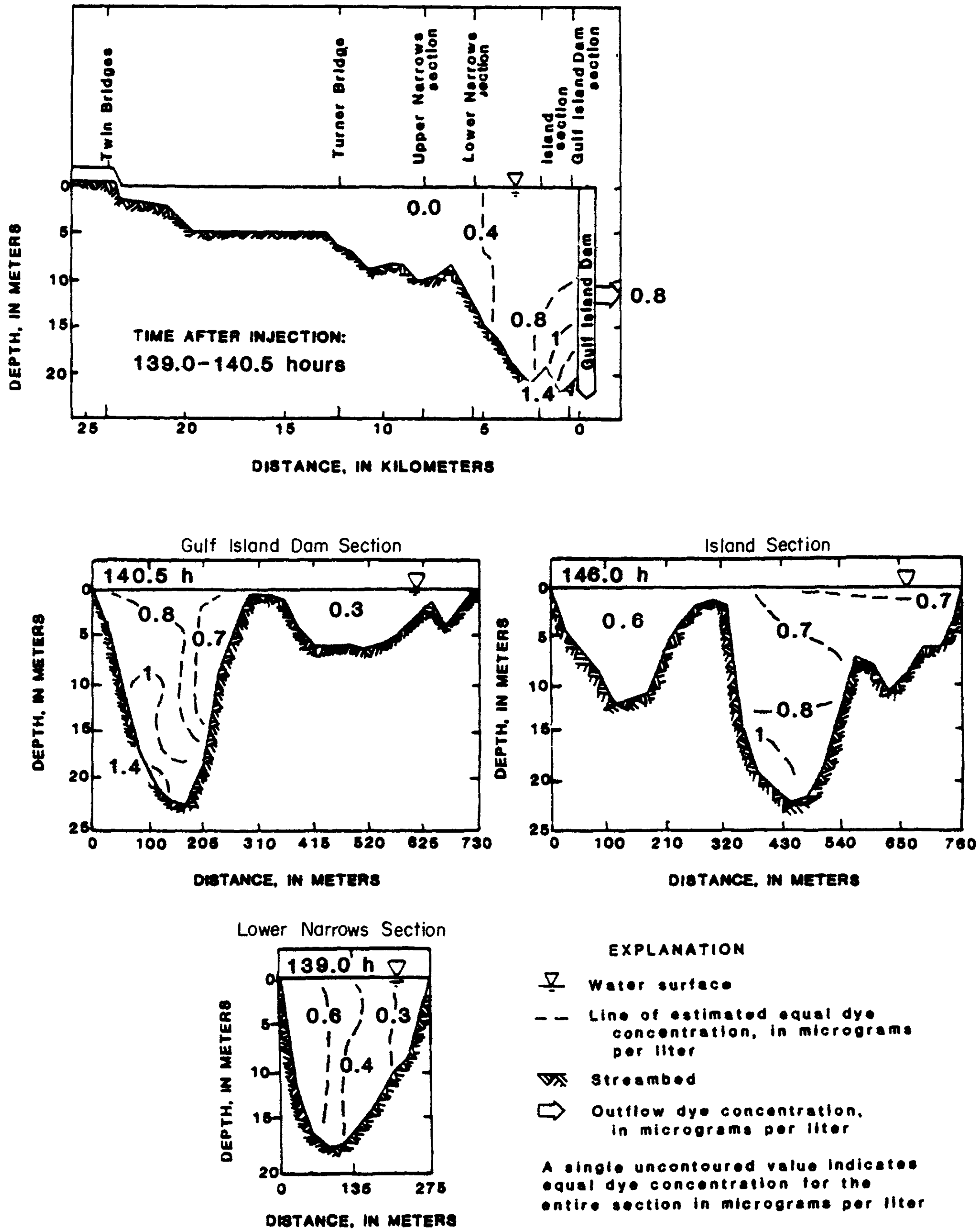


Figure C-14.--Isopleths of dye concentration in Gulf Island Pond, September 19, 1981

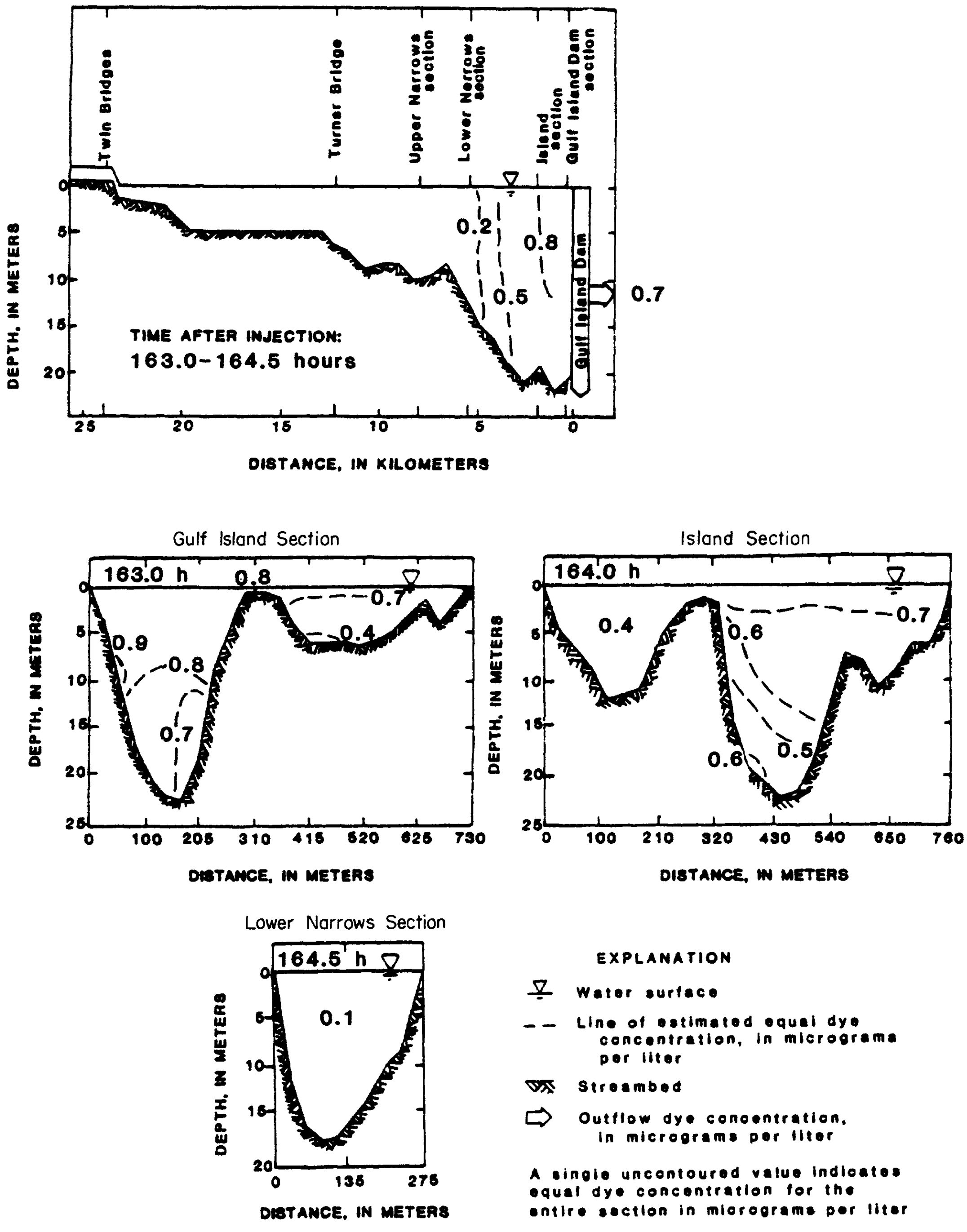


Figure C-15.--Isopleths of dye concentration in Gulf Island Pond, September 20, 1981

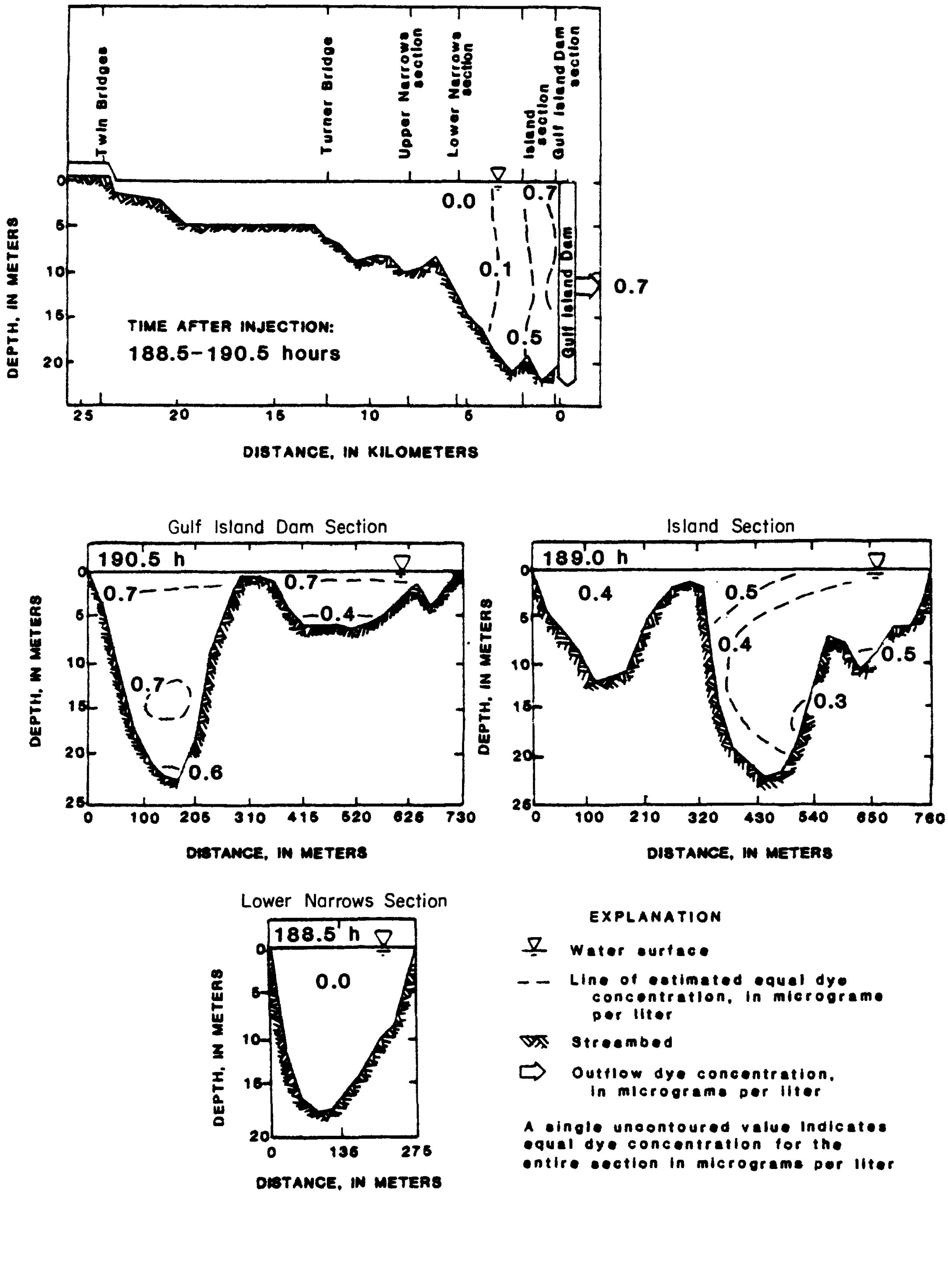


Figure C-16.--Isopleths of dye concentration in Gulf Island Pond, September 21, 1981

APPENDIX D.--ISOTHERMS IN GULF ISLAND POND

SEPTEMBER 1981

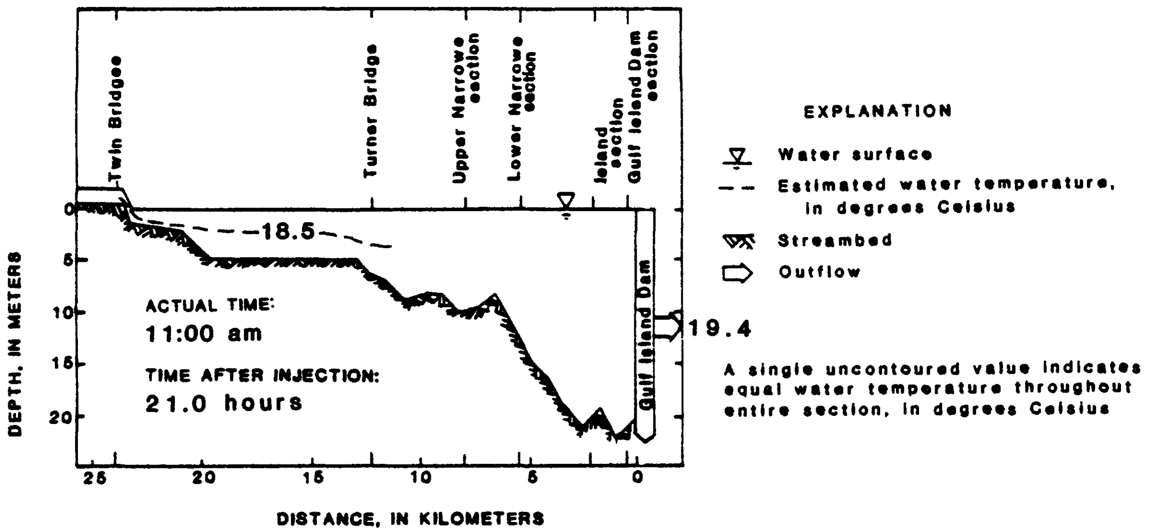


Figure D-1.--Isotherms in Gulf Island Pond, September 14, 1981

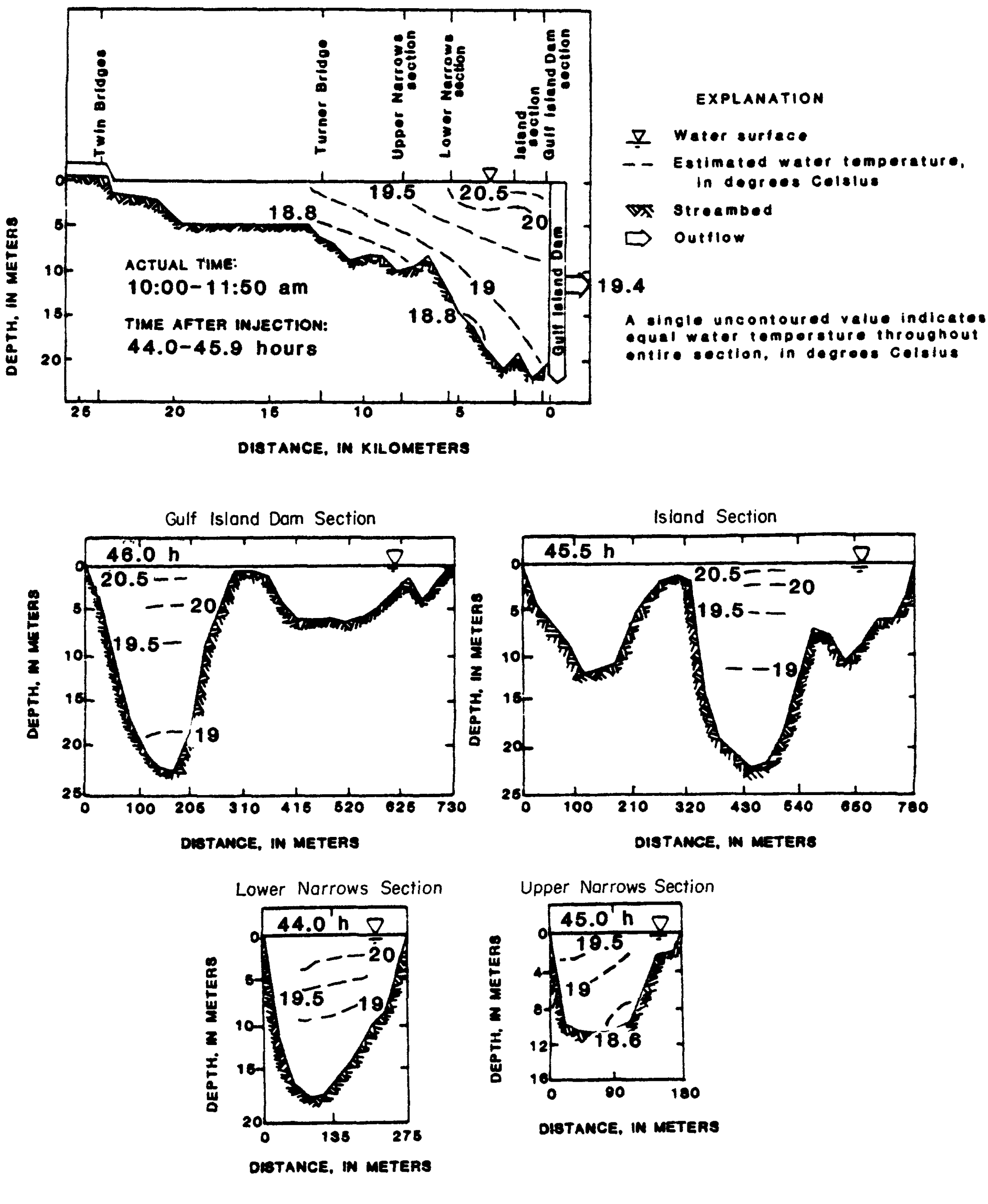


Figure D-2.--Isotherms in Gulf Island Pond, September 15, 1981

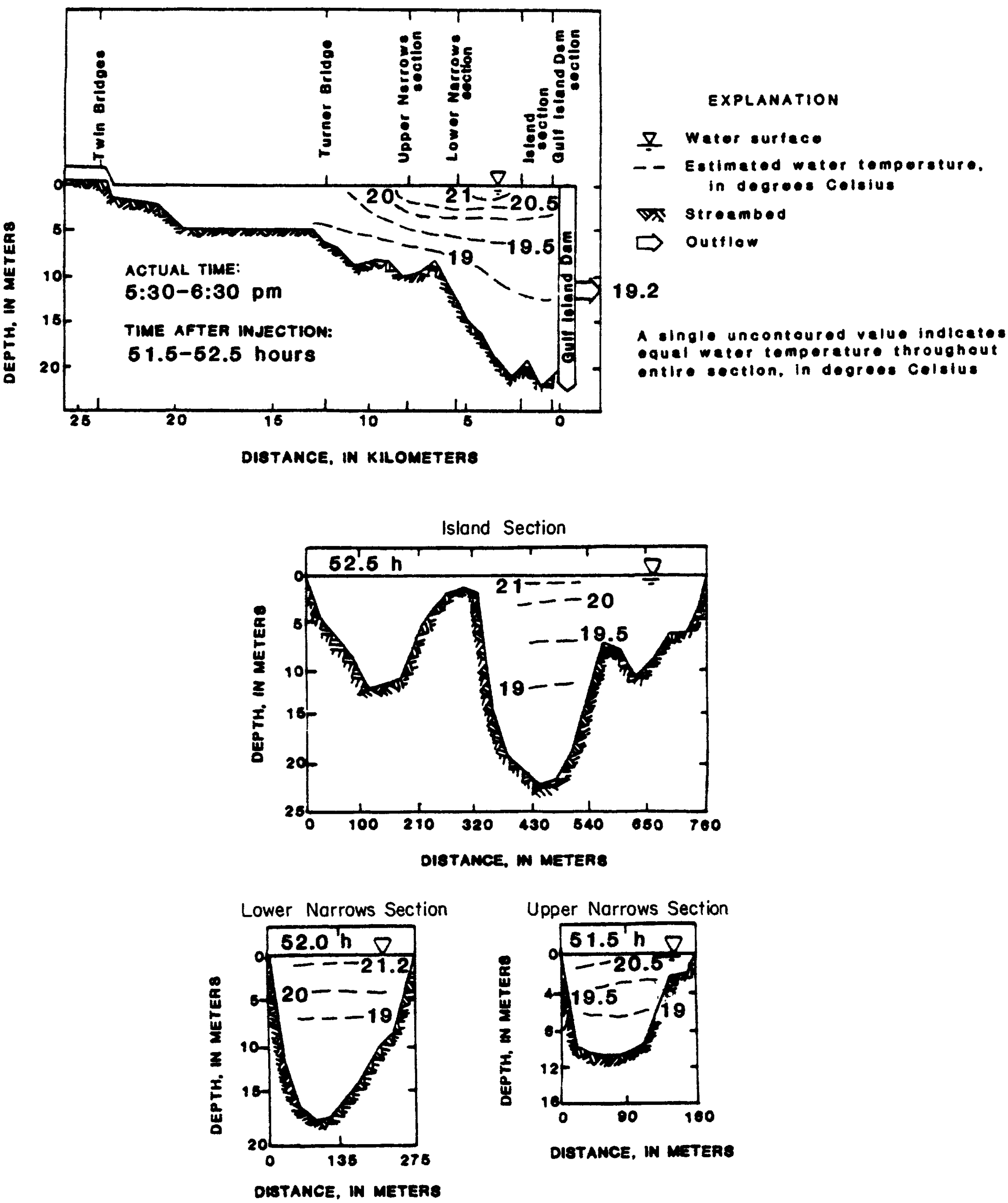
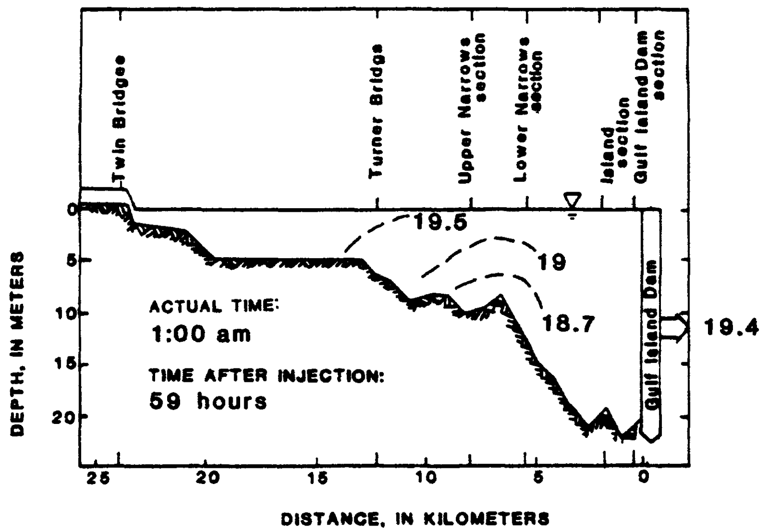


Figure D-3.--Isotherms in Gulf Island Pond, September 15, 1981



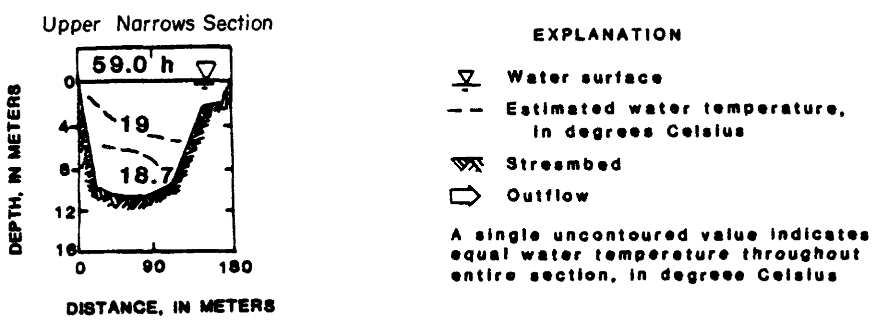
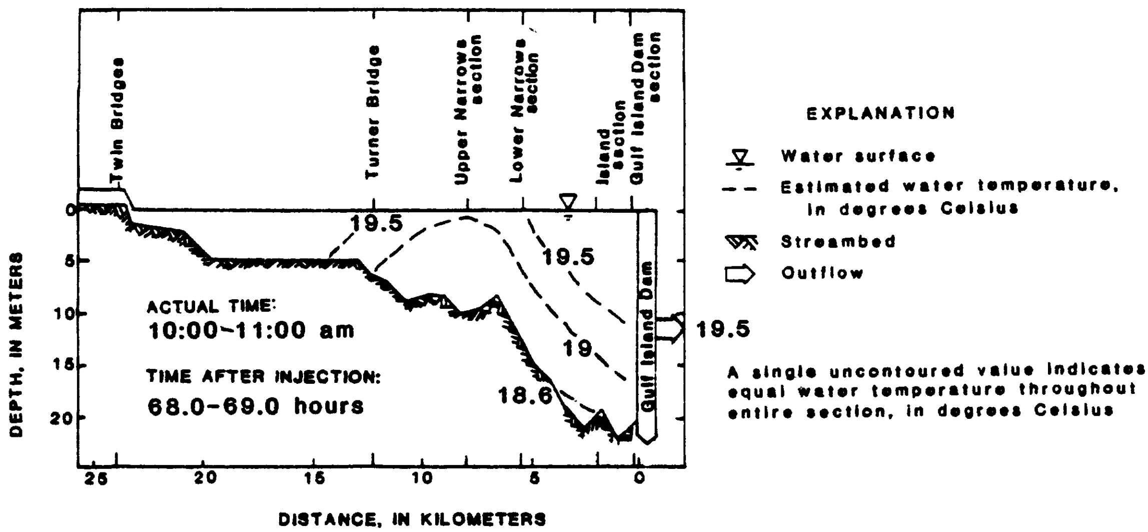
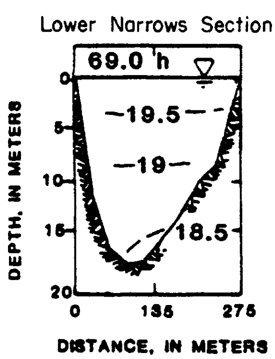


Figure D-4.--Isotherms in Gulf Island Pond, September 16, 1981





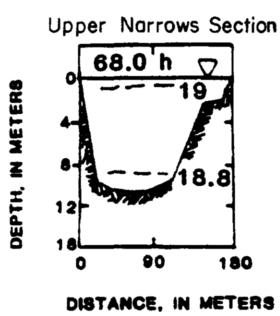


Figure D-5.--Isotherms in Gulf Island Pond, September 16, 1981

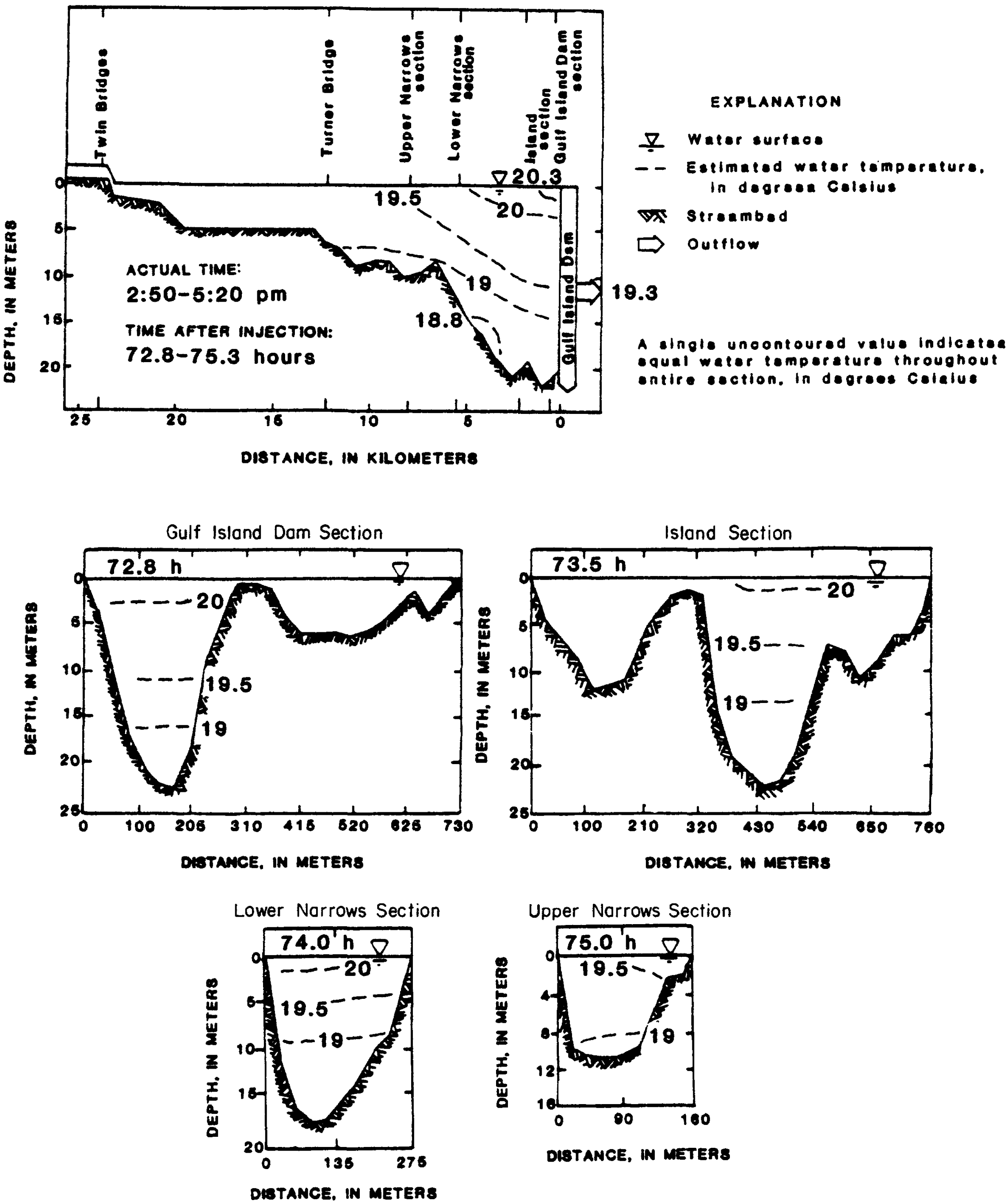


Figure D-6.--Isotherms in Gulf Island Pond, September 16, 1981

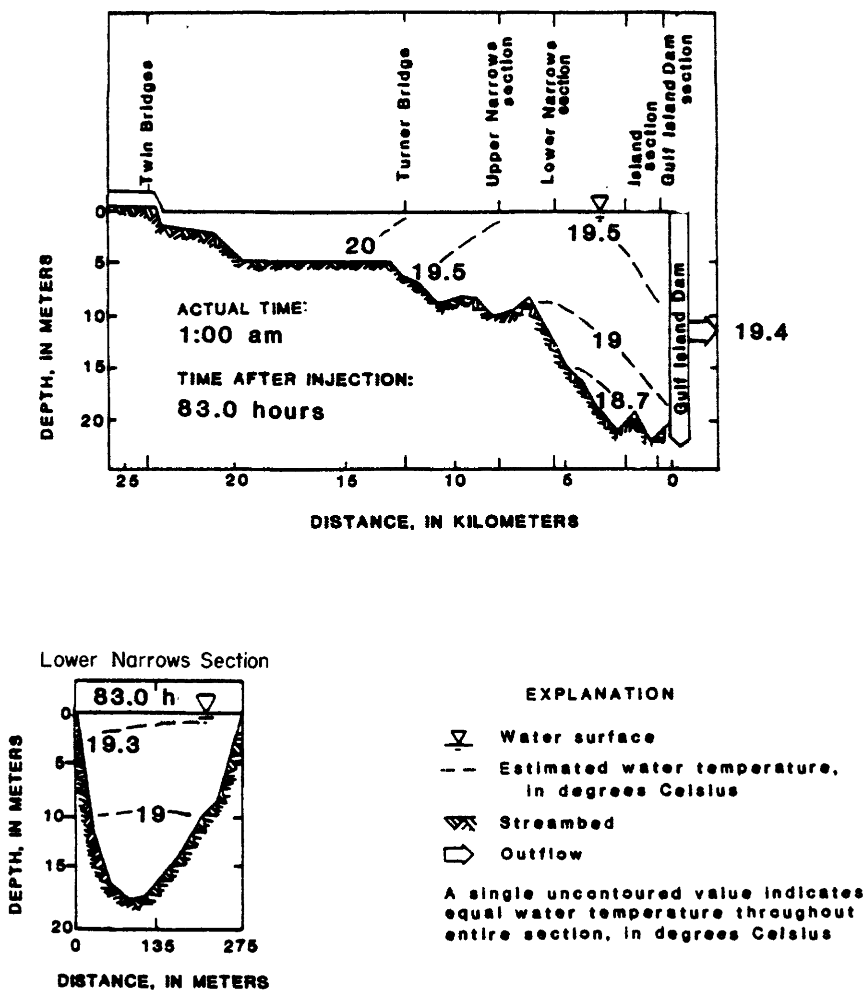


Figure D-7.--Isotherms in Gulf Island Pond, September 17, 1981

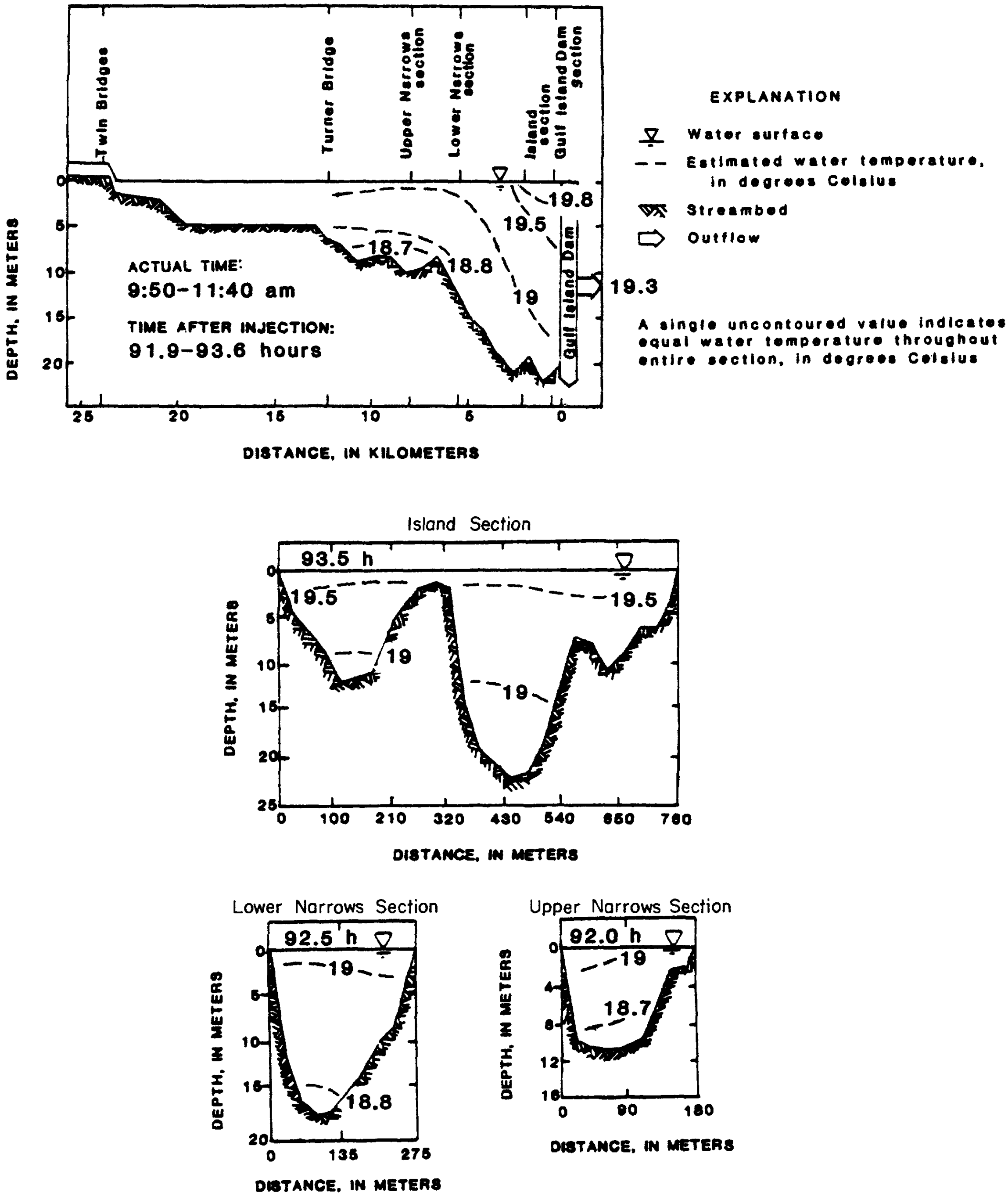


Figure D-8.--Isotherms in Gulf Island Pond, September 17, 1981

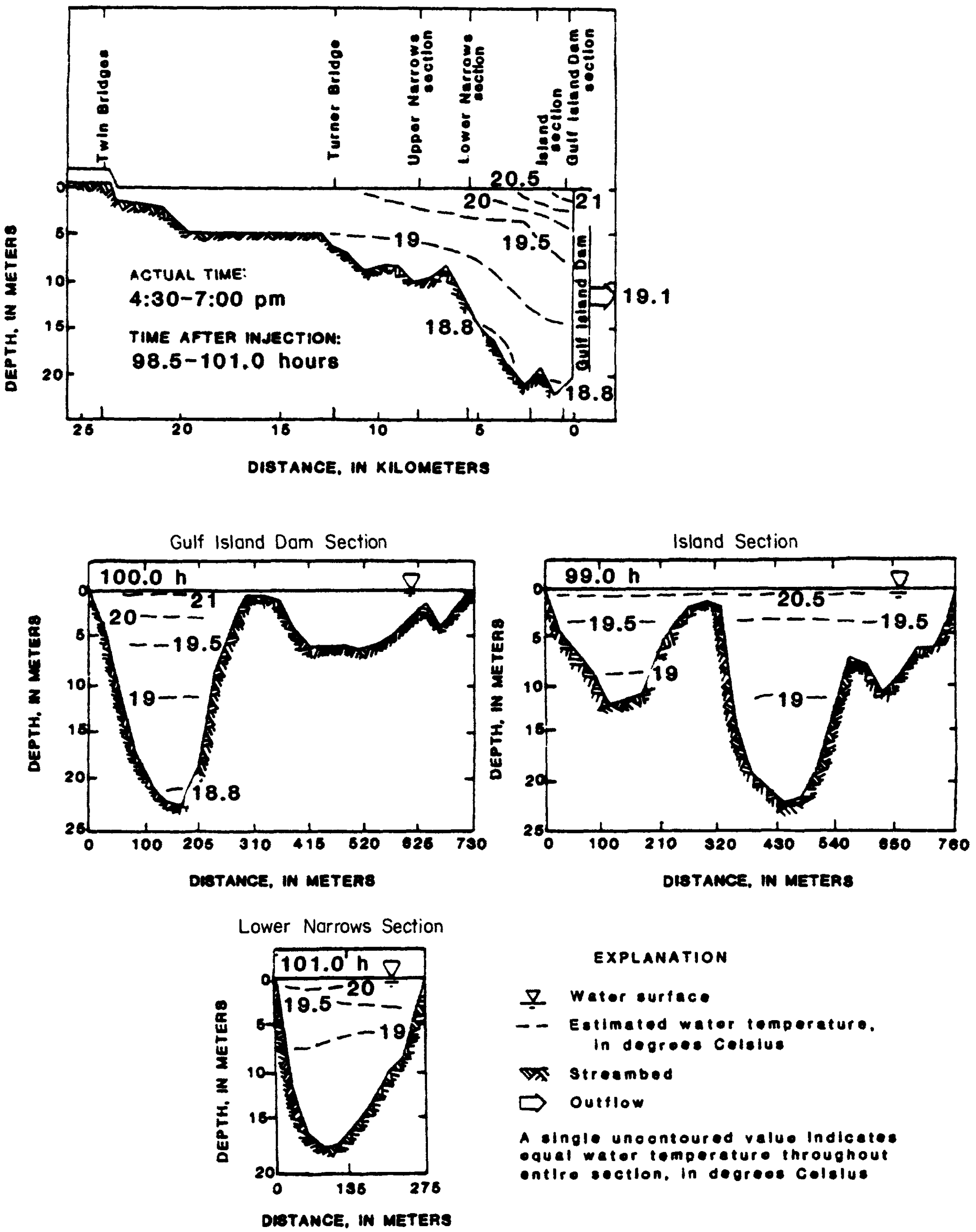


Figure D-9.--Isotherms in Gulf Island Pond, September 17, 1981

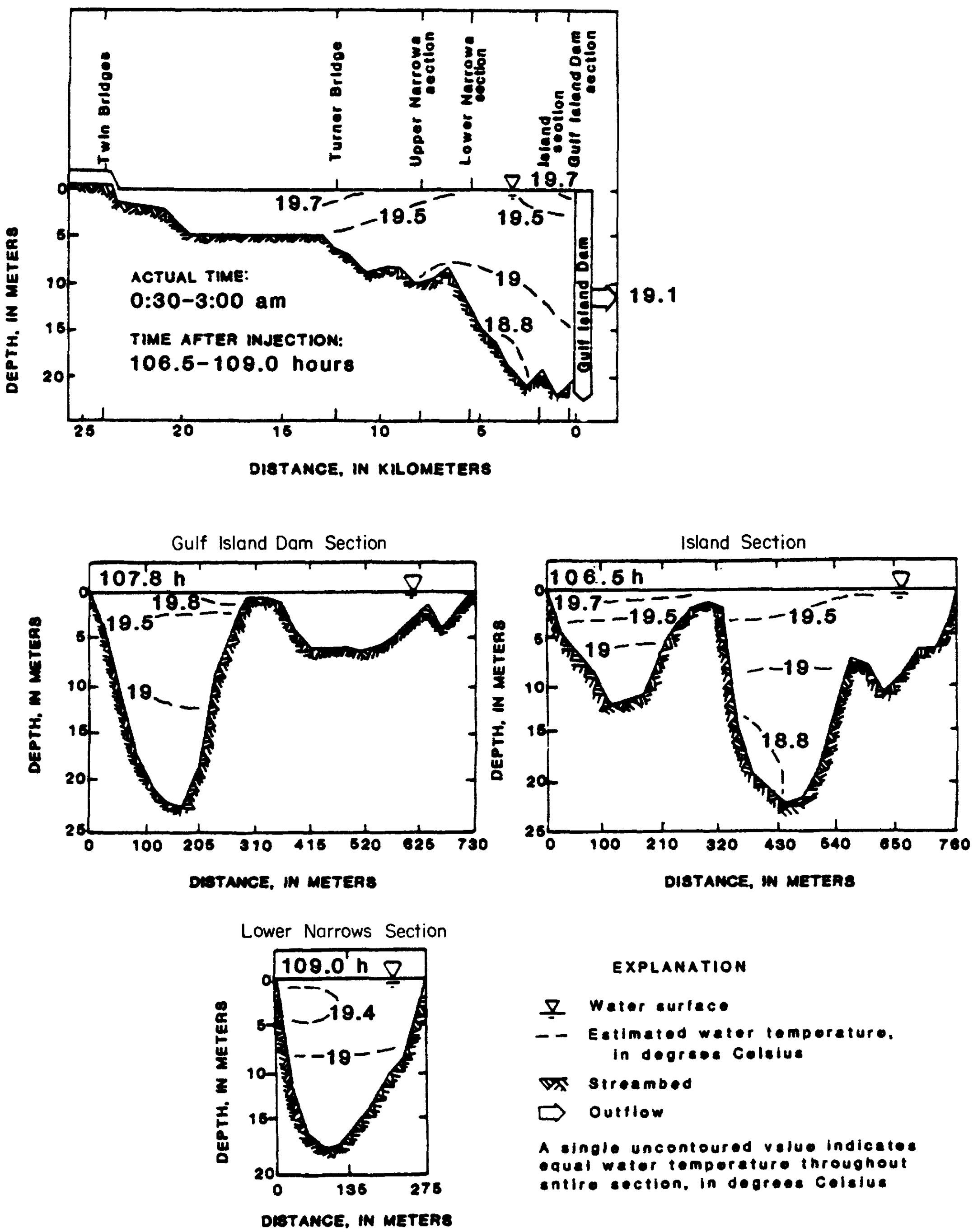


Figure D-10.--Isotherms in Gulf Island Pond, September 18, 1981

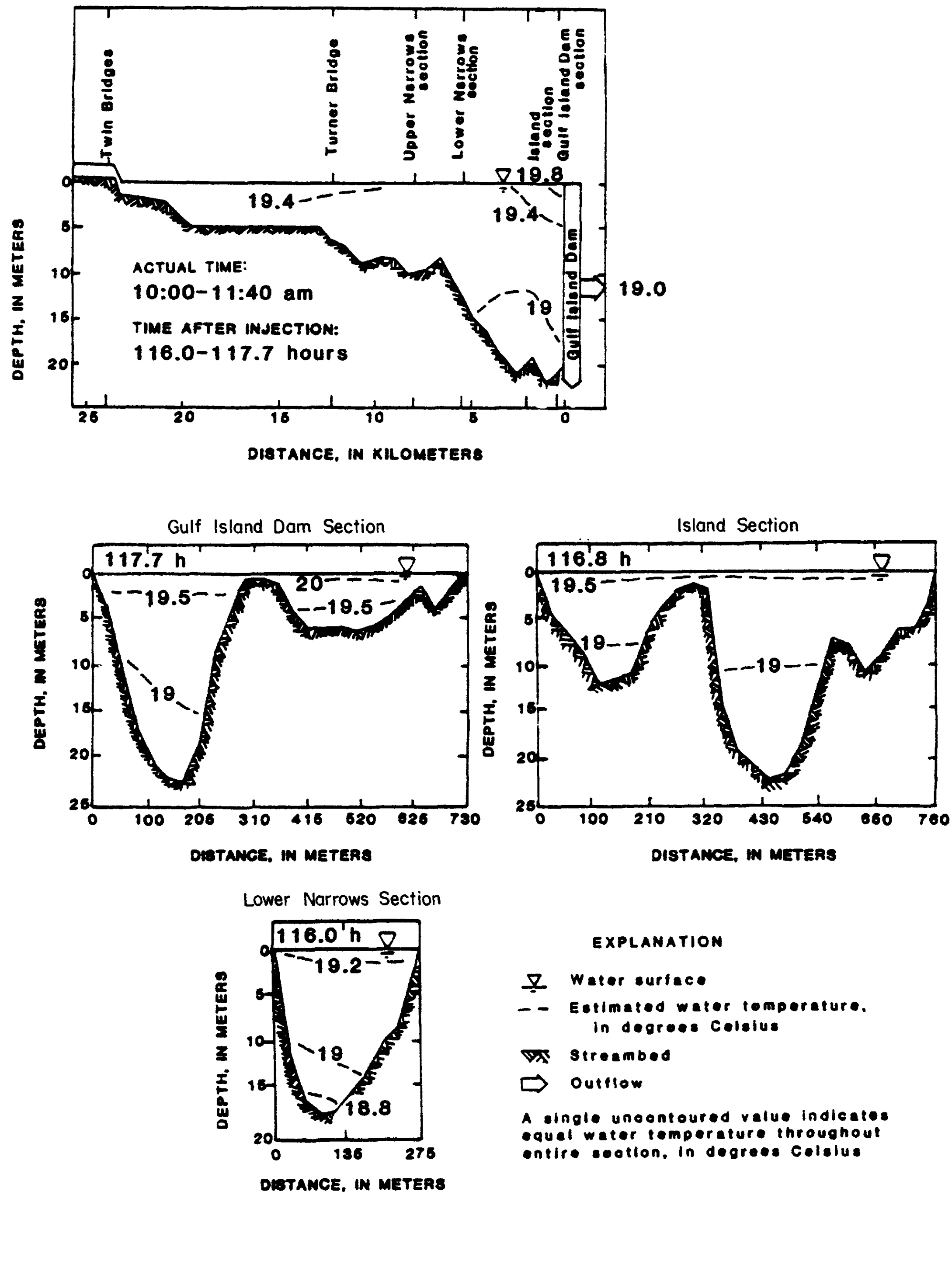


Figure D-11.--Isotherms in Gulf Island Pond, September 18, 1981

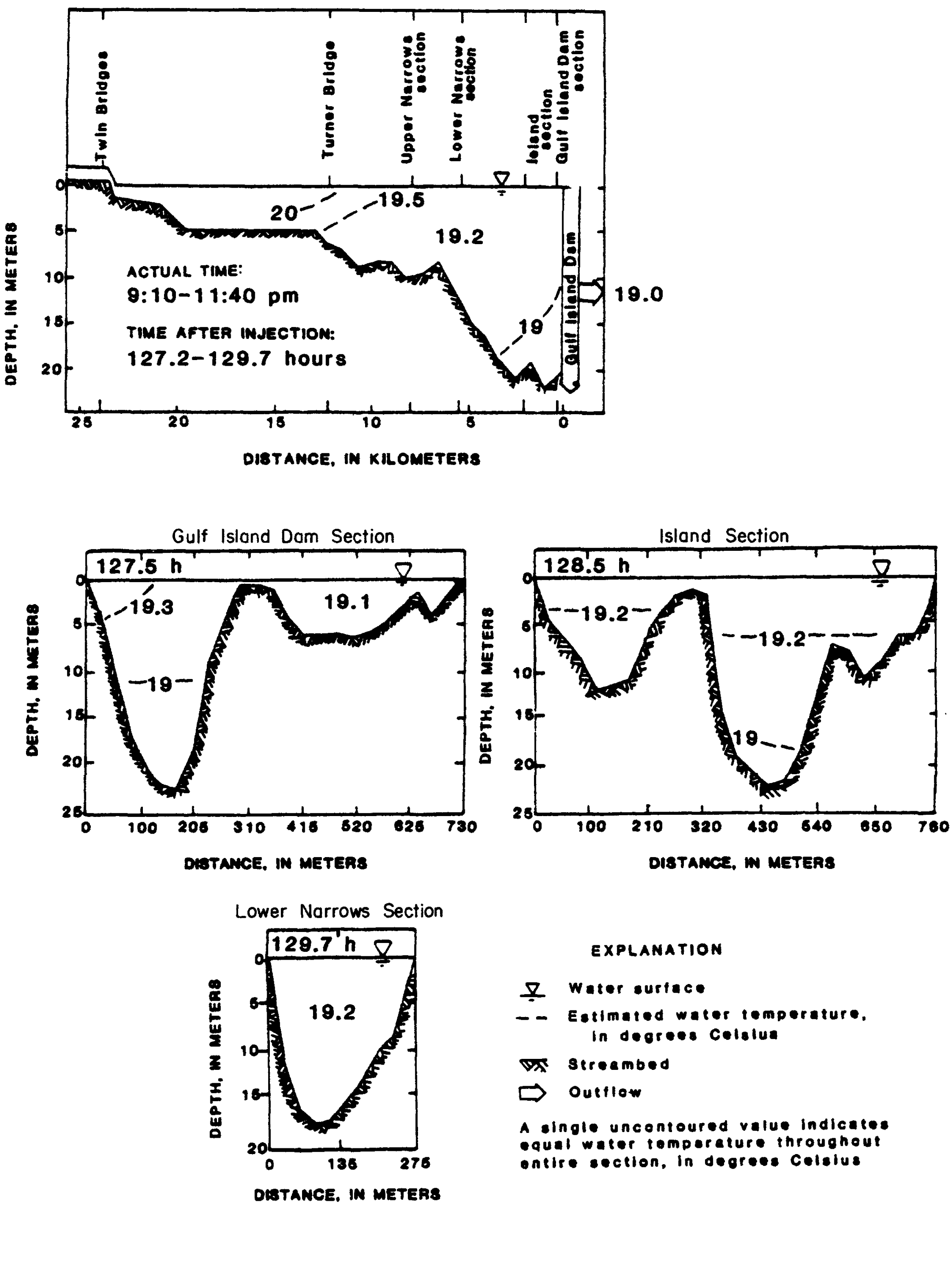


Figure D-12.--Isotherms in Gulf Island Pond, September 18, 1981

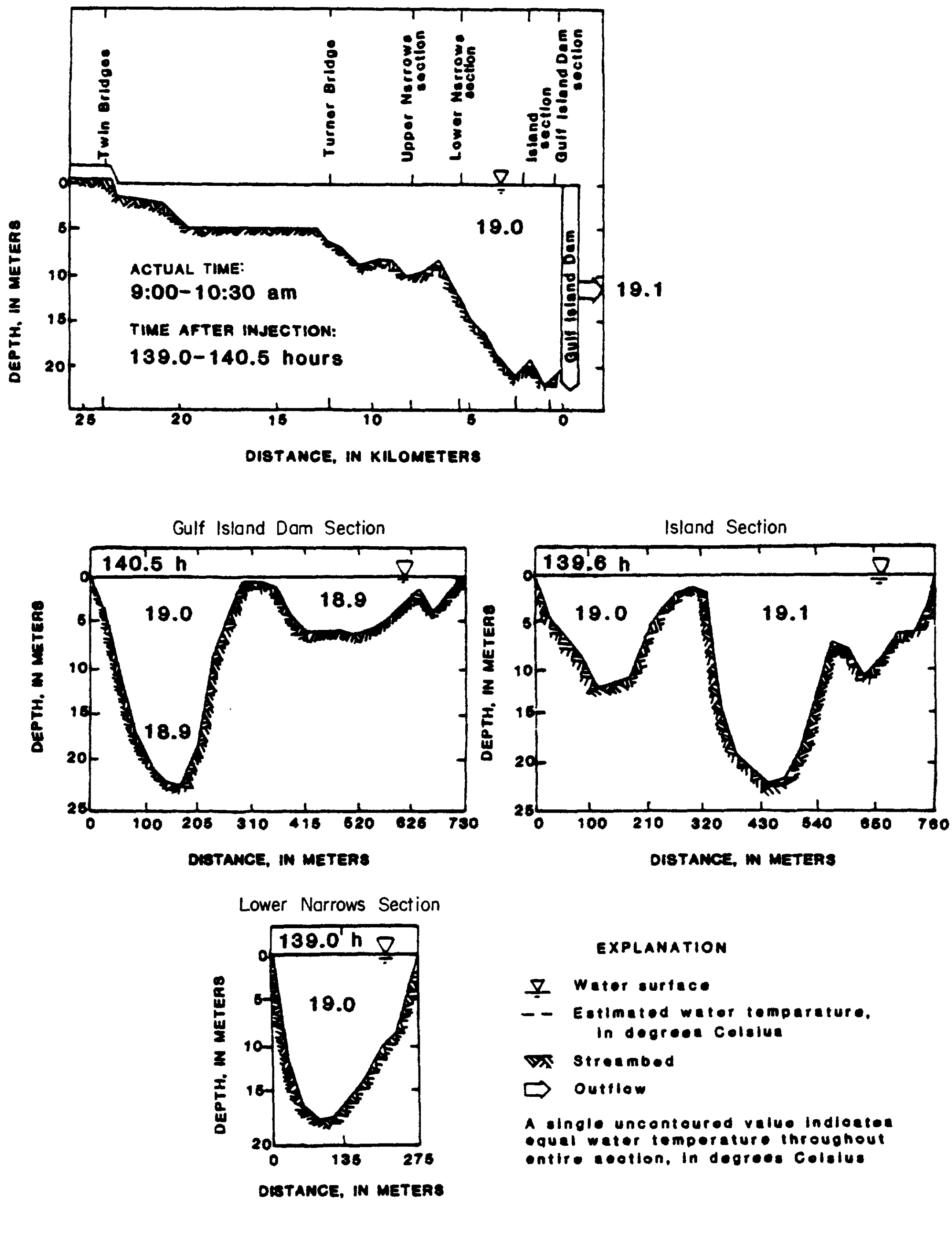


Figure D-13.--Isotherms in Gulf Island Pond, September 19, 1981

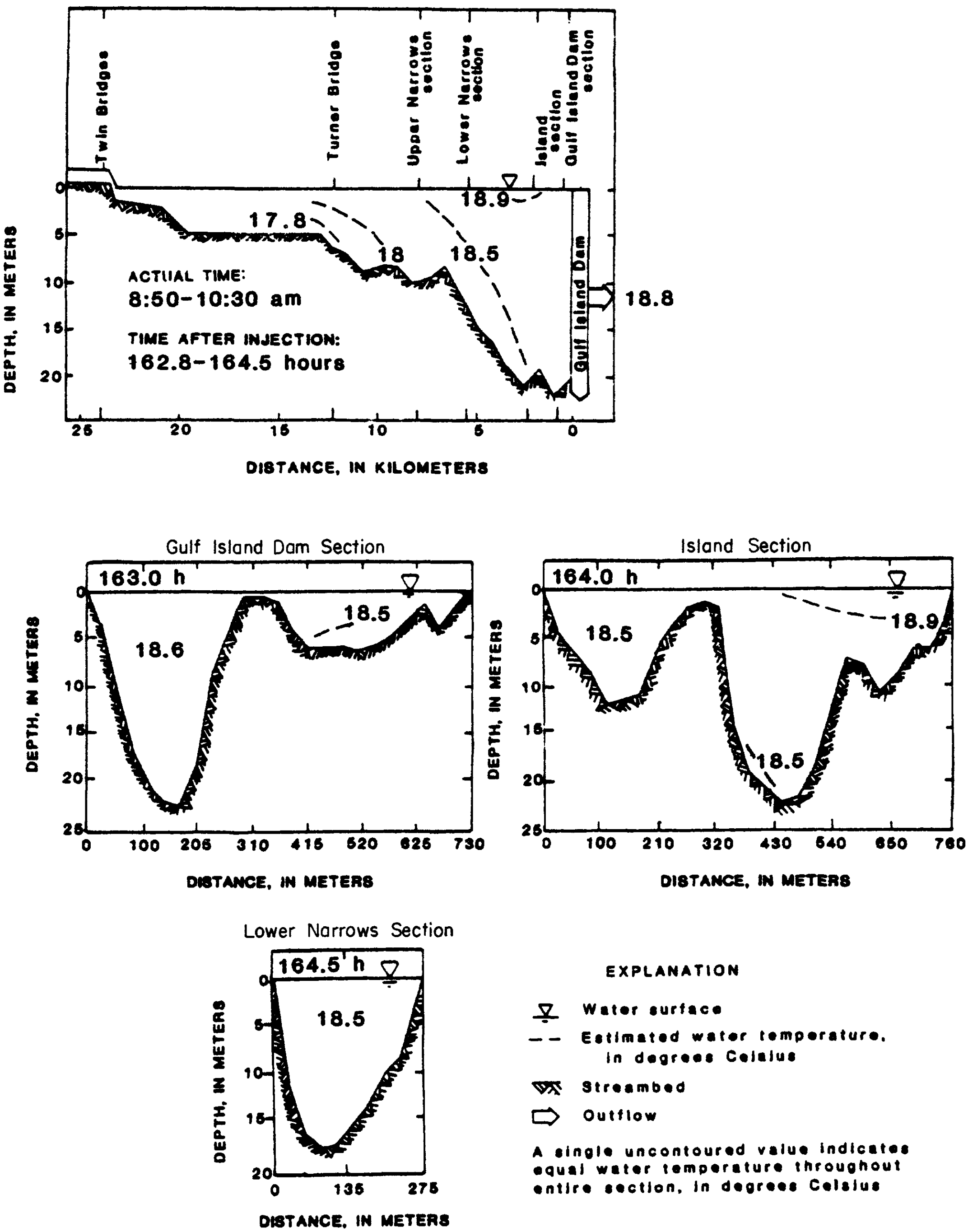


Figure D-14.--Isotherms in Gulf Island Pond, September 20, 1981

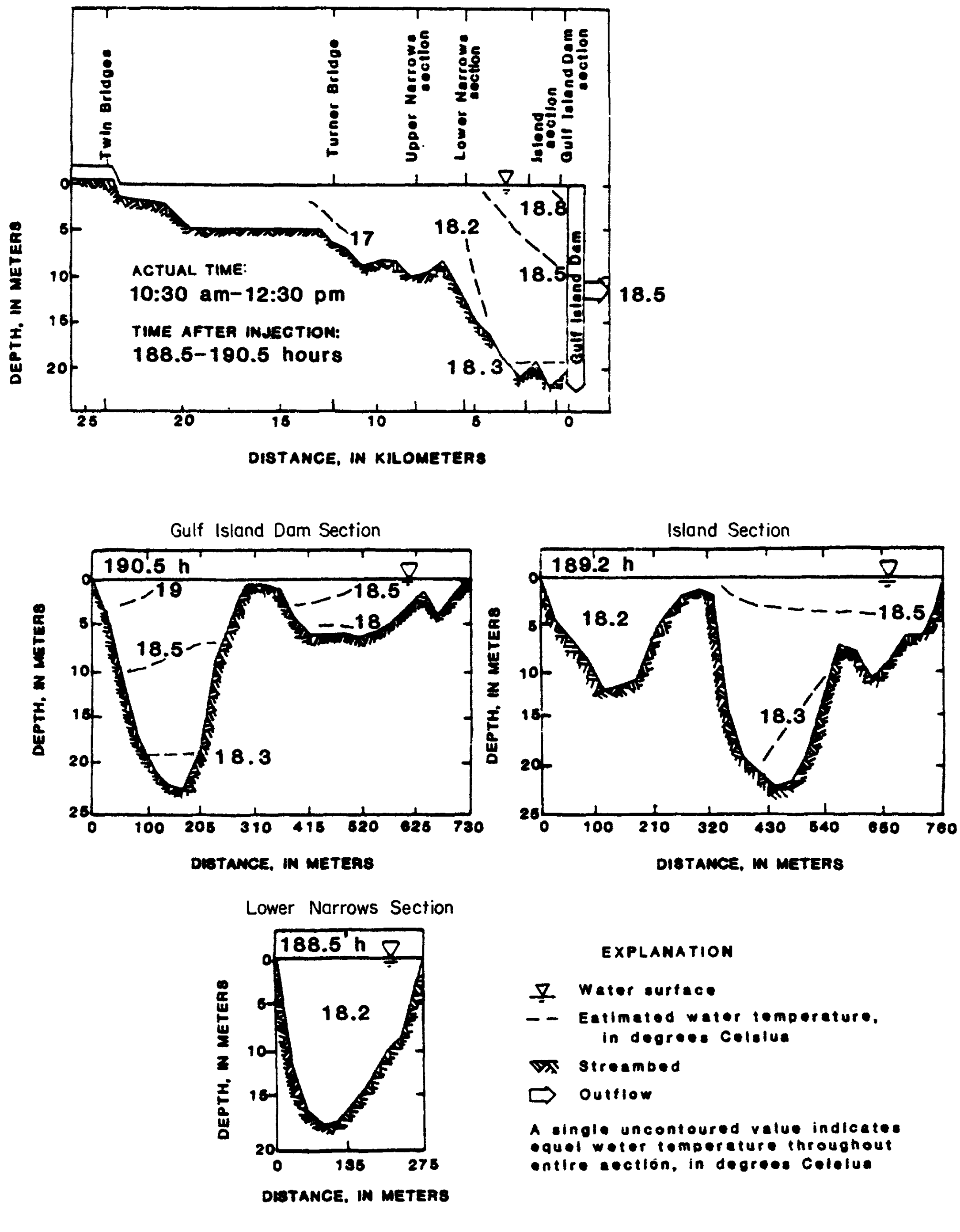


Figure D-15.--Isotherms in Gulf Island Pond, September 21, 1981

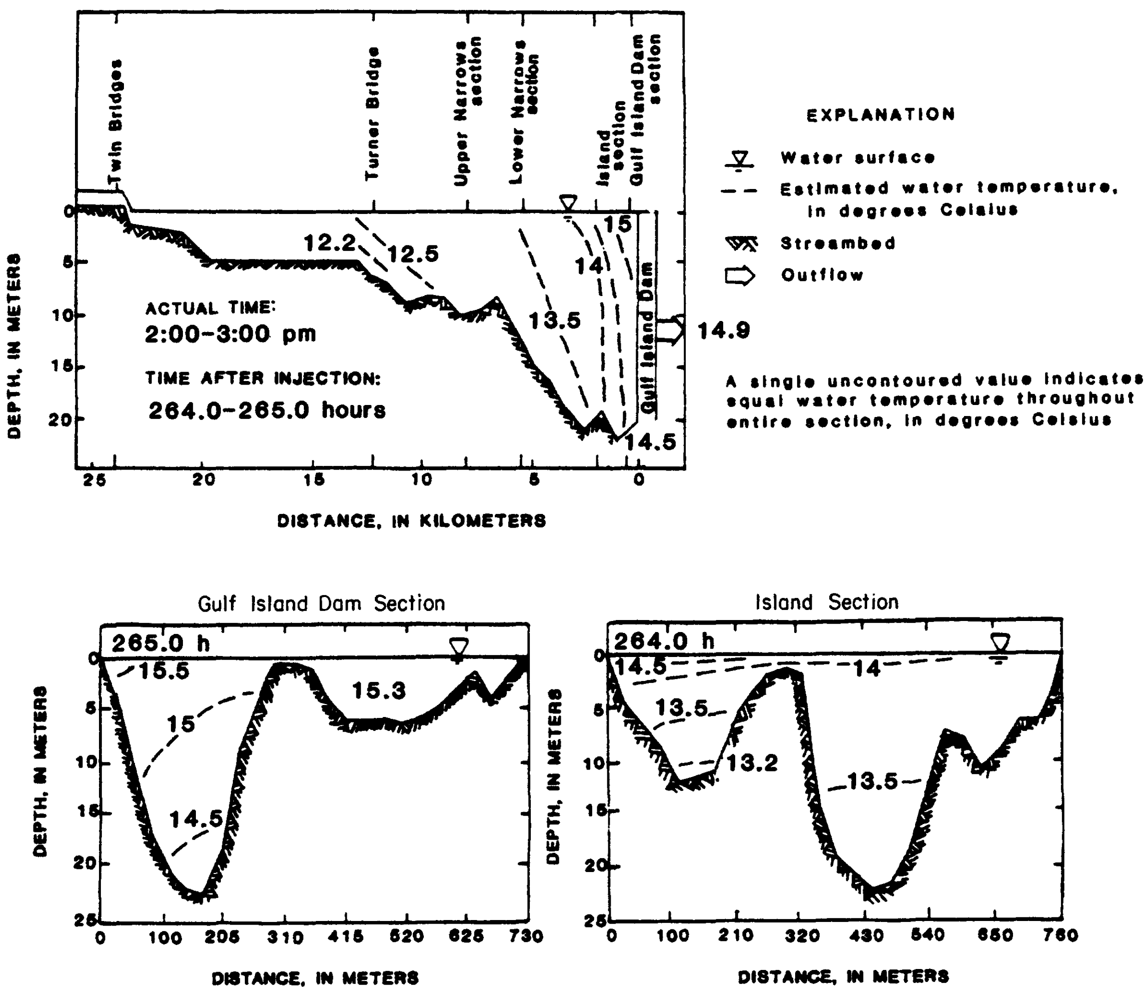


Figure D-16.--Isotherms in Gulf Island Pond, September 24, 1981

APPENDIX E.--DISCHARGE, DYE CONCENTRATION, AND DYE MASS FLOW VERSUS TIME AFTER INJECTION

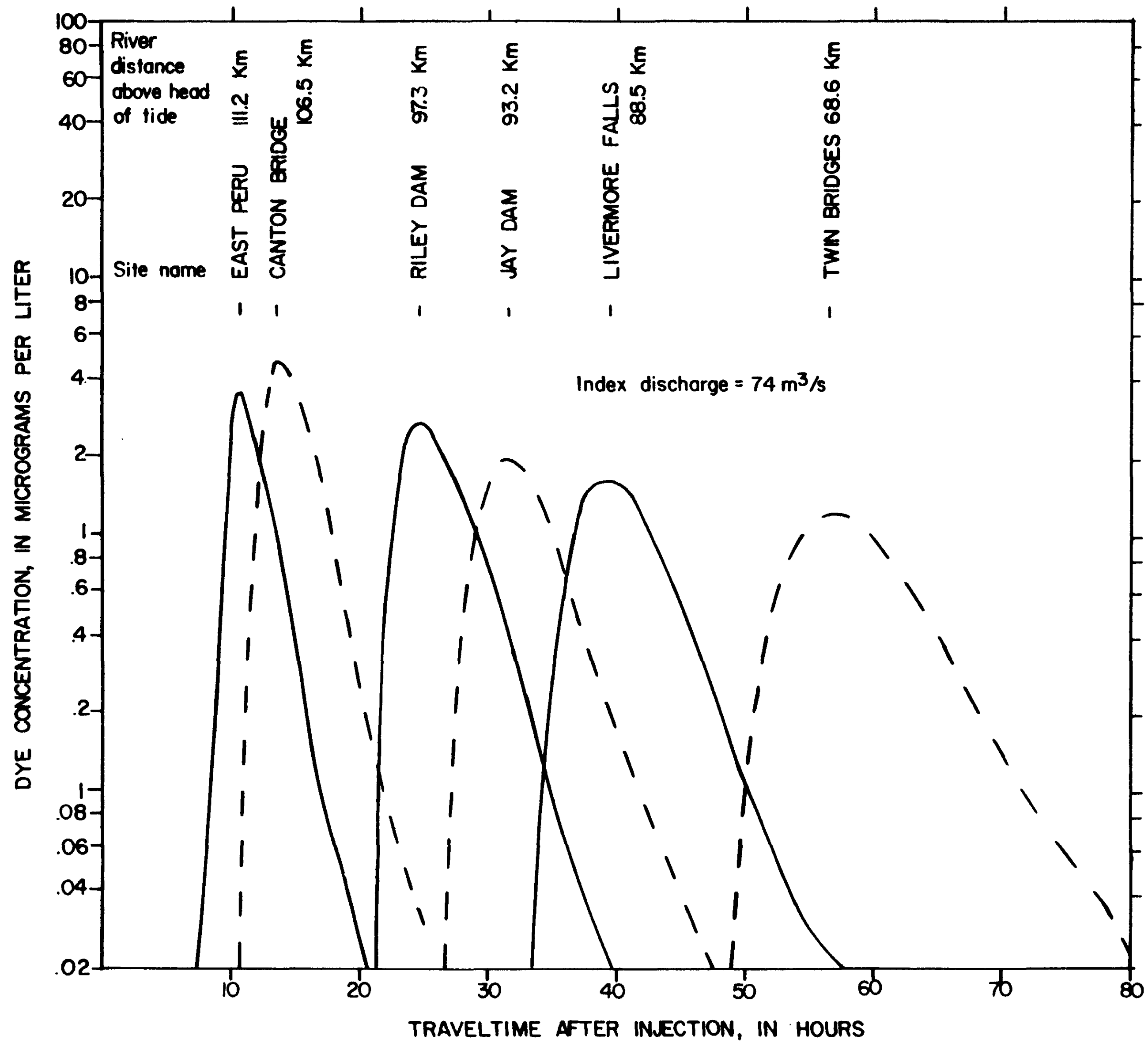


Figure E-1.--Traveltime versus dye concentration for subreach A, June 1980

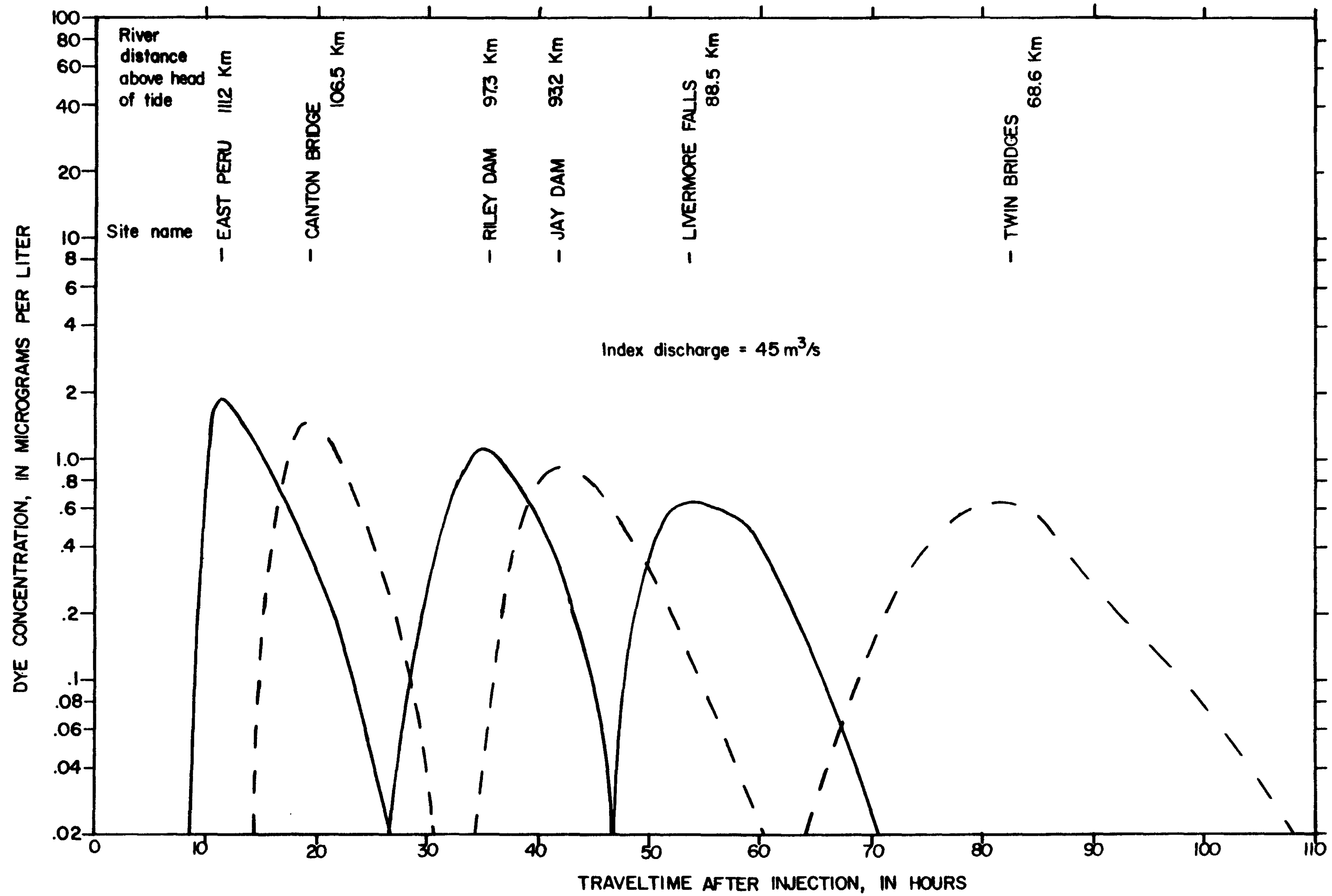


Figure E-2.--Traveltime versus dye concentration for subreach A, September 1980

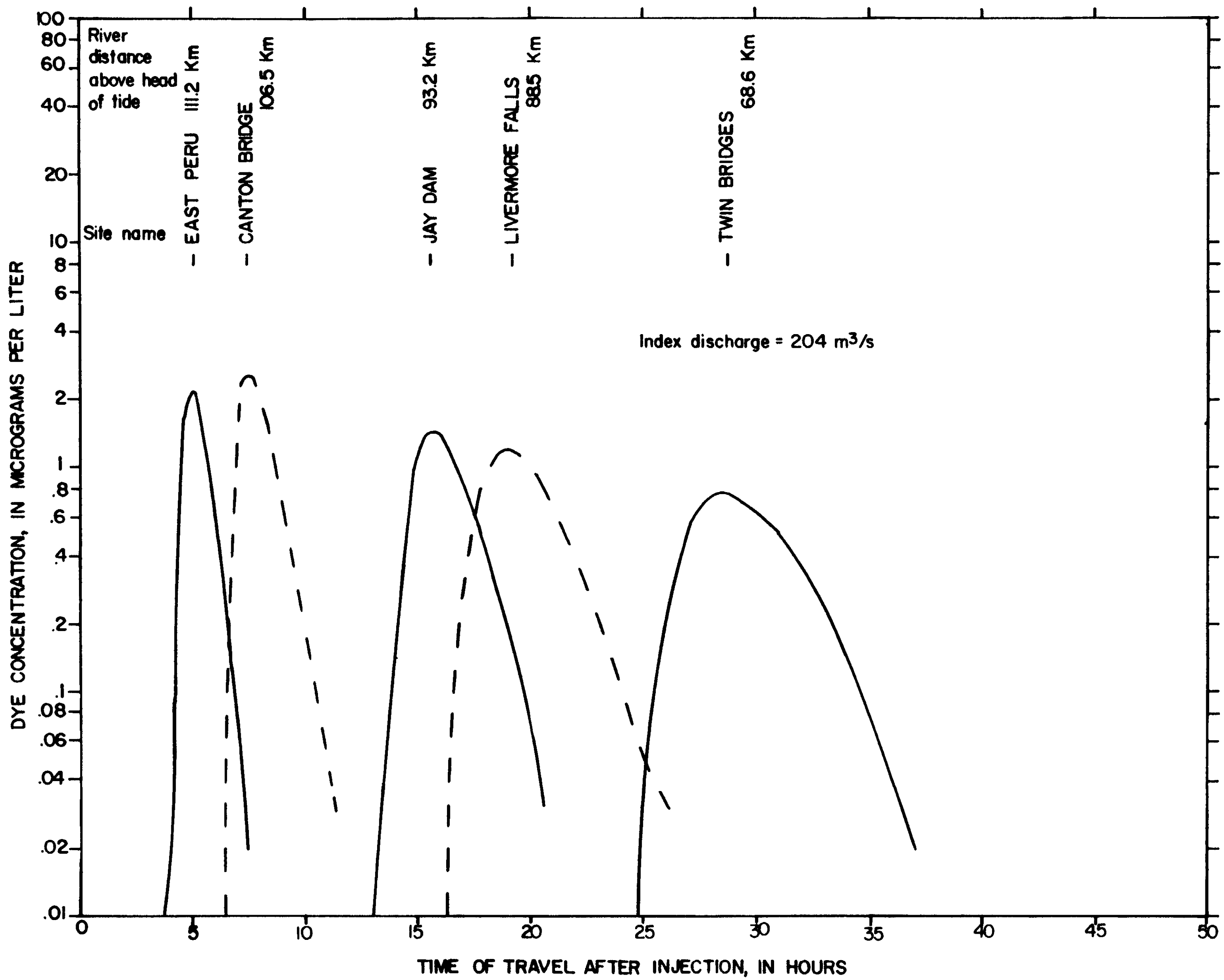


Figure E-3.--Traveltime versus dye concentration for subreach A, April 1981

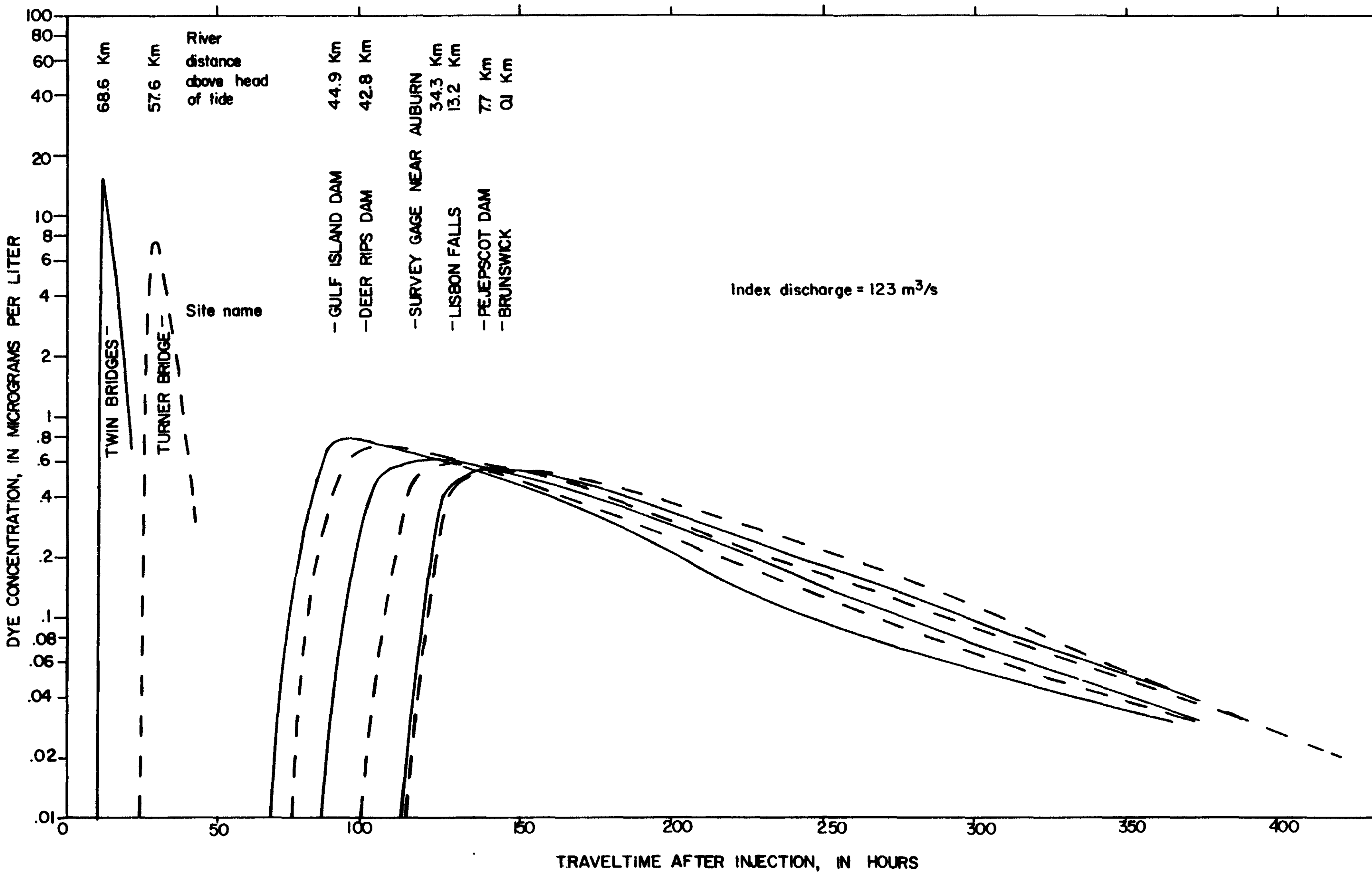


Figure E-4.--Traveltime versus dye concentration for subreaches B and C, June 1981

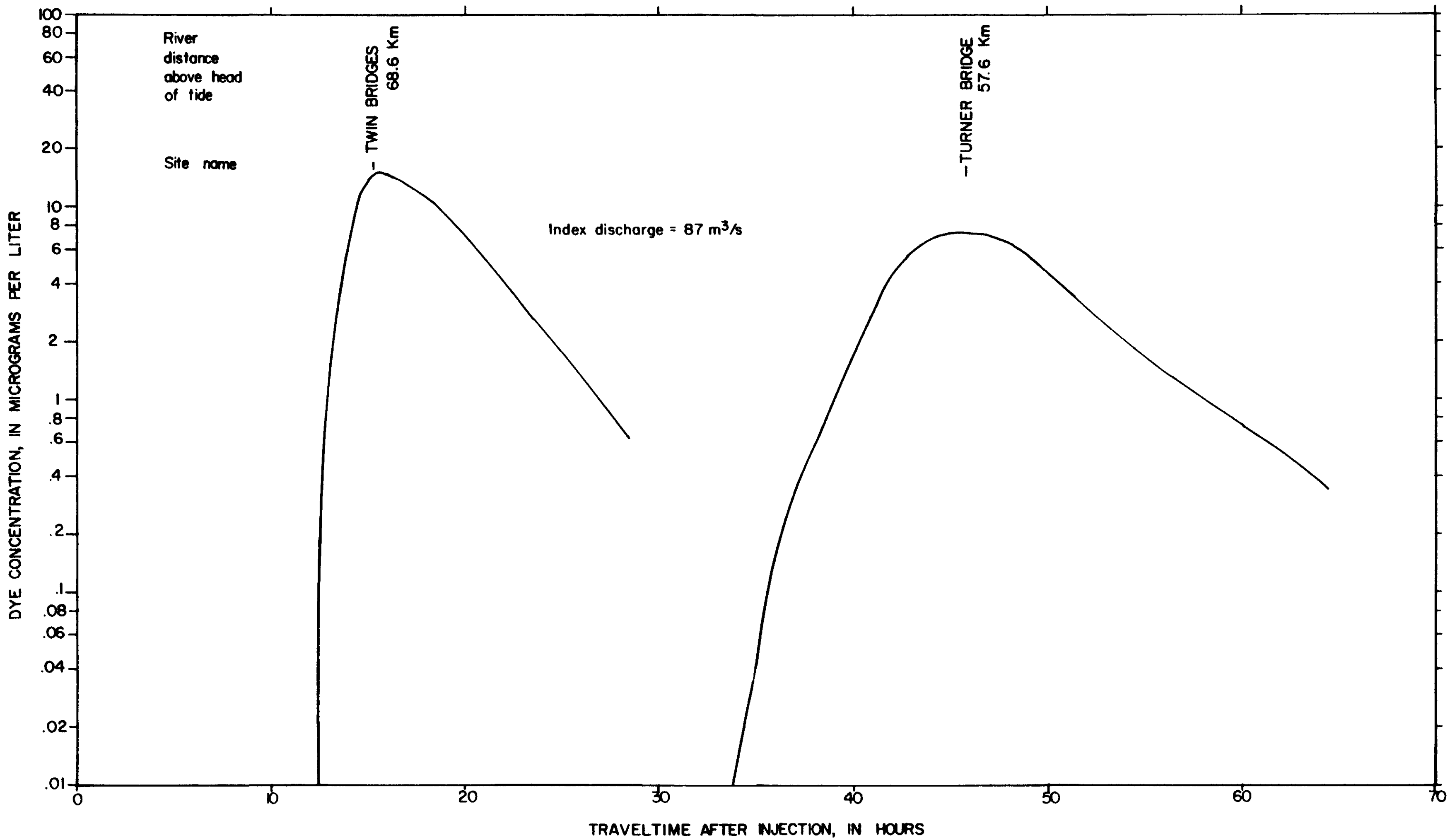


Figure E-5.--Traveltime versus dye concentration for subreach B, September 1981

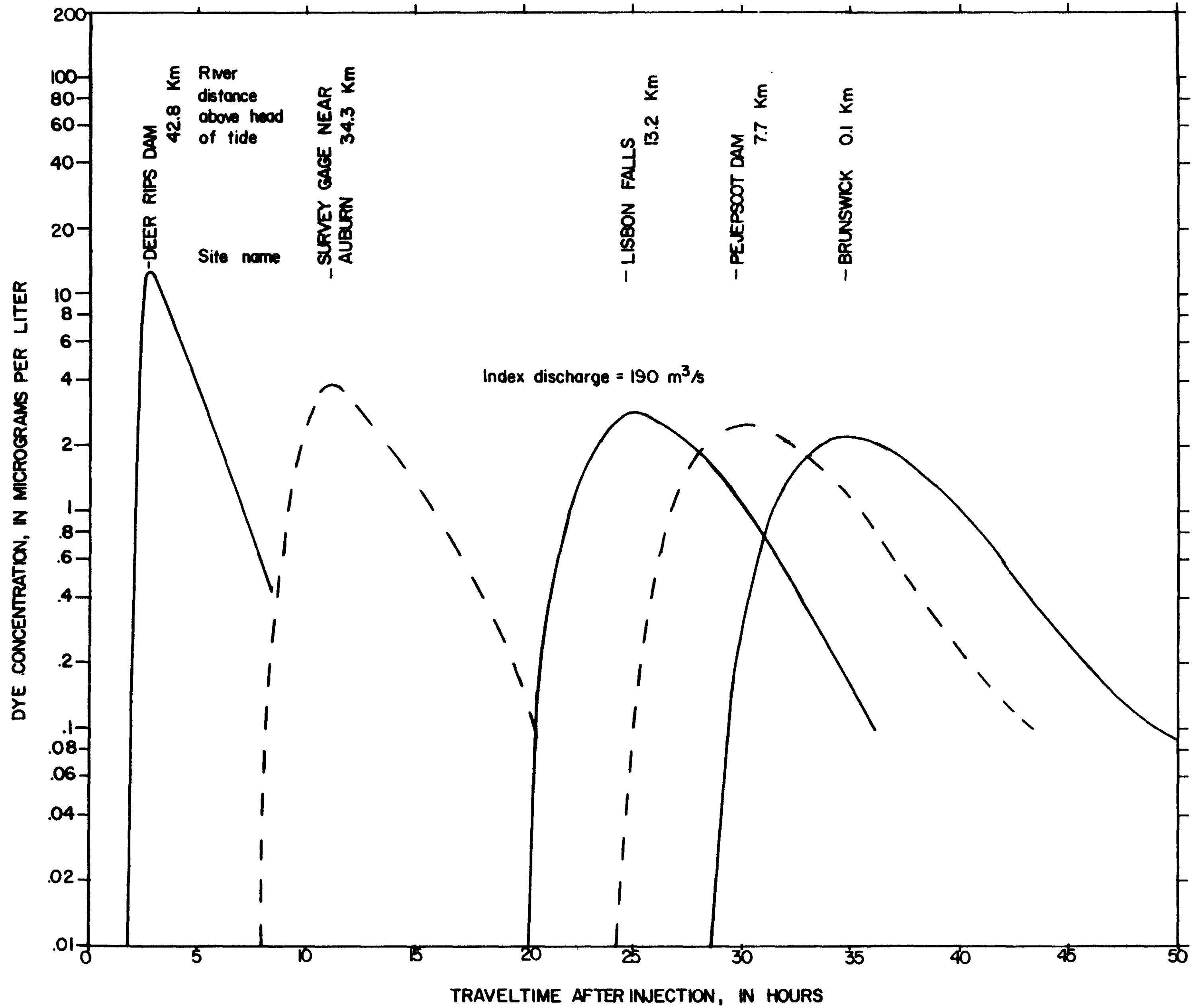


Figure E-6.--Traveltime versus dye concentration for subreach C, April 1981

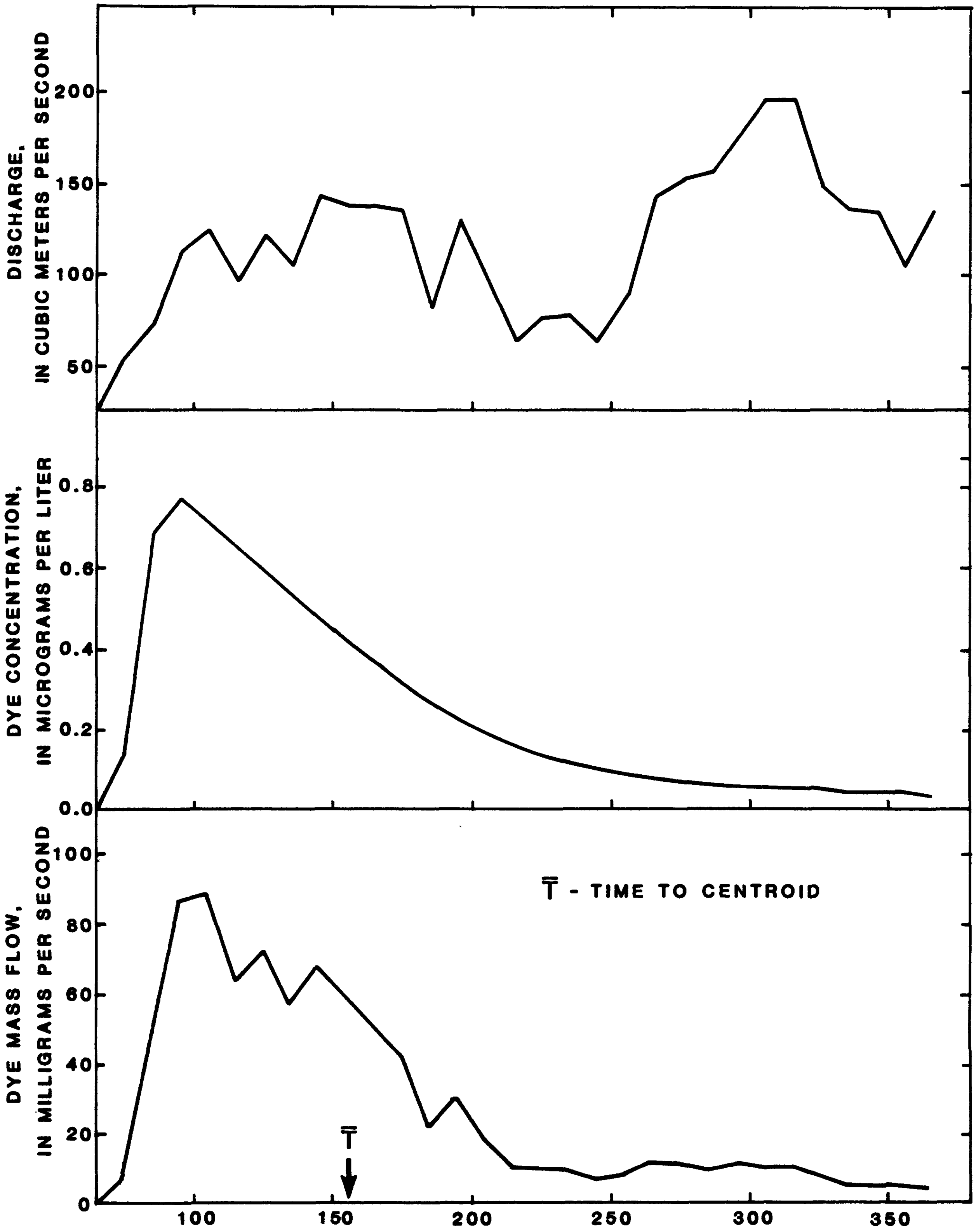


Figure E-7.--Discharge, dye concentration, and dye mass flow versus time after injection for samples collected at Gulf Island Pond, June 1981

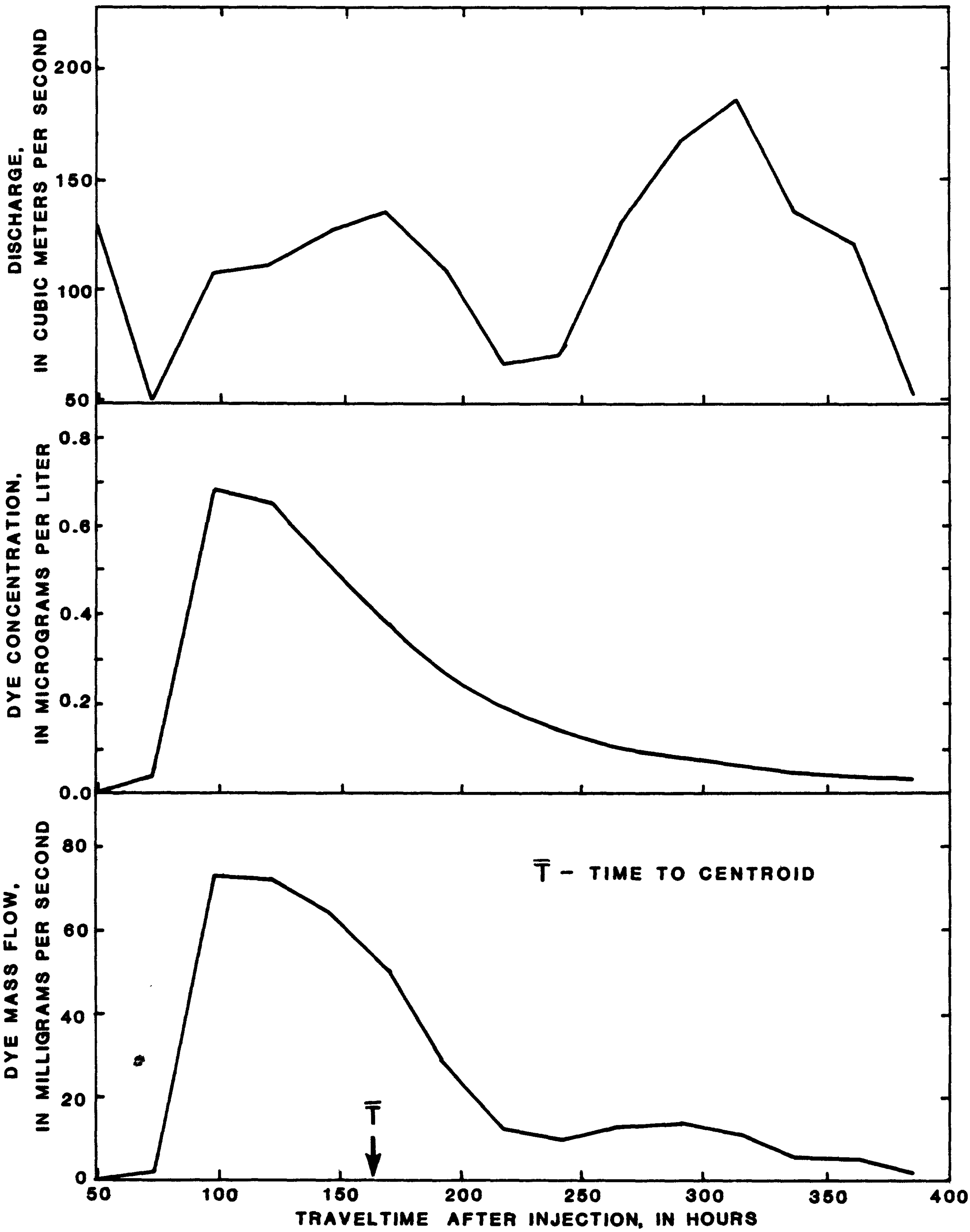


Figure E-8.--Discharge, dye concentration, and dye mass flow versus time after injection for samples collected at Deer Rips Dam, June 1981

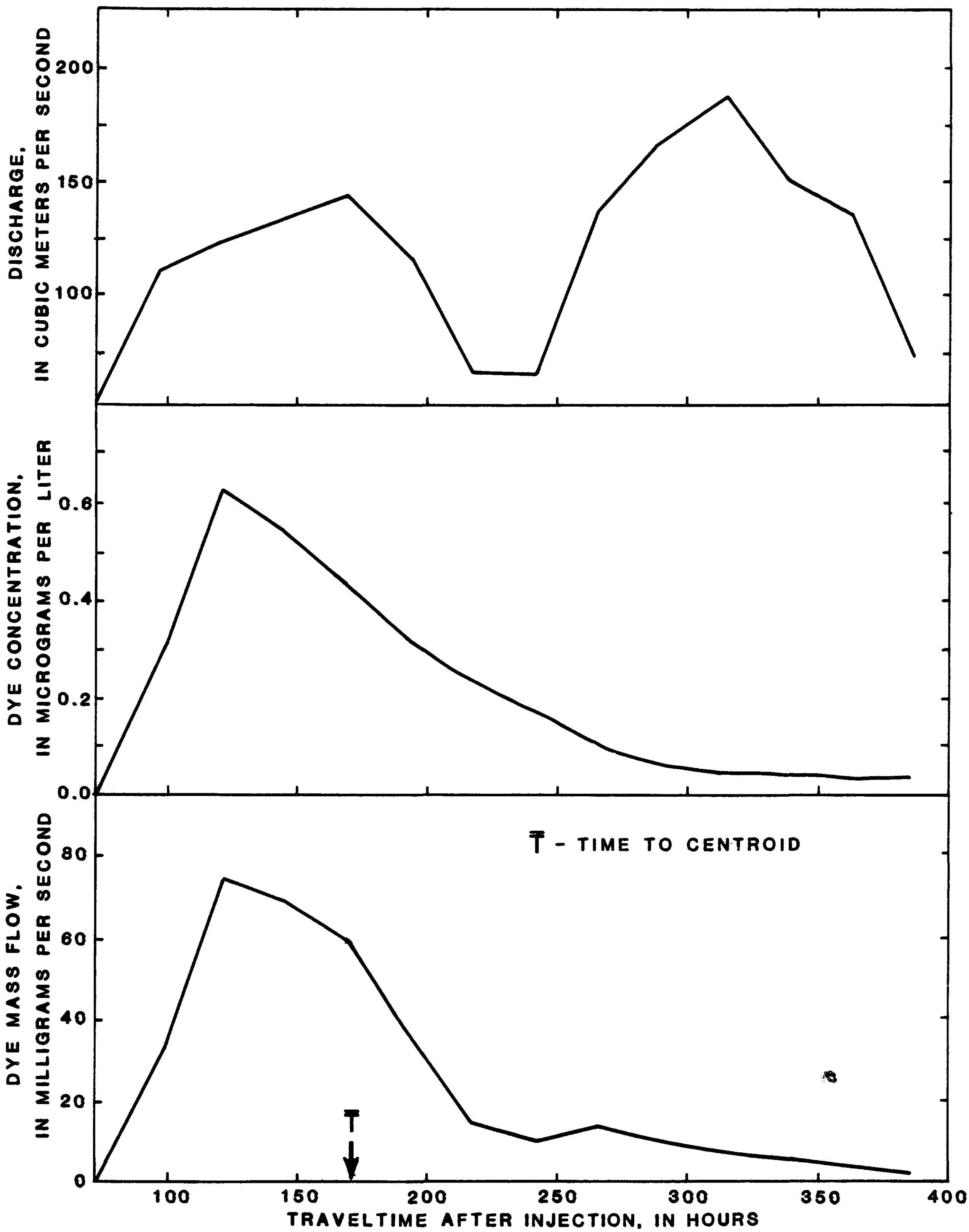


Figure E-9.--Discharge, dye concentration, and dye mass flow versus time after injection for samples collected at the Survey gage near Auburn, June 1981

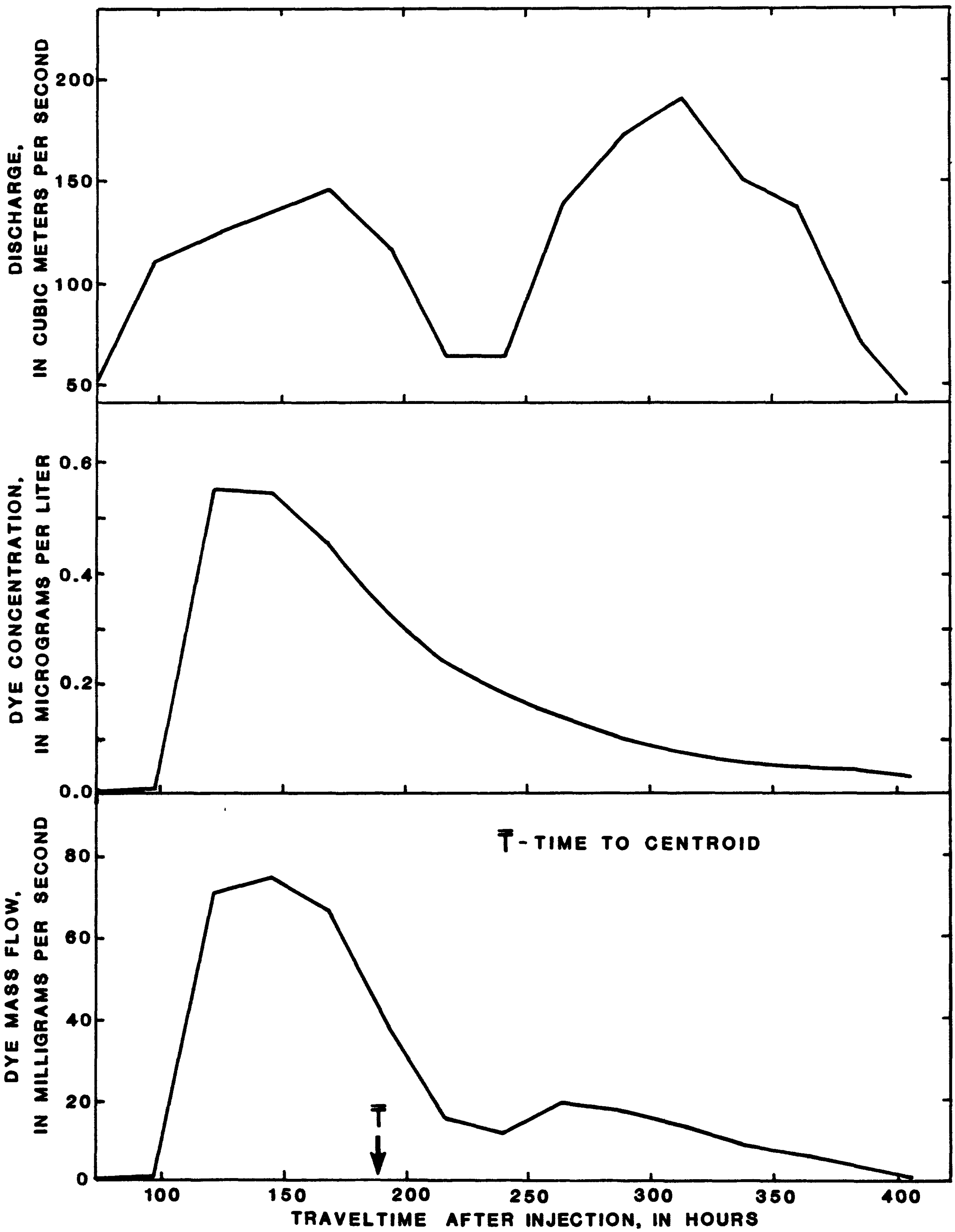


Figure E-10.--Discharge, dye concentration, and dye mass flow versus time after injection for samples collected at Lisbon Falls, June 1981

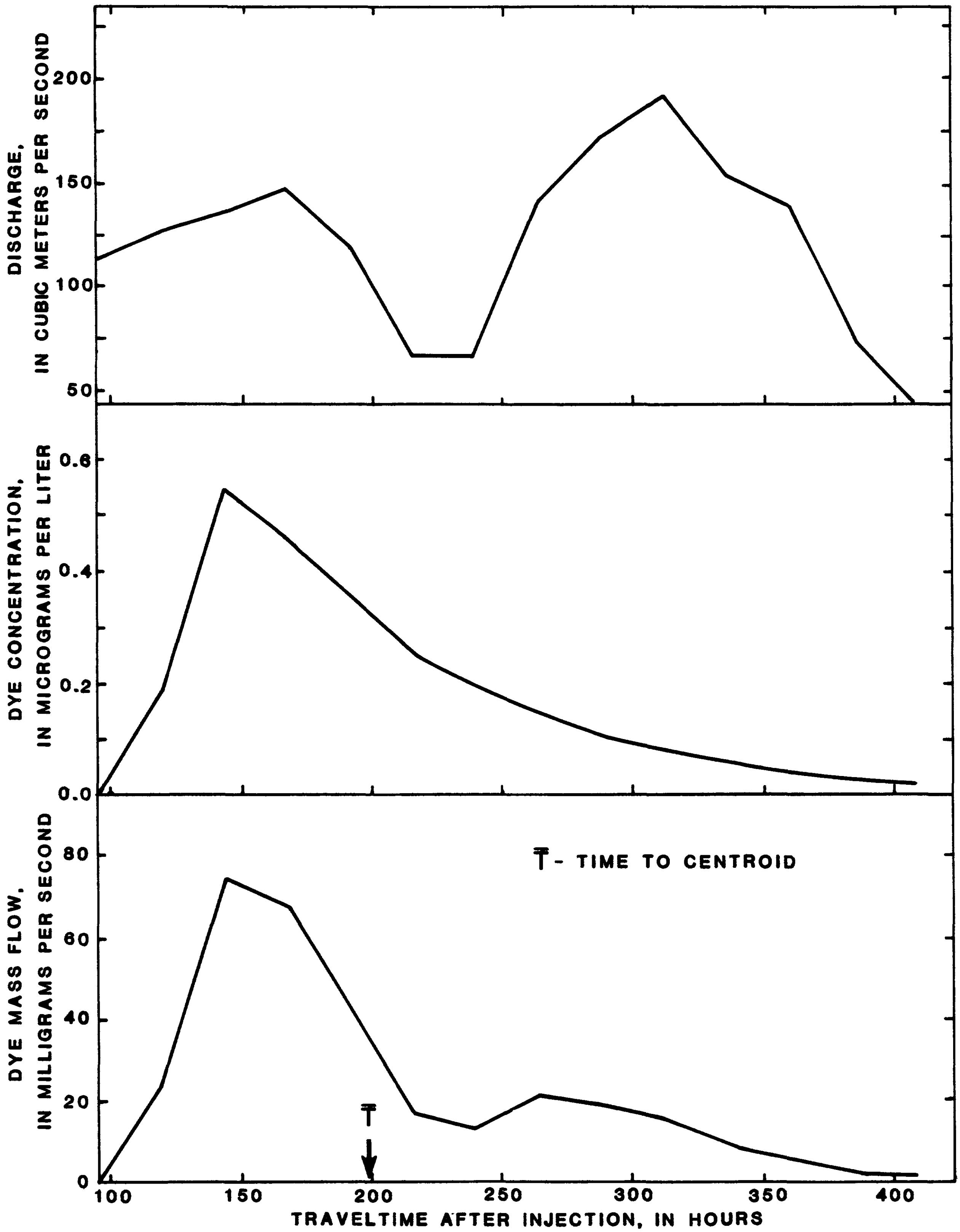


Figure E-11.--Discharge, dye concentration and dye mass flow versus time after injection for samples collected at Pejepscot Dam, June 1981

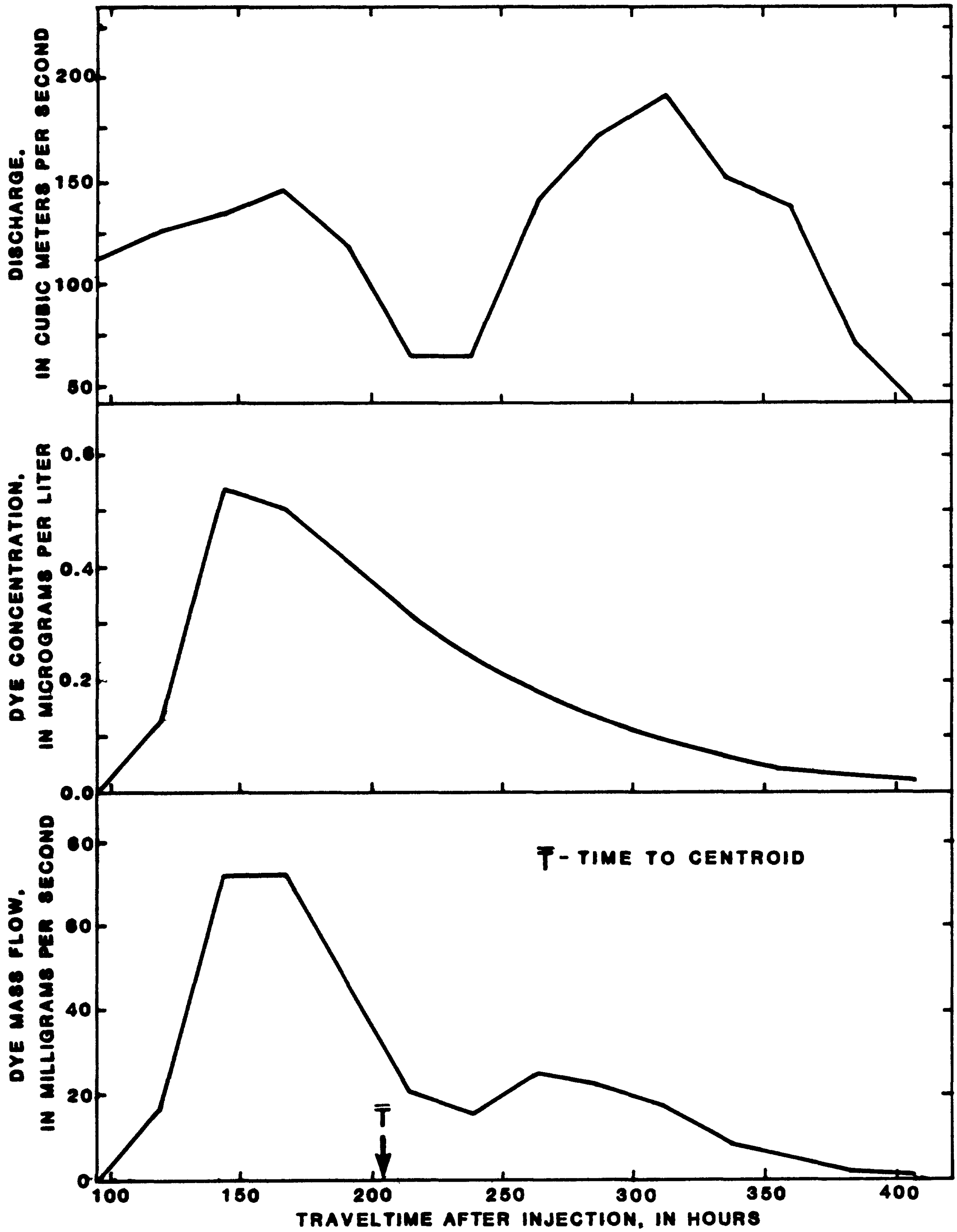


Figure E-12.--Discharge, dye concentration, and dye mass flow versus time after injection for samples collected at Brunswick, June 1981

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