Tennessee Valley Authority
Division of Water Management
Water Systems Development Branch

ANALYSIS OF FLOW PATTERNS IN THE VICINITY OF BROWNS FERRY NUCLEAR PLANT INTAKE

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INTRODUCTION

TVA's Browns Ferry Nuclear Plant (BFNP), situated on Wheeler Reservoir of the Tennessee River in north Alabama (Figure 1), has a design capacity of 3456 MW with three generating units. The plant was originally designed to operate in Open Mode for condenser cooling. In this mode, water is pumped from the river through the steam condenser where the cooling water is heated before being discharged through submerged multiport diffusers in the river.

The plant has been retrofitted with six mechanical draft cooling towers, two per unit, to provide the plant operators with the option of cooling the condenser cooling water.

The possible environmental conseqences of thermal discharges are well documented, but the water temperatures at which these effects are discernable are not well defined. Thermal water quality standards were promulgated generally to limit the maximum temperature and temperature rise of the adjacent water body.

The environmental effects of plant intakes are also of concern. Fish may be trapped within intake structures or canals and become impinged against the intake screens. Fish and other aquatic organisms too small to be impinged on the intake structures may be entrained in the cooling system of the plant. The rate of impingement and entrainment of aquatic organisms is influenced by many factors such as the condenser flow rate, configuration of the intake structure and source of water.

This report presents results of a hydrodynamic field investigation of the flow in Wheeler Reservoir in the immediate vicinity of the

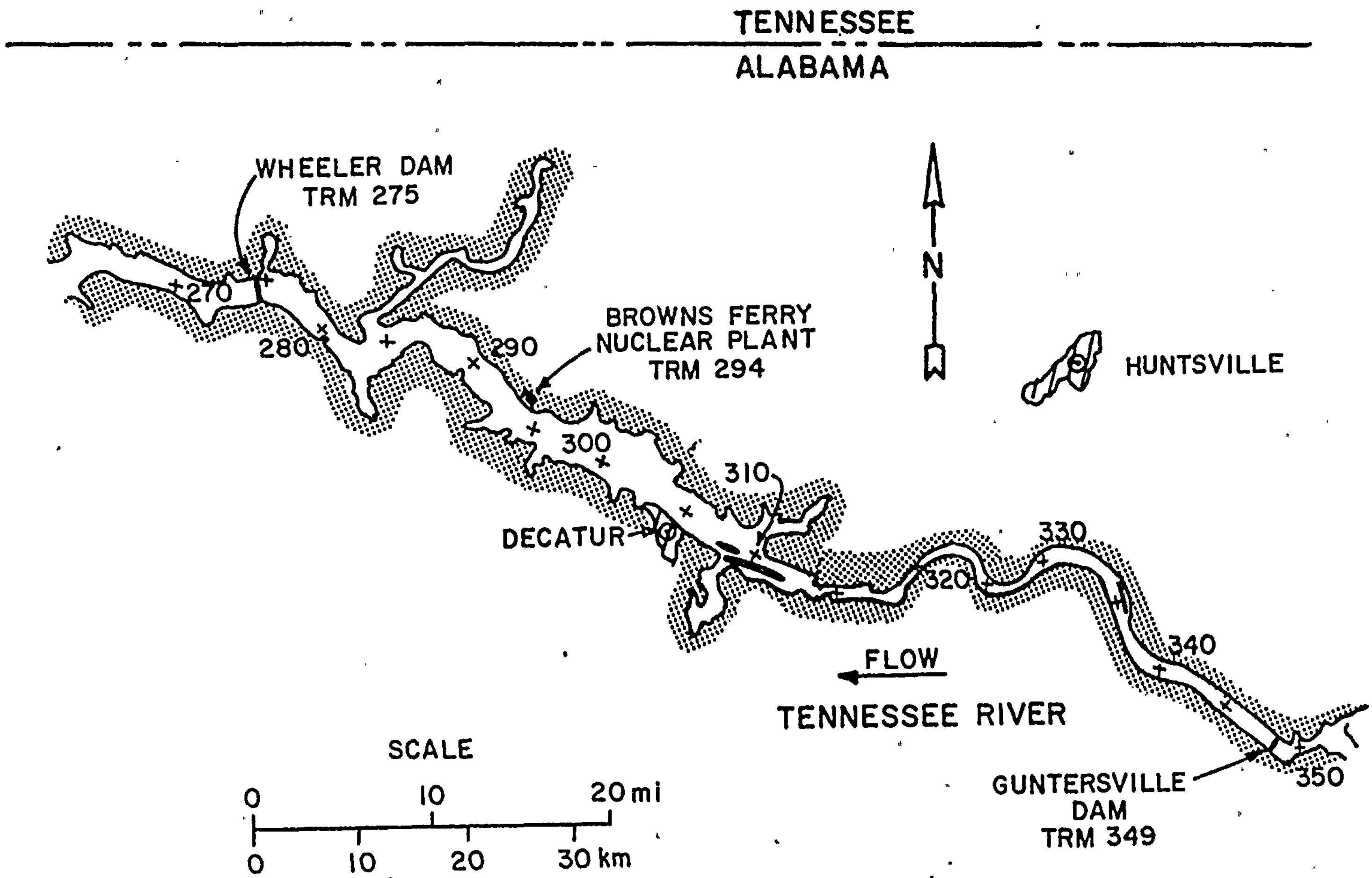


Figure I: Location Map of Browns Ferry Nuclear Plant intake structure of BFNP. The tests were planned to achieve two objectives:

1. To provide supporting hydrodynamic data for a biological evaluation of the environmental effects of the condenser cooling water intake system at BFNP.
2. To verify results of a computer model being developed by the University of Tennessee under the auspices of the Division of Wildlife and Fisheries of the Department of Interior.

Results and analyses of the field tests conducted for several reservoir flow and plant operational conditions are included.

PHYSICAL CHARACTERISTICS

This section describes the general features of the reservoir and the plant which affect the flow patterns in the vicinity of the plant intake structure.

The Site

The BFNP is situated on the right bank of Wheeler Reservoir at Tennessee River Mile (TRM) 294. River flows in the vicinity of the plant are primarily dependent upon discharges from Guntersville Dam (TRM 349), which is 55 miles (88 km) upstream, and from Wheeler Dam (TRM 275), which is 19 miles (31 km) downstream. The mean annual flow rate of the river at BFNP is 45,000 ft^3/sec (1270 m^3/sec). Since discharges from these dams are normally used for hydroelectric generation at periods of peak power demand, the flow in Wheeler Reservoir is often unsteady. As a result, flows near the plant usually change drastically throughout the day.

Under present operating practices, the water level in Wheeler Reservoir varies no more than six feet (1.8 m) throughout the year. From approximately April through July, the reservoir elevation fluctuates only slightly from the maximum level while during most of the remainder of the year the surface elevation is five to six feet (1.5 to 2.0 meters) below the maximum.

The 14-mile (23 km) reach upstream of the plant is characterized by a main river channel, which was the original riverbed, flanked by wide, shallow overbank regions (Figure 2). The main channel is approximately 30 feet (9 m) deep and 2000 feet (600 m) wide. The right overbank region immediately upstream of the plant is relatively

Figure 2: Location of Temperatue Monitors

shallow with the exception of an old creek channel adjacent to the right bank which is approximately 20 feet (6 m) deep. However, when the reservoir elevations are near maximum, depths in most of the right overbank region upstream of the plant range from five to ten feet (1.5 to 3 m). During low reservoir elevations, the overbank is exposed in some regions and is approximately three feet (one m) deep in others.

The proportion of flow between the main channel and the overbank depends upon the reservoir elevation and the total flow in the reservoir. A significantly greater percentage of the total flow is confined to the main channel during the months when the reservoir elevations are low. For both high and low reservoir elevation, during higher flows a higher percentage can be expected in the main channel because the effect of bottom friction is more pronounced in the overbank than in the main channel. Under all conditions, the majority of the river flow is confined to the main river channel in this region.

The Plant

Condenser cooling water for BFNP is pumped from an intake basin which is separated from the Wheeler Reservoir (Figure 3) by a shallow skimmer wall extending approximately 10 feet (3 m) below the normal maximum surface elevation. A dredged channel approximately 35 feet (10 m) deep extends from the intake basin to the deepest part of the main river channel as shown in the underwater topography of Figure 3. This dredged channel permits flow from the lower depths of the main channel to enter the intake basin as well as the flow from the right overbank region of the reservoir.

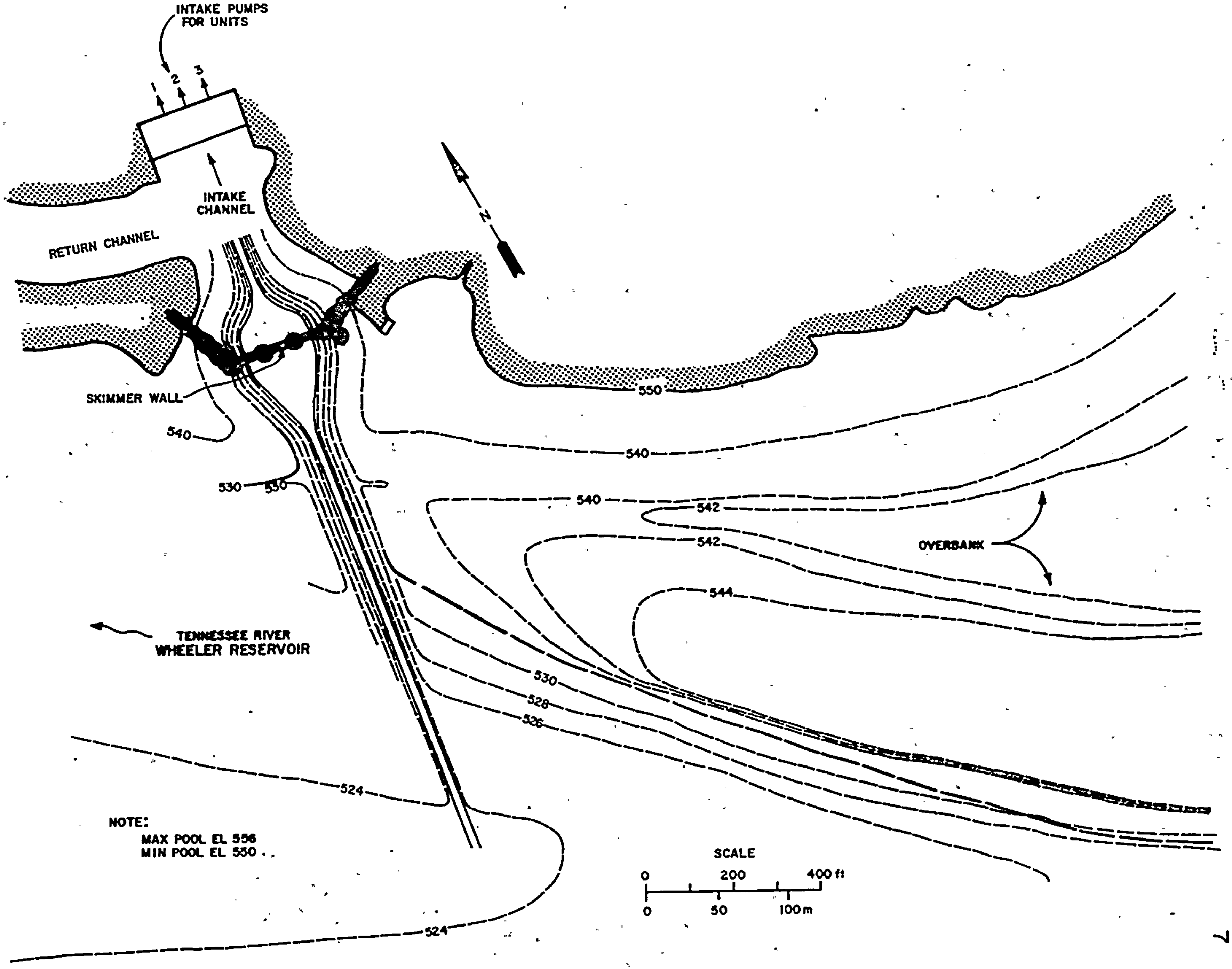


Figure 3: Underwater Topography
Near the BFNP Intake

The plant condenser cooling water system can be operated in three modes: Open, Helper and Closed. In the Open Mode, the condenser cooling water is discharged directly into the river through submerged multiport diffusers. When this method of disposing of the excess heat from the plant is not sufficient to meet applicable thermal standards, the condenser cooling water may be routed to the cooling towers and the effluent from the cooling towers routed to the diffusers for discharge into the river (Helper Mode), or routed to the plant intake channel for reuse as condenser cooling water (Closed Mode). These three modes of operation of the BFNP cooling system are illustrated in Figure 4.

In the Open Mode, the plant pumps 4410 ft^3/sec (125 m^3/sec) from the river of which 4350 ft^3/sec (123 m^3/sec) are pumped through the steam condenser. As the cooling water passes through the condenser, it is heated approximately 25°F (14°C) before being discharged through submerged, multiport diffusers into the river. When operating in the Helper Mode, the plant intake flow rate is 3675 ft^3/sec (104 m^3/sec) with a slightly higher design condenser rise of 31.7°F (17.6°C). In the Closed Mode of operation, only a small quantity of water, between 200 and 300 ft^3/sec (5.7 and 8.5 m^3/sec), is drawn from the river primarily for "makeup" water for the cooling system. Although there are fewer potential environmental effects from the Closed Mode of operation, the power required to operate the cooling tower lift pumps and fans, and the loss of generating efficiency which results from increased cooling water temperatures can produce a net loss in generation of as much as 150 MW at the BFNP.

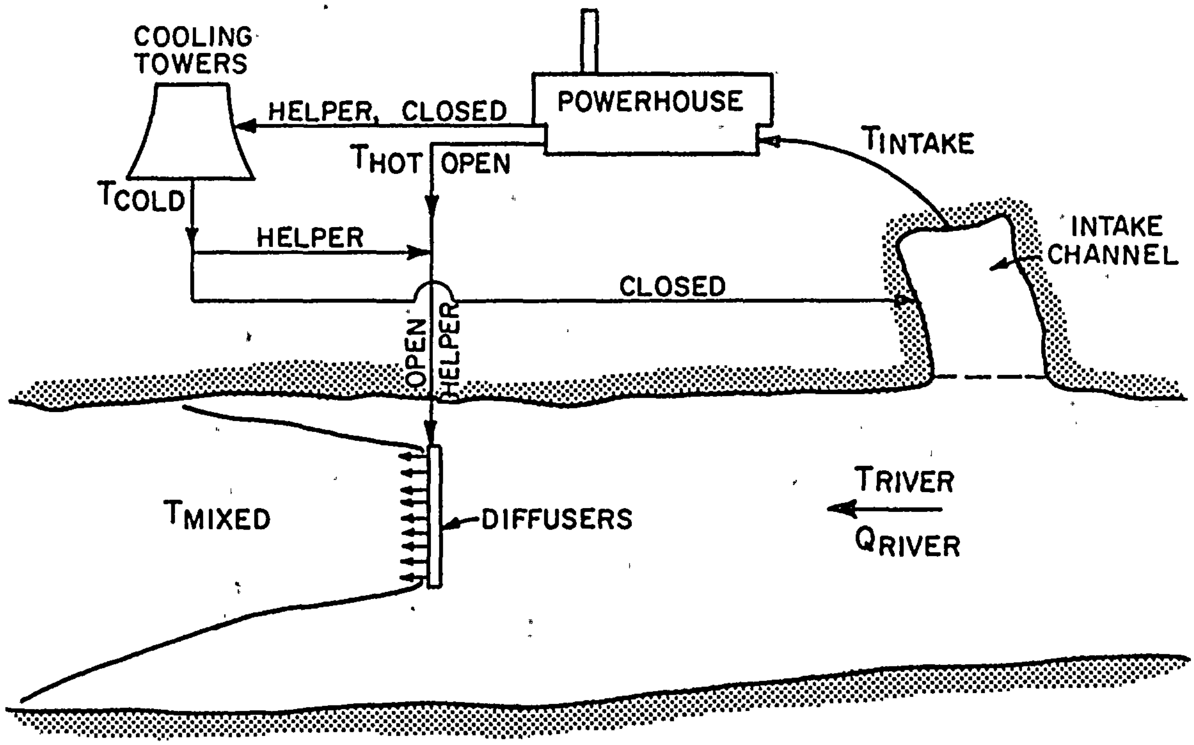


Figure 4: Schematic of Three Condenser Cooling Modes of Browns Ferry Nuclear Plant

FIELD INVESTIGATIONS

Three procedures were used to analyze the flow field in the vicinity of the BFNP water intake. Velocities were recorded from a boat anchored at several locations both inside and outside of the intake basin. These measurements produced velocity vectors in the horizontal plane. Drogues released at various locations and designed to move with the horizontal flow at a specified depth were also tracked. The trajectories of these drogues provided an indication of pathlines of the flow entering the intake basin. In addition, the flow in the right overbank region upstream of the plant intake was traced with a flourescent dye. The concentration of dye in the overbank area immediately upstream of the plant intake was recorded and compared to the maximum recorded concentrations of dye inside the intake basin. The dilution of the concentration of dye inside of the intake gate was attributed to water being withdrawn from the main channel which contained no dye. Although these three procedures were sometimes used concurrently, they will be discussed separately.

Water temperatures of the survey area were obtained from two permanent water temperature monitors at TRM 295.8 (Figure 2). Each of these monitors has a string of several thermistors positioned at prescribed depths and recorded the water temperature hourly. Monitor 7 indicates water temperatures of the overbank area and Monitor 14 provides temperatures of the main channel. Both are considered accurate to ±0.2°F (0.1°C).

Velocity Surveys

Procedure and Conditions

On May 17 and 18, 1977, velocities were recorded in the intake basin and in the reservoir near the intake. Measurements were made at depth increments of 3.3 feet (1.0 m) from an anchored boat using a Marsh-McBirney electromagnetic current meter. This instrument utilizes the electric field generated by water moving through a magnetic field to determine two components of the velocity vector over a range of zero to three meters per second with an accuracy of ±0.05 ft/sec (1.5 cm/sec).

During this survey, all of the condenser cooling water pumps were in operation producing a total intake flow rate of 4410 ft^3/sec (125 m^3/sec). The plant was operating in the Open Mode throughout these tests. The Tennessee River flow rate was computed to be 38,000 ft^3/sec (1075 m^3/sec) with a water surface elevation of approximately 555.6 ft (169.0 m).

Water temperatures in the overbank were 1 to 2°F (0.5 to 1.0°C) warmer than those at comparable depths in the main channel.

Results

Velocities measured at the surface and at depths of 3.3, 10, 16 and 23 feet (1.0, 3.0, 5.0 and 7.0 m) in the main channel and, where depths permitted, in the overbank areas upstream of the intake are presented in Figures 5 through 9, respectively. Winds were relatively calm during the survey period; therefore, surface velocities were undisturbed. These data reveal that velocities in the vicinity of the old creek channel near the right bank of the overbank region were slightly greater than in the more shallow regions of the overbank, but even

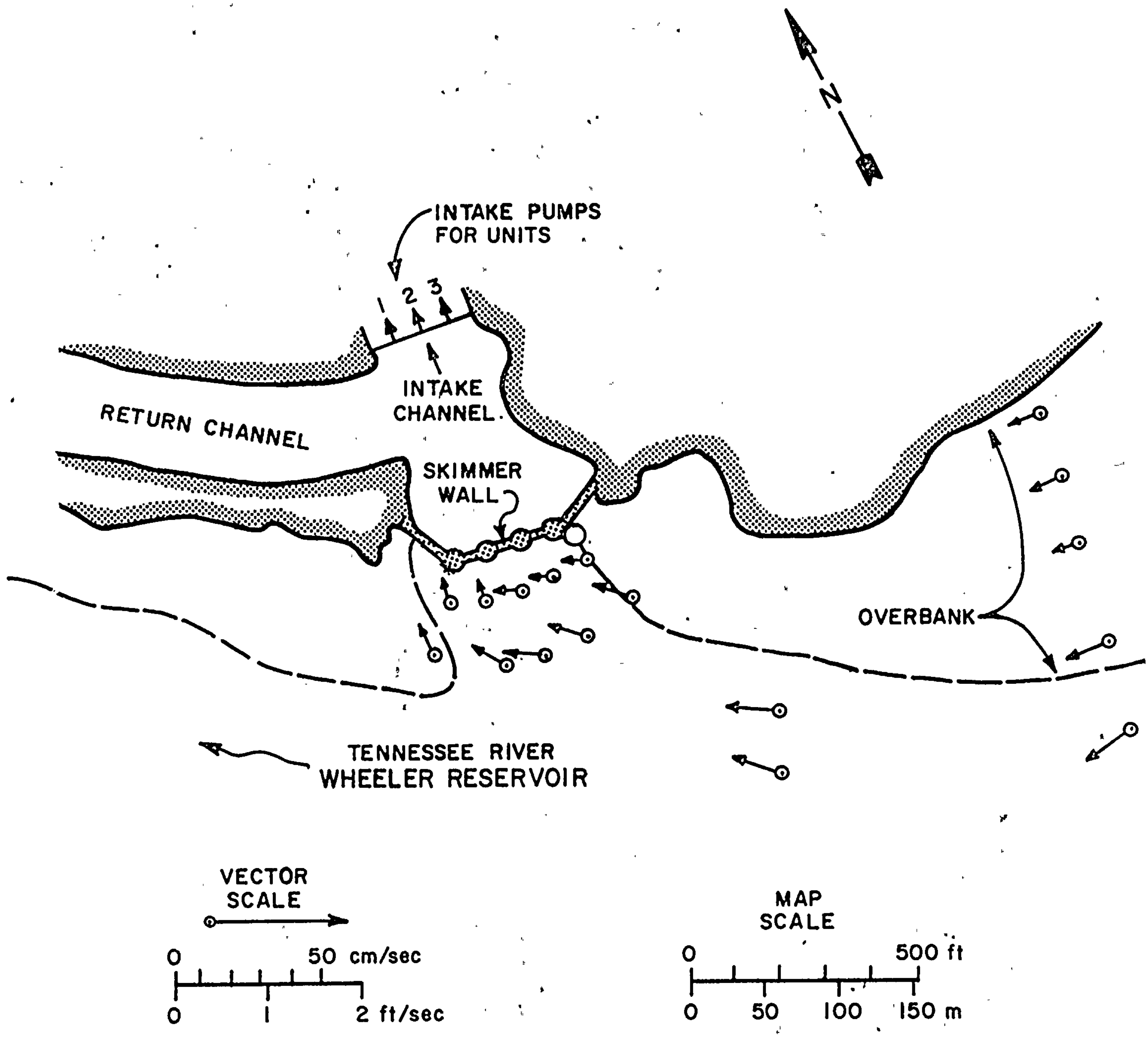


Figure 5 : Velocity Measurements at Water Surface for Browns Ferry Nuclear Plant on May 18, 1977

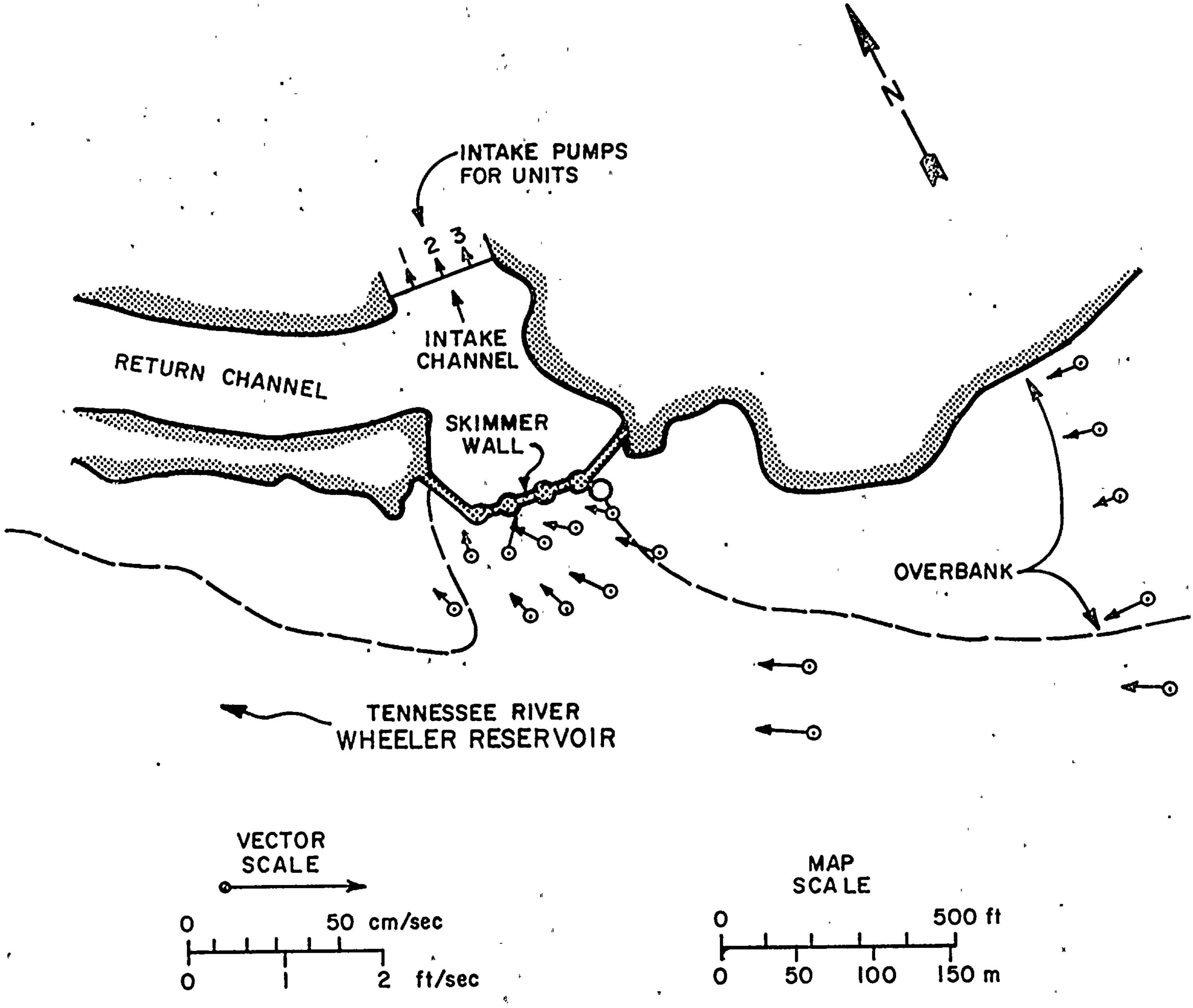


Figure 6: Velocity Measurements at 1 Meters Depth for Browns Ferry Nuclear Plant on May 18, 1977

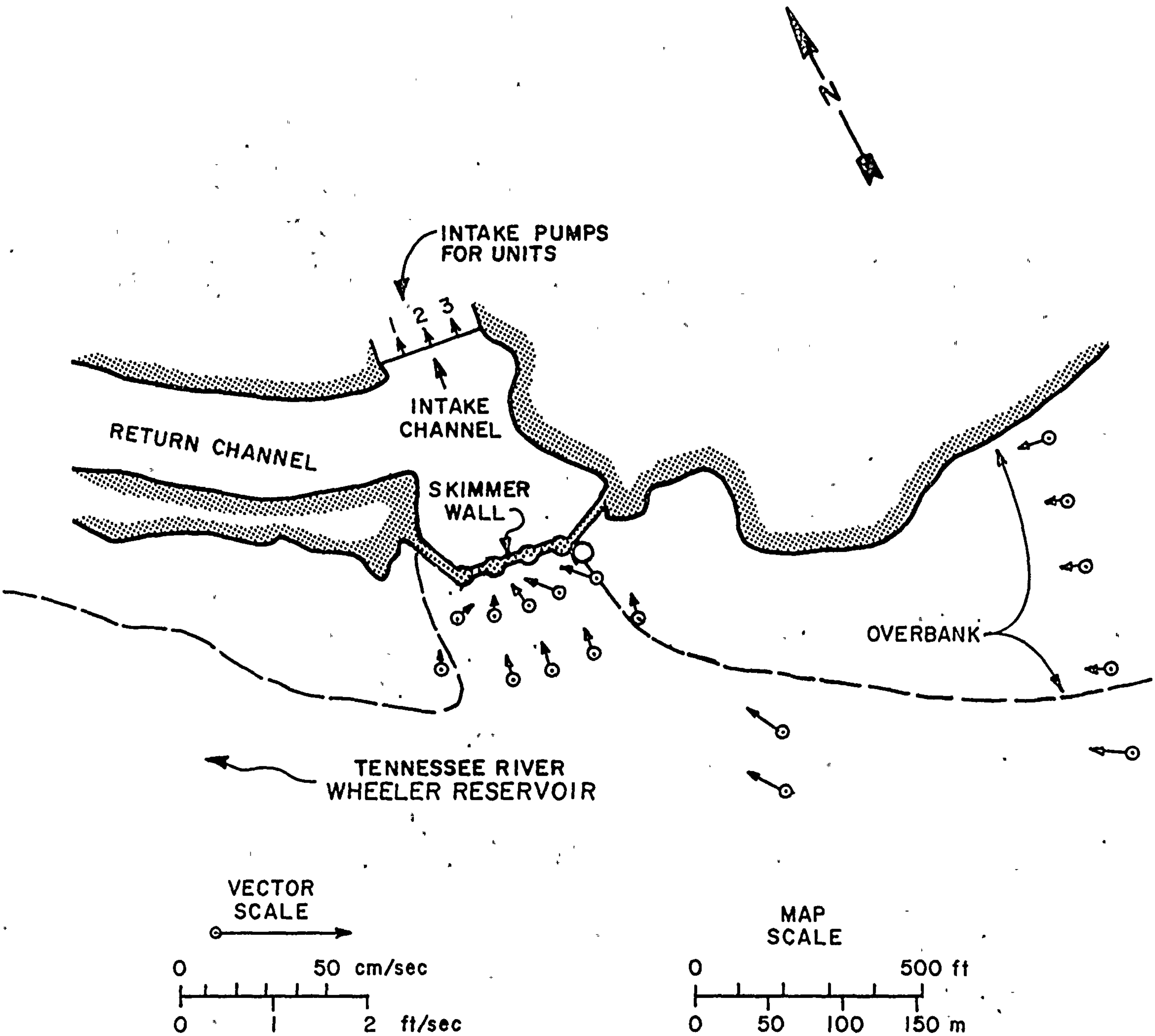


Figure 7: Velocity Measurements at 3 Meters Depth for Browns Ferry Nuclear Plant on May 18, 1977

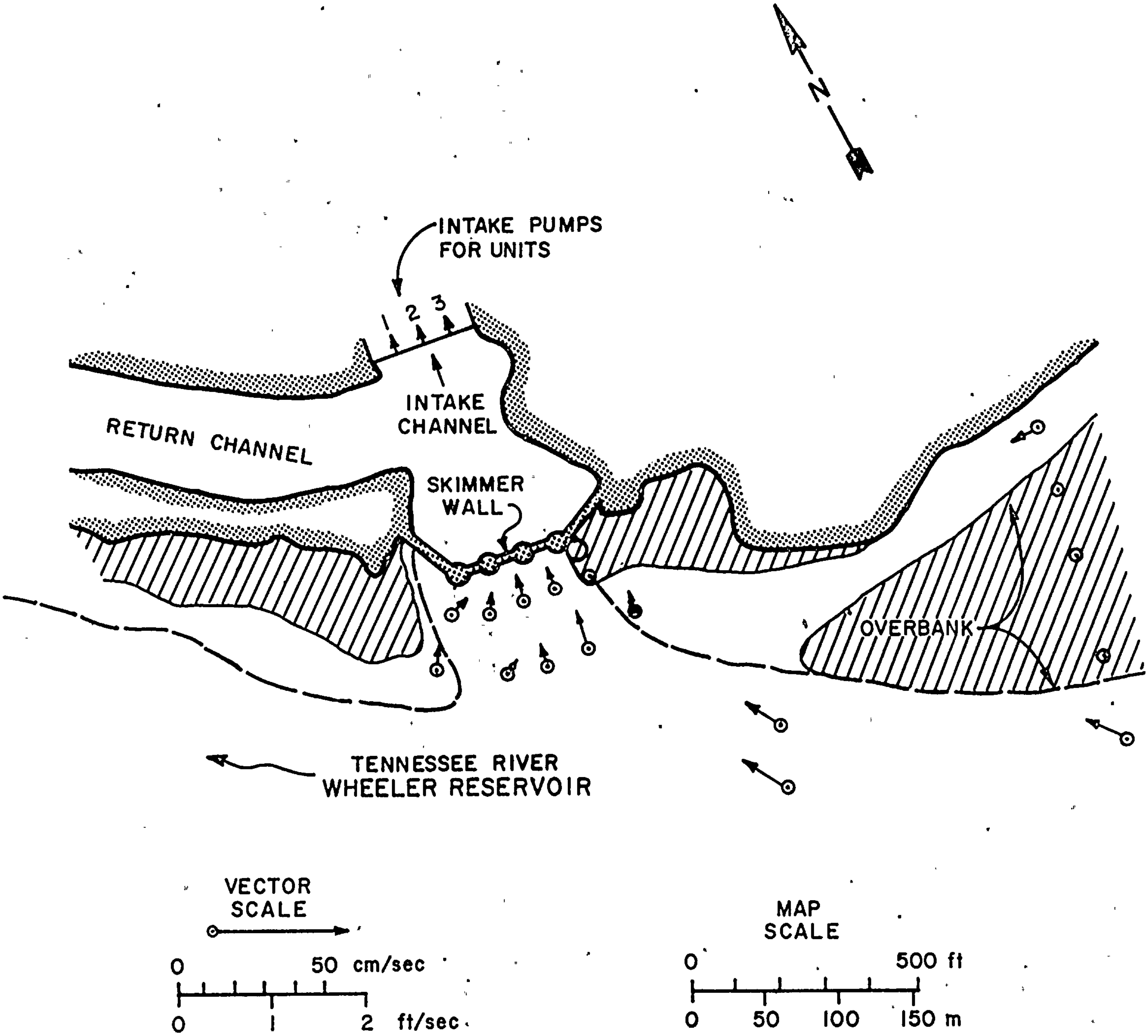


Figure 8 : Velocity Measurements at 5 Meters Depth for Browns Ferry Nuclear Plant on May 18, 1977

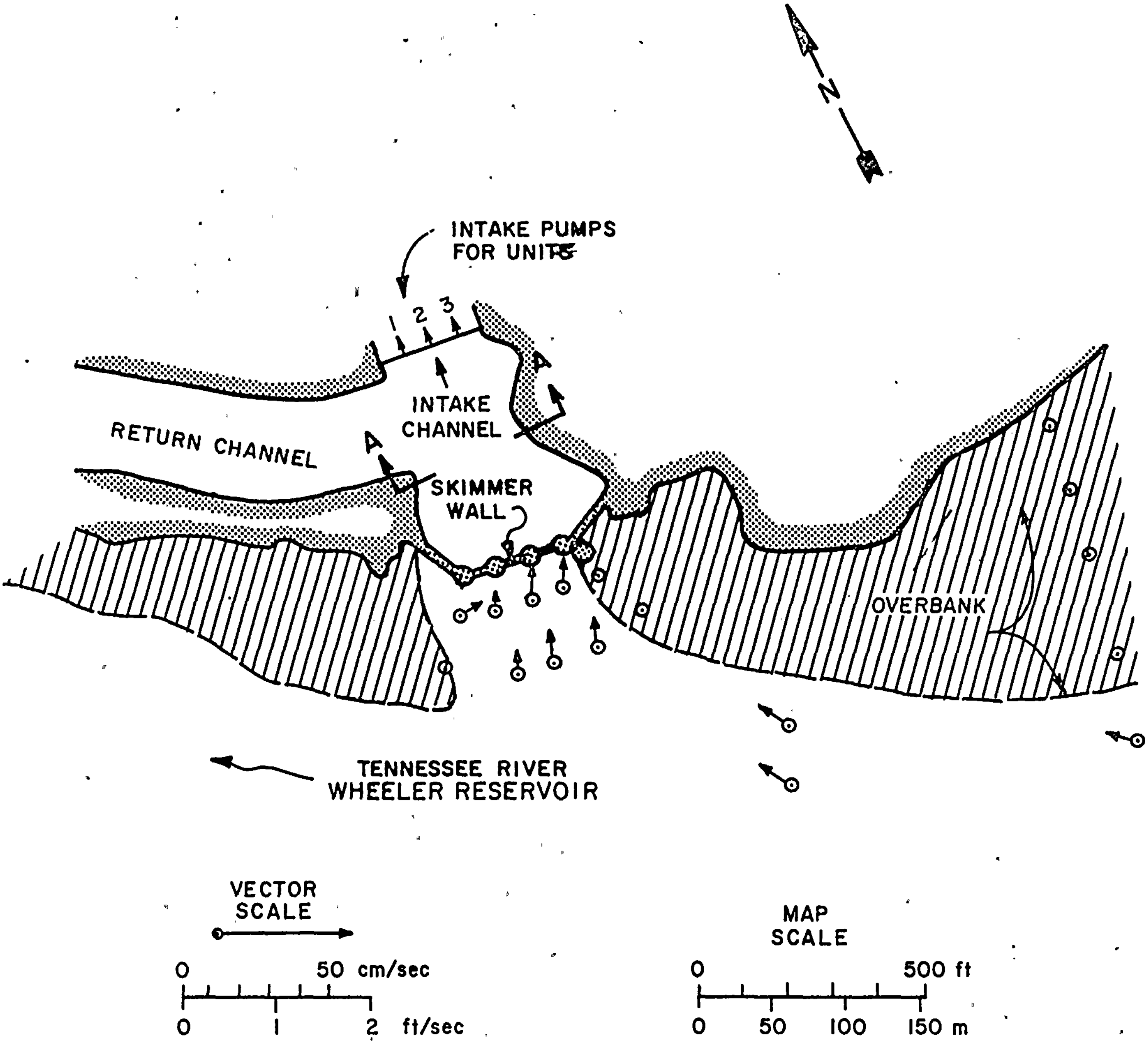


Figure 9: Velocity Measurements at 7 Meters Depth for Browns Ferry Nuclear Plant on May 18, 1977

those velocities near the right bank were somewhat less than those of the main channel. A numerical integration of the velocities revealed that the total flow of the overbank was approximately 3000 ft^3/sec (85 m^3/sec) during this river flow and stage.

Velocities near the surface (Figure 5) in the immediate vicinity of the intake show a downstream component implying that some of the surface flow from the overbank area was not entrained into the plant. This is attributed to buoyancy produced by the warm surface temperatures of the overbank water. This condition is typical during the spring because the large surface area of the shallow, slower flowing overbank regions have less thermal inertia than the main channel and hence warm more rapidly.

At depths of 10 feet (3 meters) or greater, the velocity vectors indicate that all flow in the dredged intake channel to the plant were directed toward the plant. This water appears to have come primarily from the main channel of the reservoir. Water flowing at depths of less than 10 feet (3 meters) in the reservoir near the plant intake came primarily from the overbank.

Velocities recorded inside the intake channel are presented in Figure 10. The location of this cross-sectional view of the channel is denoted in Figure 9. These data indicate that the flow in the intake channel is evenly distributed both top to bottom and side to side. The mean velocity at this cross-section is 1.3 ft/sec (39 cm/sec).

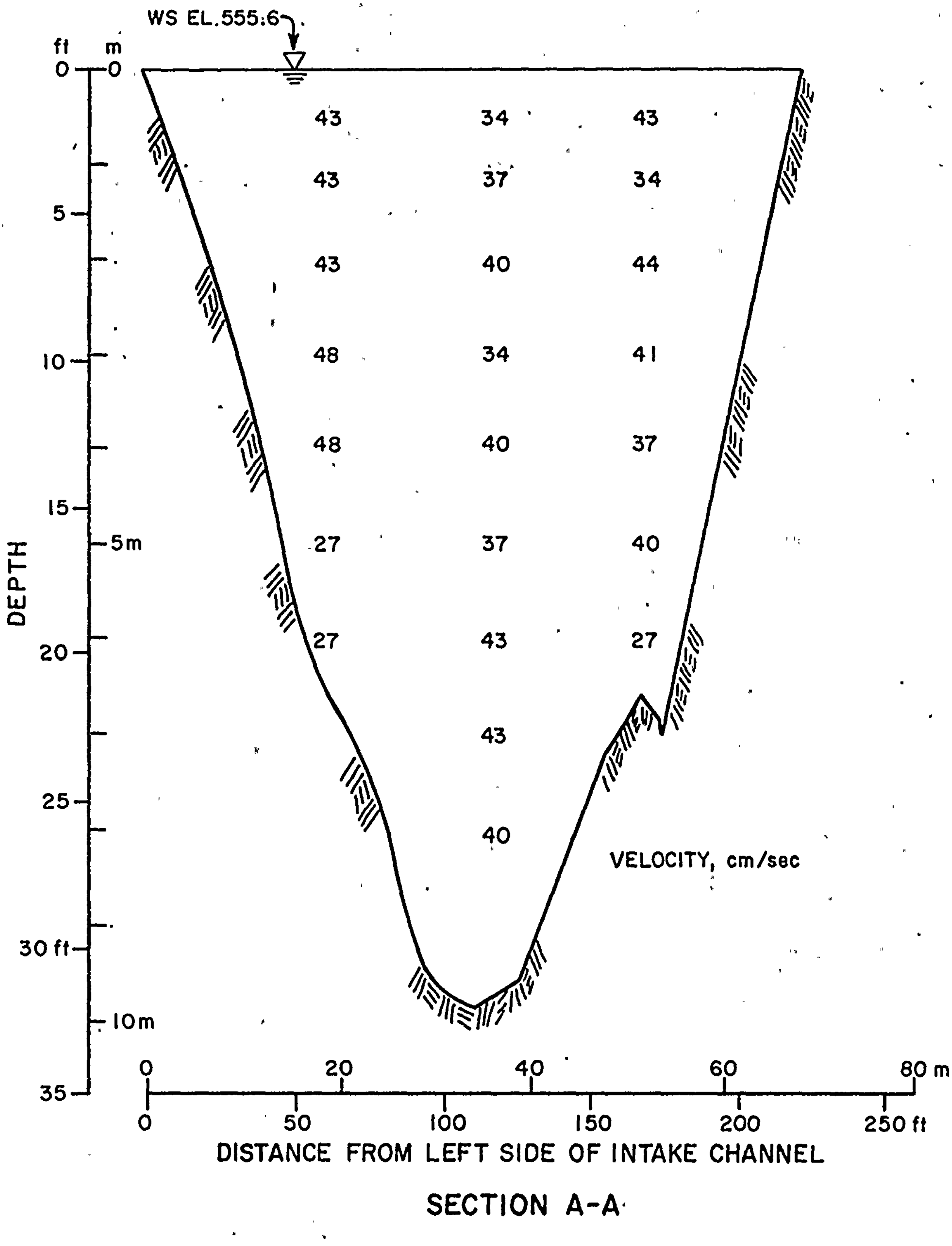


Figure 10: Velocity Measurements 75 Meters from the Intake Pumps, May 17, 1977

Drogue Trajectory Analysis

Procedure and Conditions

On July 20 and 21, 1977, flow patterns in the reservoir near the intake were investigated with drogues. These drogues had broad lateral fins one foot (0.3 meters) high (Figure 11). These fins created high drag at the depth of the fins and thereby moved with the horizontal flow at that depth. A float and weight kept the drogue vertical and the fins at the prescribed depth. The floats were color-coded and were tracked visually with surveying transits positioned at two locations on the shore.

Intake flows varied between 3400 ft^3/sec (96 m^3/sec) and 4000 ft^3/sec (113 m^3/sec) during the surveys. River flows fluctuated between 20,000 ft^3/sec (566 m^3/sec) and 25,000 ft^3/sec (710 m^3/sec) on July 20, and remained relatively constant near 36,000 ft^3/sec (1020 m^3/sec) on July 21.

Winds were variable during both days but generally increased in intensity throughout the day. During some of the tests, the wind obviously affected the drogues nearest the surface, i.e., 1.5-foot (0.5-meter) depth. Those cases are noted on the data to be presented.

Because the reservoir had entered the cooling phase of its annual cycle, water temperatures in the overbank were typically 1 to 2°F (0.5 to 1.0°C) cooler than those at comparable depths in the main channel.

Results

The results of the drogue analysis for the tests conducted on July 20 are presented in Figures 12-14; and for the tests conducted on July 21 in Figures 15-17. Trajectories for fins positioned at depths

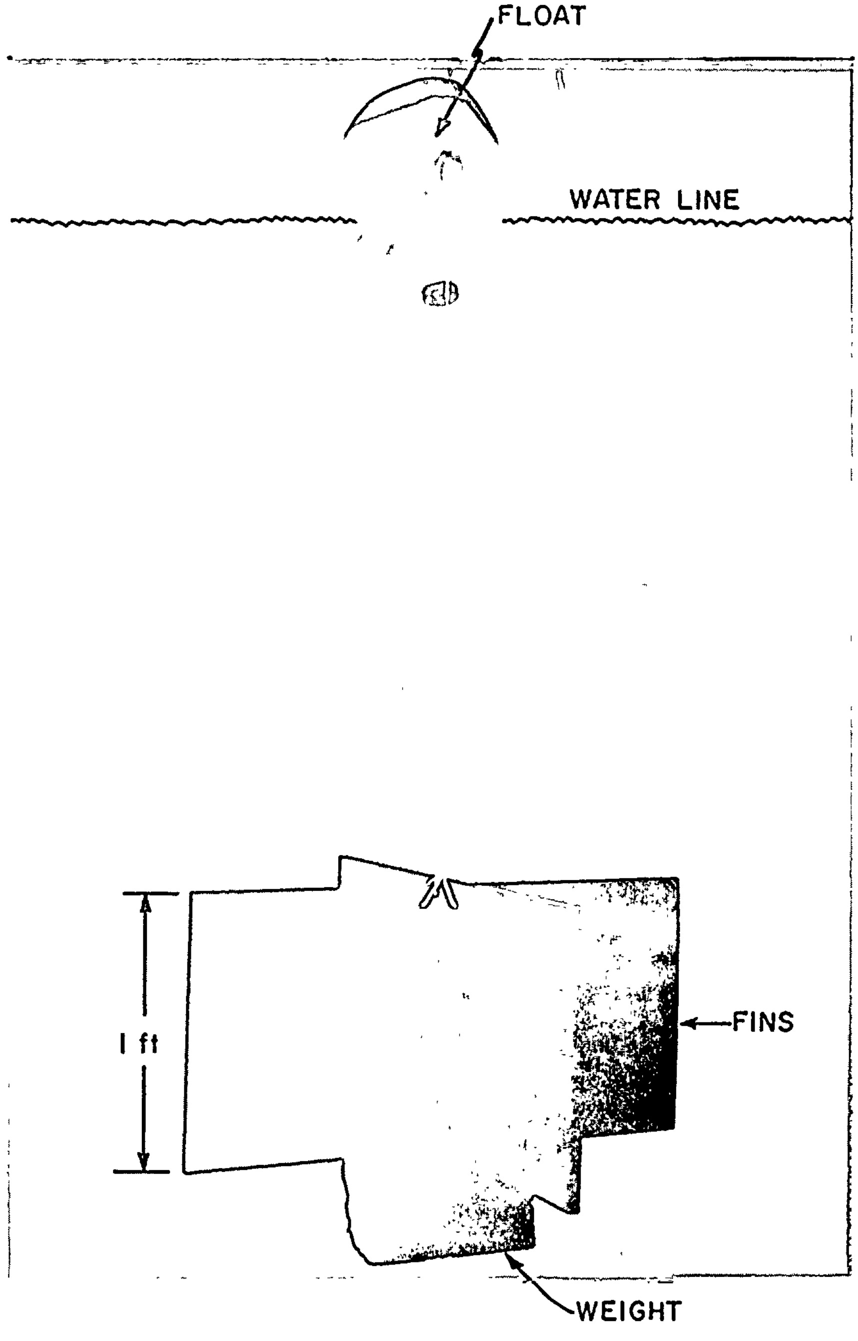


Figure 11: Drogue used for Trajectory Analysis

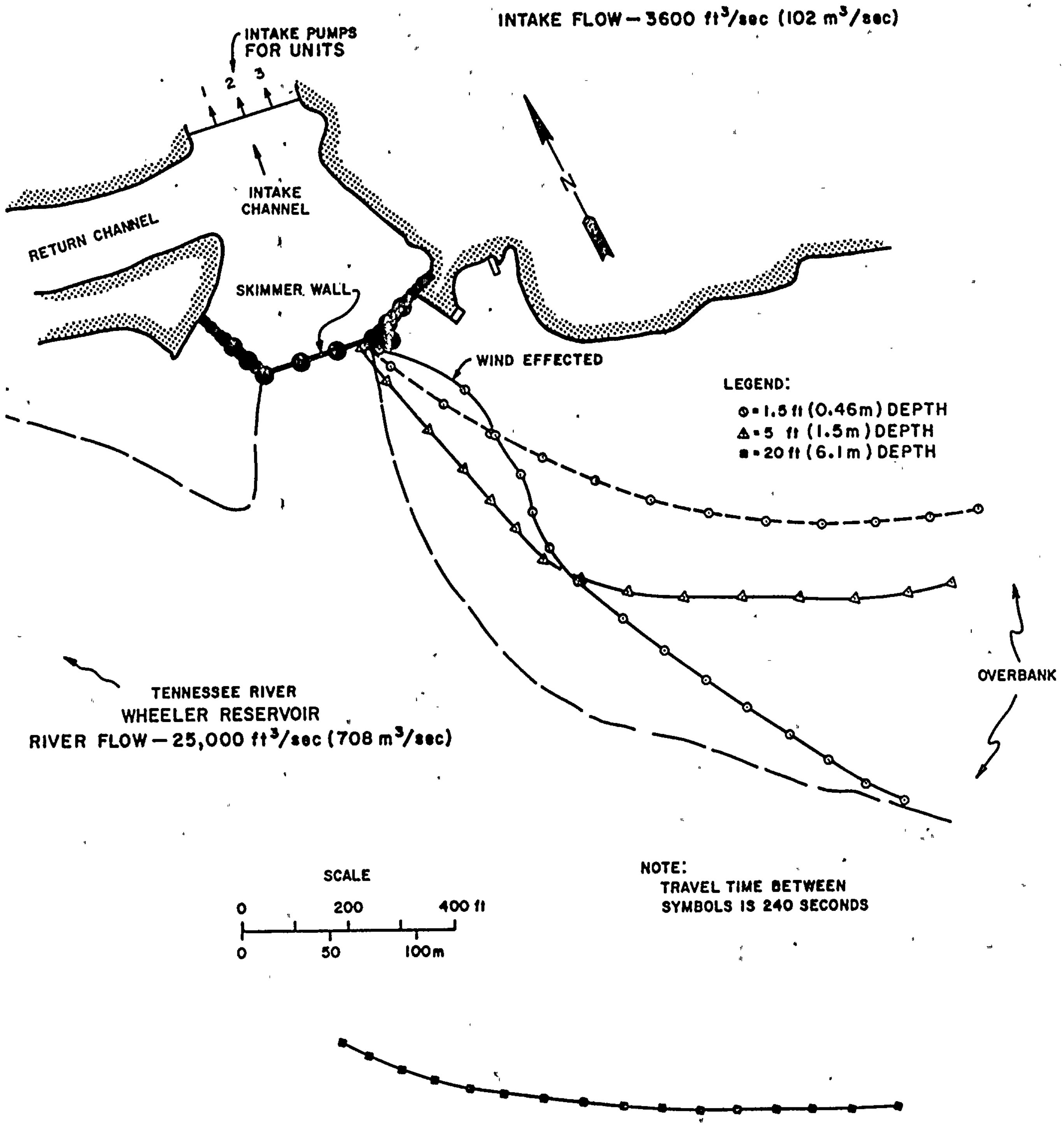


Figure 12: Drogue Trajectories From 0700 hrs To 0830 hrs on July 20, 1977

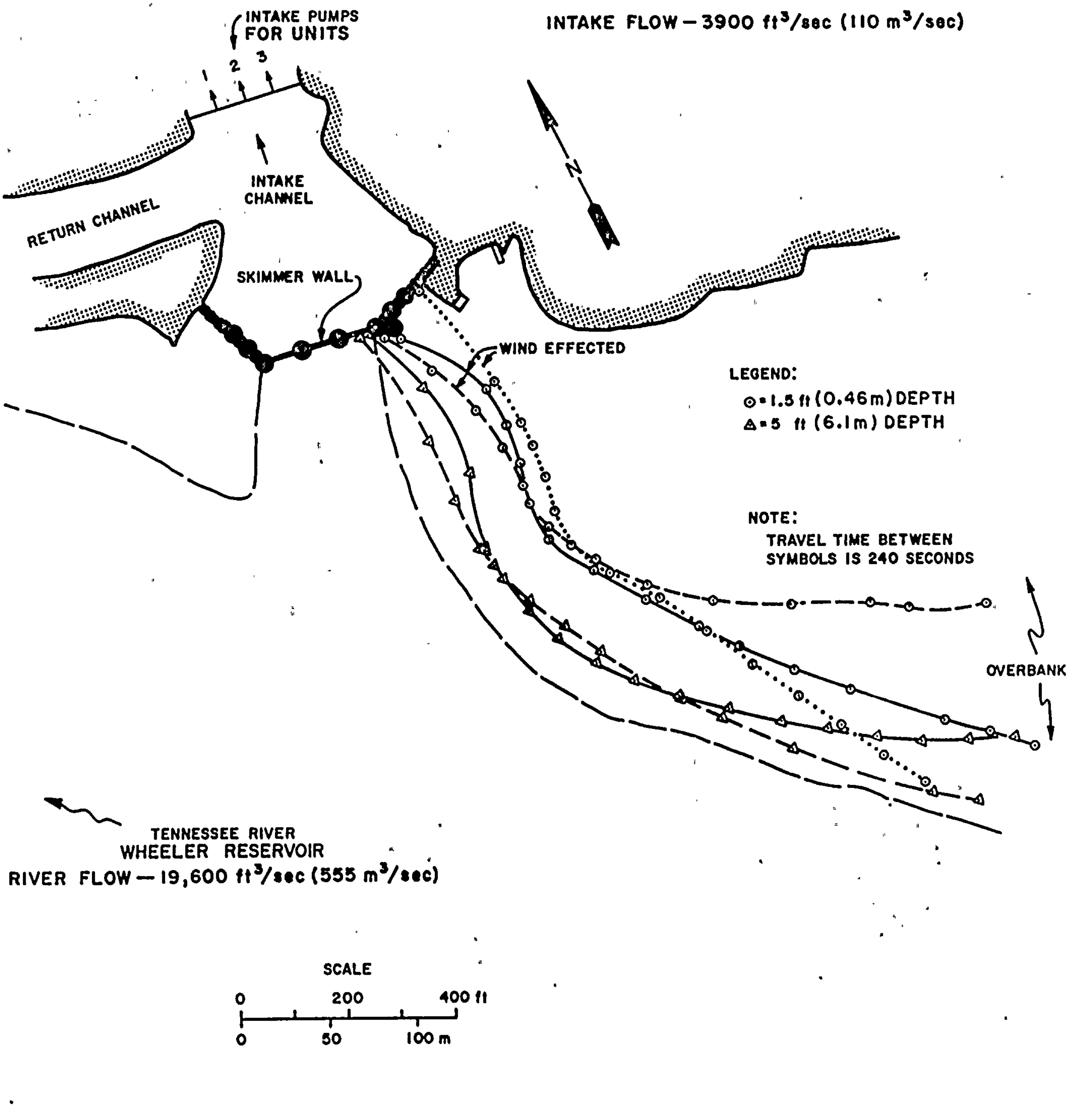


Figure 13: Drogue Trajectories From 0900 hrs To 1030 hrs on July 20, 1977

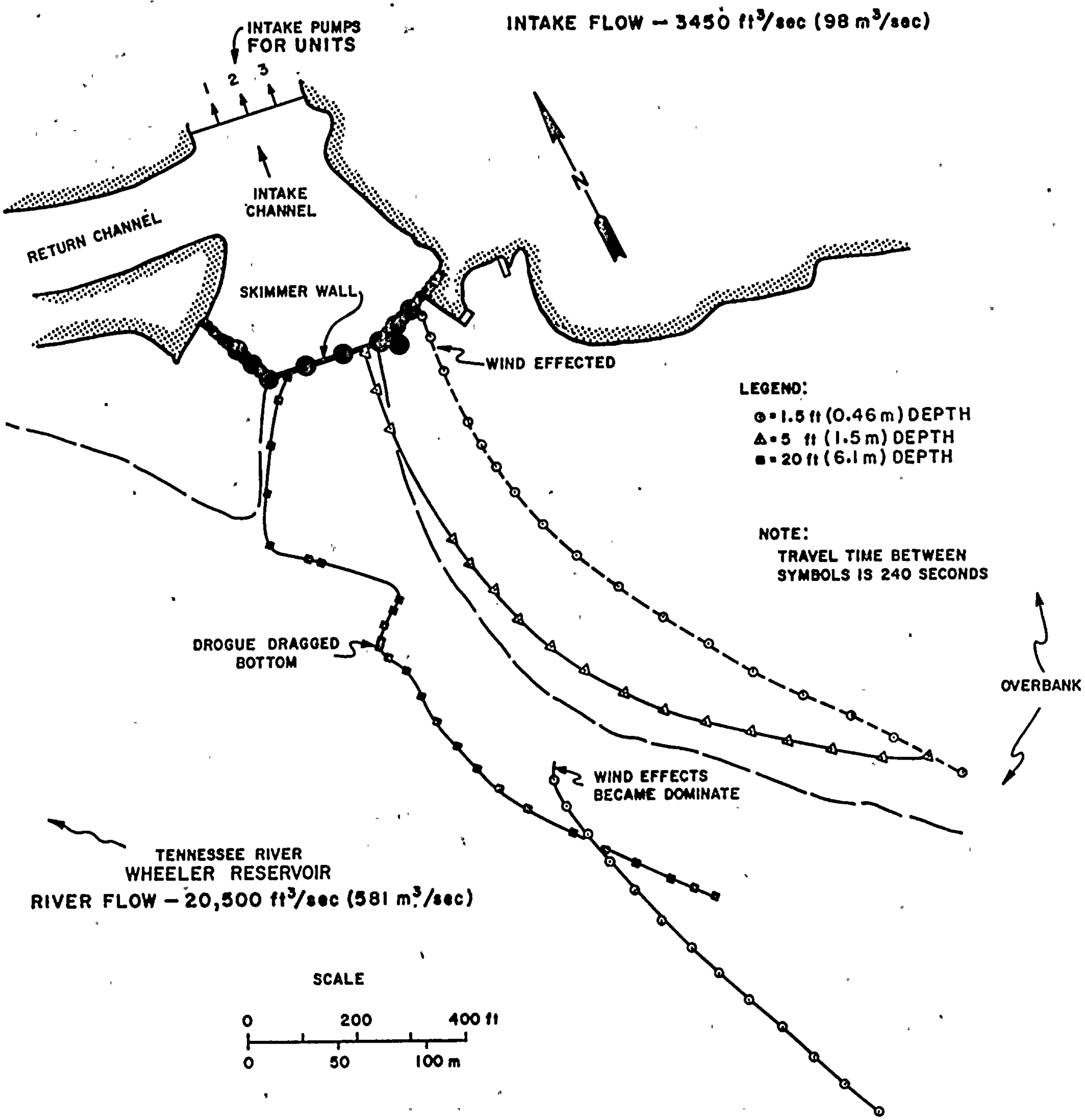


Figure 14: Drogue Trajectories From 1045 hrs To 1245 hrs on July 20, 1977

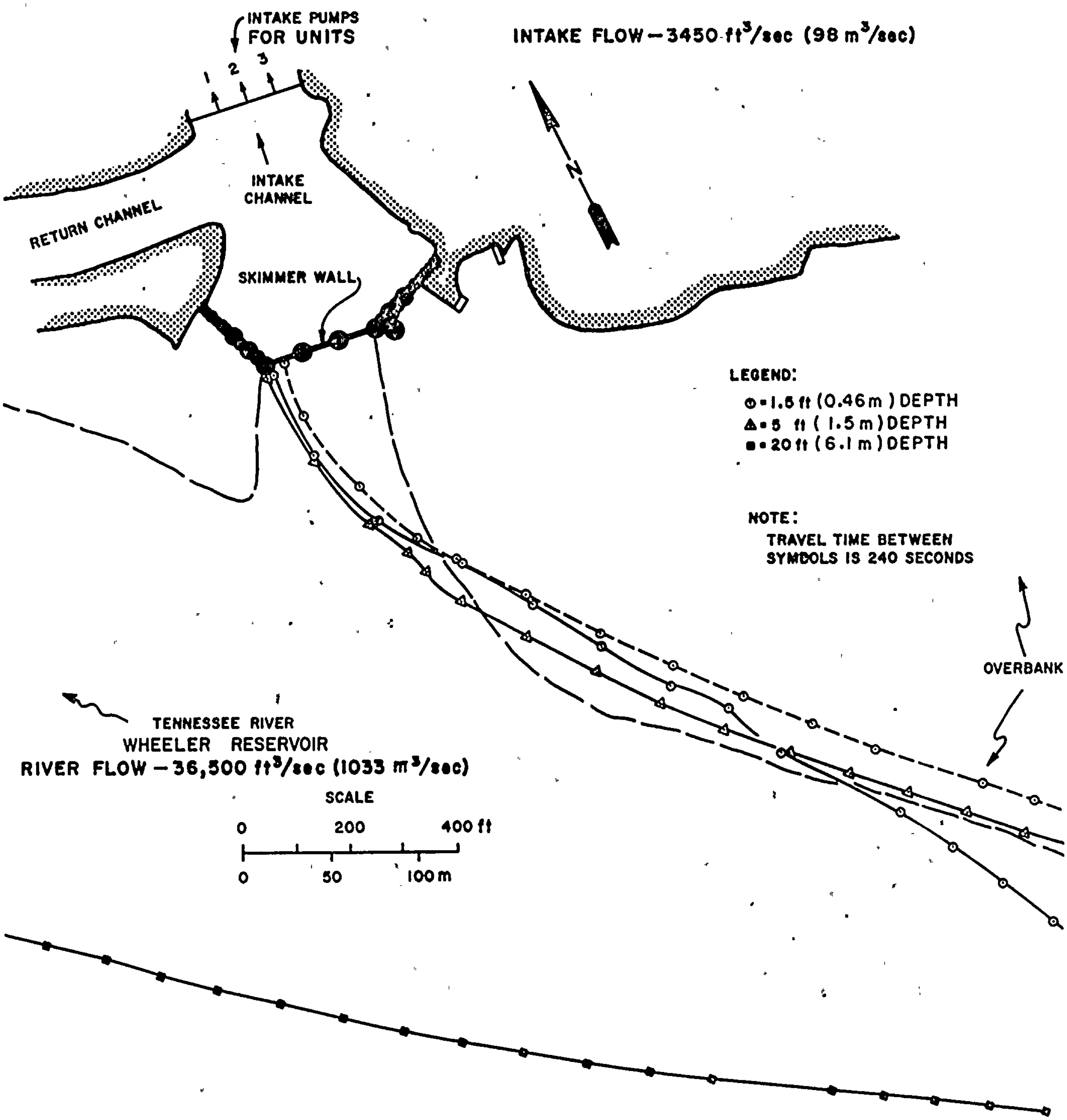


Figure 15: Drogue Trajectories From 0830 hrs To 1000 hrs on July 21, 1977

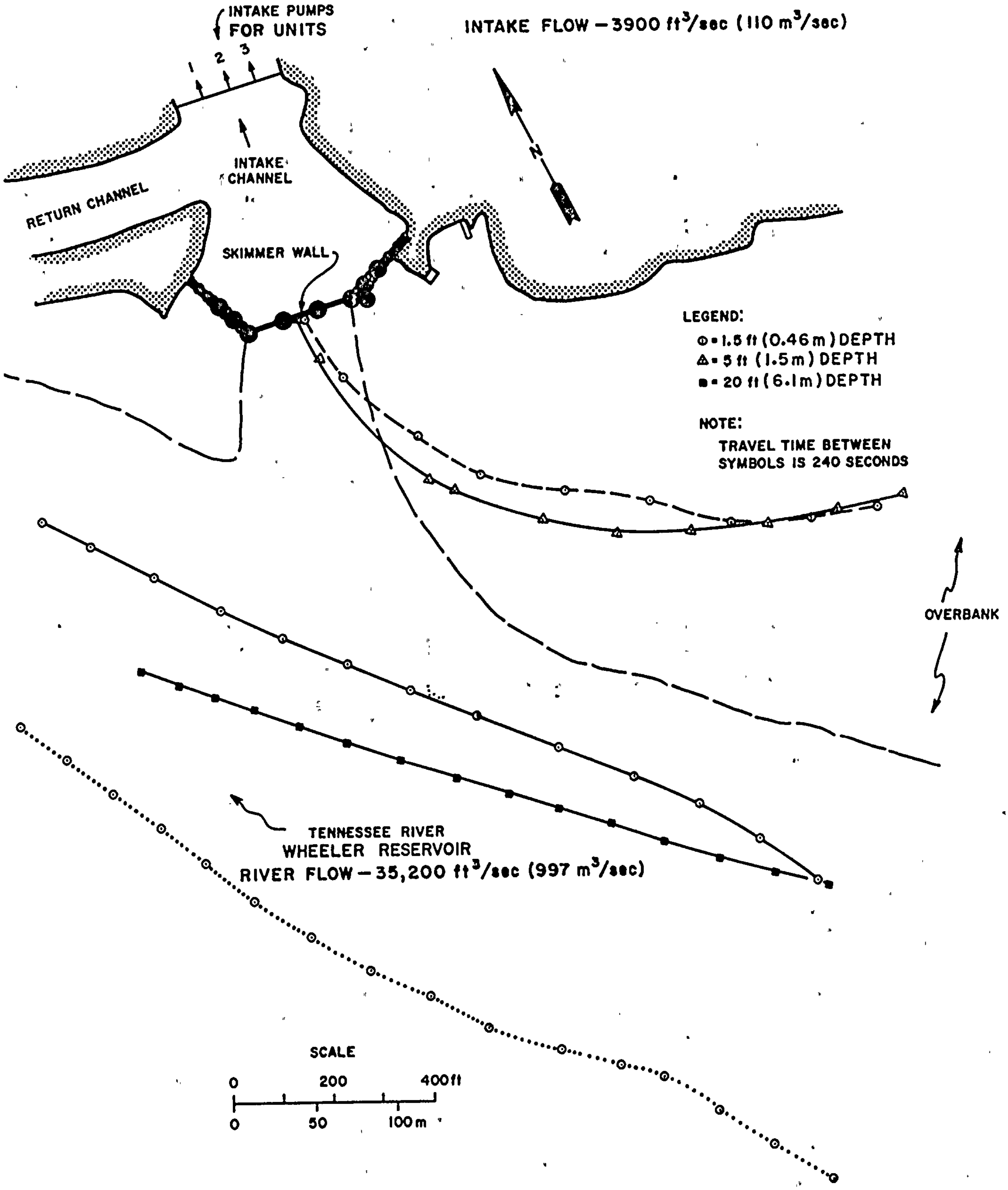


Figure 16: Drogue Trajectories From 1030 hrs To 1130 hrs on July 21, 1977

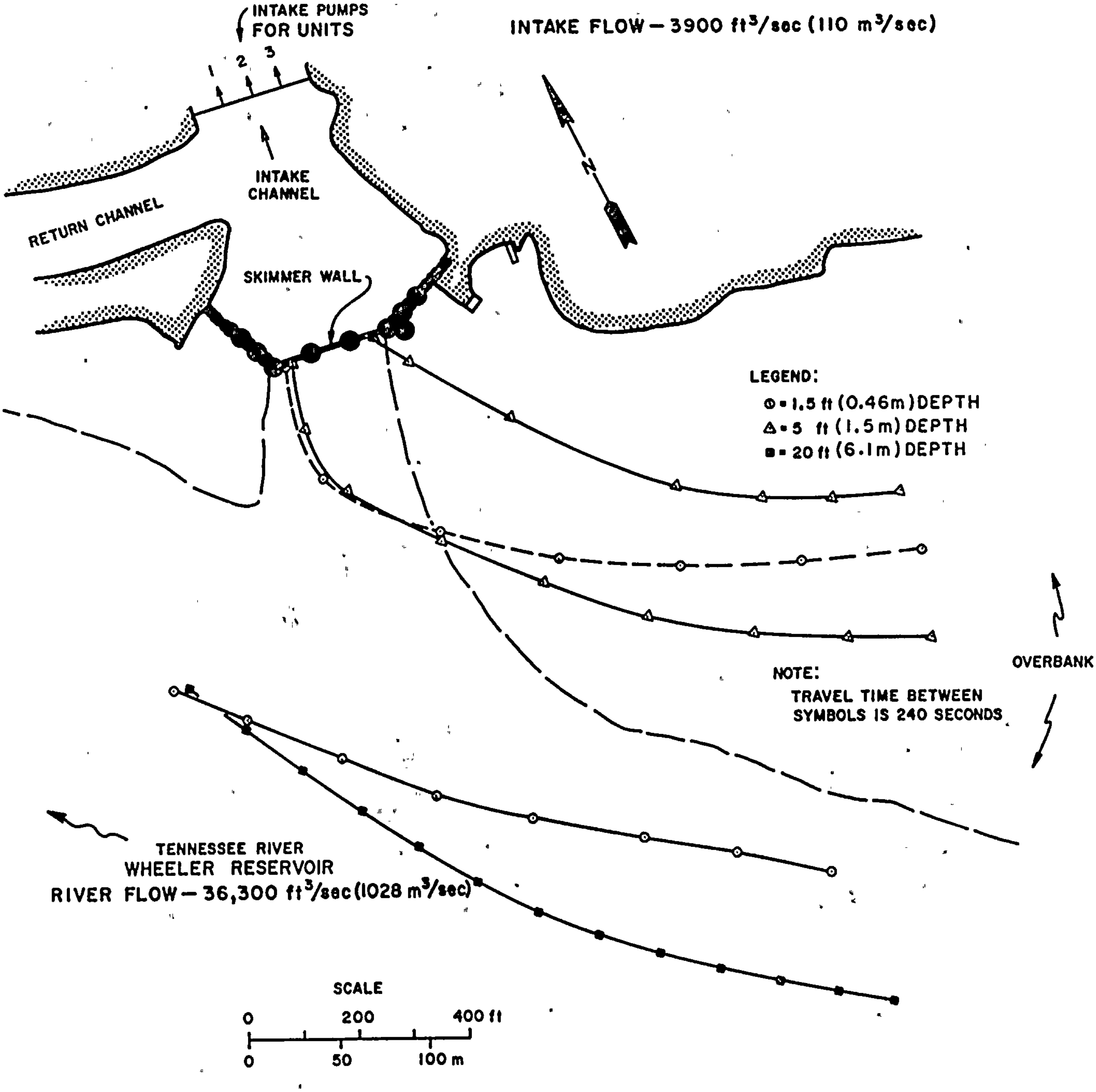


Figure 17: Drogue Trajectories From 1400 hrs To 1500 hrs on July 21, 1977

of 1.5 feet (0.5 m), 5.0 feet (1.5 m), and 20 feet (6 m) are shown. Symbols showing drogue positions at intervals of 240 seconds provide an indication of the speed at which each drogue was moving along its trajectory.

On July 20, when the river flows were relatively low, all drogues released on the overbank drifted to the upstream side of the intake. One drogue released in the main channel approximately 300 feet (100 m) from the right overbank tracking flow at a depth of 20 feet (6 m) (Figure 14) drifted into the dredged channel and ultimately against the downstream side of the intake gate implying that water from the lower depths of the right side of the main channel was flowing into the intake channel. Another drogue released near the center of the main channel (Figure 12) appeared relatively unaffected by the intake flow.

Trajectories were considerably different on July 21 when flows were much higher. The downstream inertia of the river flow appeared to have had a more pronounced effect upon the flow patterns near the intake. As a result, the overbank flow nearest the right bank appeared to enter the intake on the upstream side; flow from the center of the overbank entered the middle; and flow from the outer edge and the channel entered on the downstream side of the intake. Although not verified by these drogue studies, results of the previous velocity survey (May 18) conducted under similar flow conditions indicated that water from the lower depths (i.e., below the 20 feet [6 m] drogue) of the right side of the main channel also flowed into the plant intake channel. This is also implied from the results of the dye studies to be presented subsequently.

Dye Studies

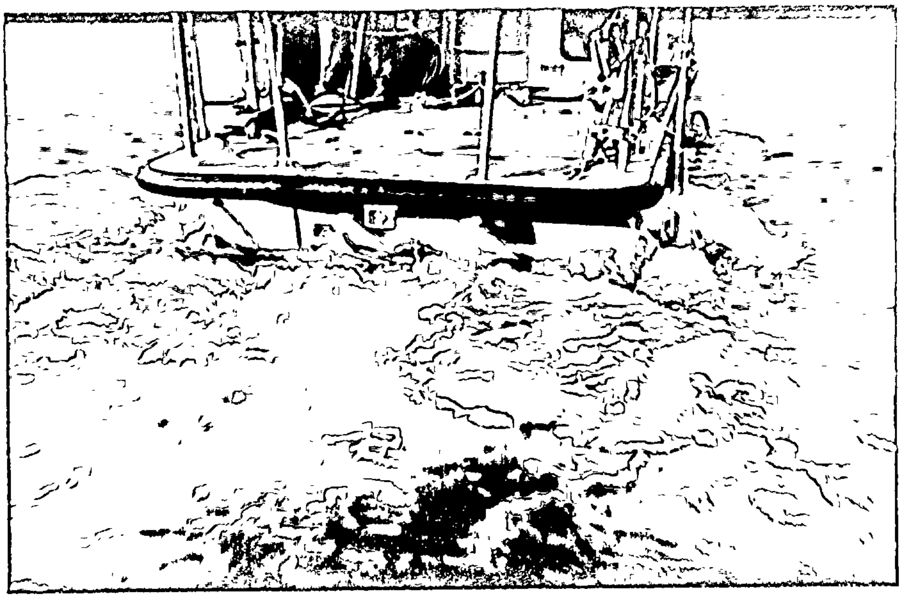
Procedure and Conditions

A portion of the overbank upstream of the plant intake was injected with a fluorescent dye in order to determine the fraction of water in the plant intake channel obtained from the overbank. Dye concentrations recorded immediately upstream of the intake gate were compared with concentrations recorded inside of the intake channel. The lower concentrations in the intake channel provided a quantative measure of the dilution attributable to the influx of water from the main channel which contained no dye.

The dye was injected approximately 0.6 miles (1 km) upstream of the intake. A zone approximately 1000 feet (300 m) long extending across the entire breadth of the right overbank was injected with a 20 percent solution of Rhodamine WT dye, a very dark red, aqueous liquid which is particularly suitable for flow tracing by fluorometry and visual methods.

The dye was injected into the water through two 1.5-inch (3.8 cm) diameter manifolds rigidly mounted on each side of a boat (Figure 18). Dye was supplied from a 30-gallon (115-liter) drum which was kept under constant pressure to assure an even flow of dye. Discharge ports in the manifold were positioned at depths of 0.5, 2.5, and 5.0 feet (0.15, 0.76 and 1.5 m). By throttling the boat to selected speeds and varying the flow from the discharge ports, the desired concentrations could be achieved. Turbulence of the boat wake and natural dispersion as the water flowed toward the plant provided vertical and horizontal mixing and thus minimized dye concentration gradients in the overbank near the plant intake.

Boats equipped with Turner Model 111 or Model 10 fluorometers and anchored at predetermined monitoring stations were used to obtain



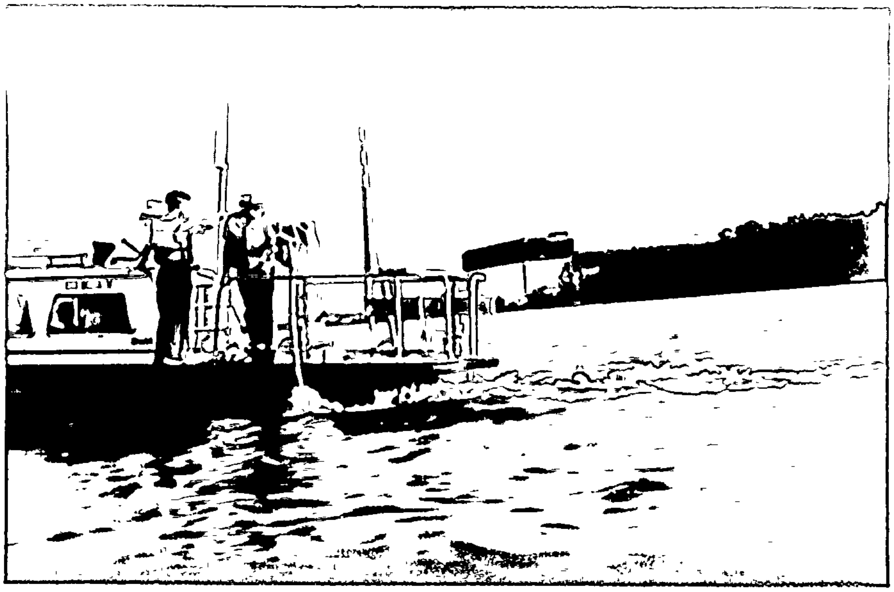


Figure 18 : Dye Injection Procedure

samples of the water at various depths. These data were used to determine maximum concentrations of dye at various locations as the dye cloud passed from the overbank and through the intake channel.

Four separate surveys were conducted for river flows ranging from 11,000 ft^3/sec (310 m^3/sec) to 38,000 ft^3/sec (1075 m^3/sec). These flows were obtained through prearranged special operation of the upstream and downstream hydroelectric plants. The plant was operating in Open Mode during the survey on May 18, and was operating in a combination of Open and Helper Modes for the latter three tests. During the spring survey (May 18), the water temperature in the overbank was significantly warmer than the main channel, but by July 20 when the last test was conducted, this condition had reversed. Specific plant operating conditions and ambient conditions existing during each test are provided with the discussion of that test.

Results

Although the four tests were conducted for a wide range of plant operational and river conditions, the percentage of water pumped into the plant from the overbank is remarkably consistent. Each test will be discussed separately.

May 18, 1977--The intake flow of the plant was near the maximum value of 4410 ft^3/sec (125 m^3/sec). River flows were constant at 38,000 ft^3/sec (1075 m^3/sec), and the temperature in the overbank was detectably warmer than in the main channel (Figure 19) and the overbank existed near the latter part of the survey period and thereafter.

Because of the buoyancy of the flow from the overbank when it merged with the cooler water from the main channel near the plant

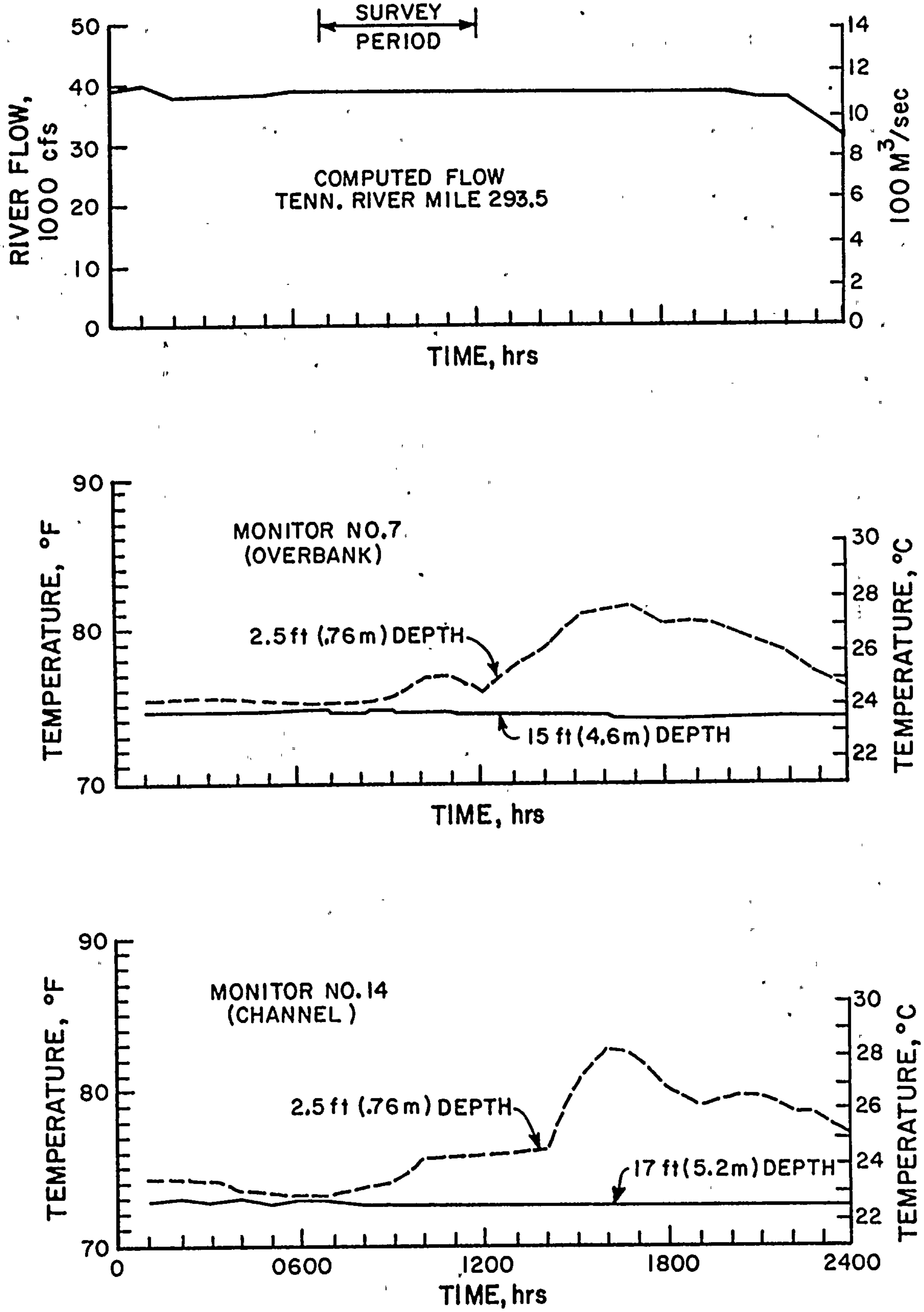


Figure 19: River Flow and Temperature vs Time
May 18, 1977

intake, a portion of the water from the upper three feet (one meter) of the water column was not entrained into the plant intake. A qualitative description of the warm surface affected at any time (not simultaneously) by the red dye is shown in Figure 20, which indicates that the dye was visible until it was thoroughly mixed with the discharge from the diffuser.

Quantative sampling on the overbank immediately upstream of the intake revealed average dye concentrations of 20 parts per billion (ppb) by volume. Comparing this to the maximum value, 11 ppb of the cross-sectional average of concentrations recorded in the intake channel midway between the skimmer wall and the pumps, indicated that approximately 55 percent of the flow entering the plant came from the overbank. These test conditions and results are summarized in Table 1 along with data from the remaining three tests.

June 7, 1977--During the second test, river flows of 35,000 ft^3/sec (1000 m^3/sec) were similar to those of May 18. However, the thermal structure of the reservoir was slightly different and the plant was operating with lower intake flow rates as shown in Figures 21-22 and summarized in Table 1. The downstream inertia of the overbank flow and the slight temperature difference produced a qualitative picture of the surface, presented in Figure 23, which is similar to Figure 20 (May 18 test).

The sampling positions for measuring dye concentrations are also denoted in Figure 23. Concentrations recorded in the reservoir and in the intake channel are presented in Figures 24 and 25, respectively. Because of the proximity to the dredged channel leading to the plant intake, it was determined that data recorded at Station A

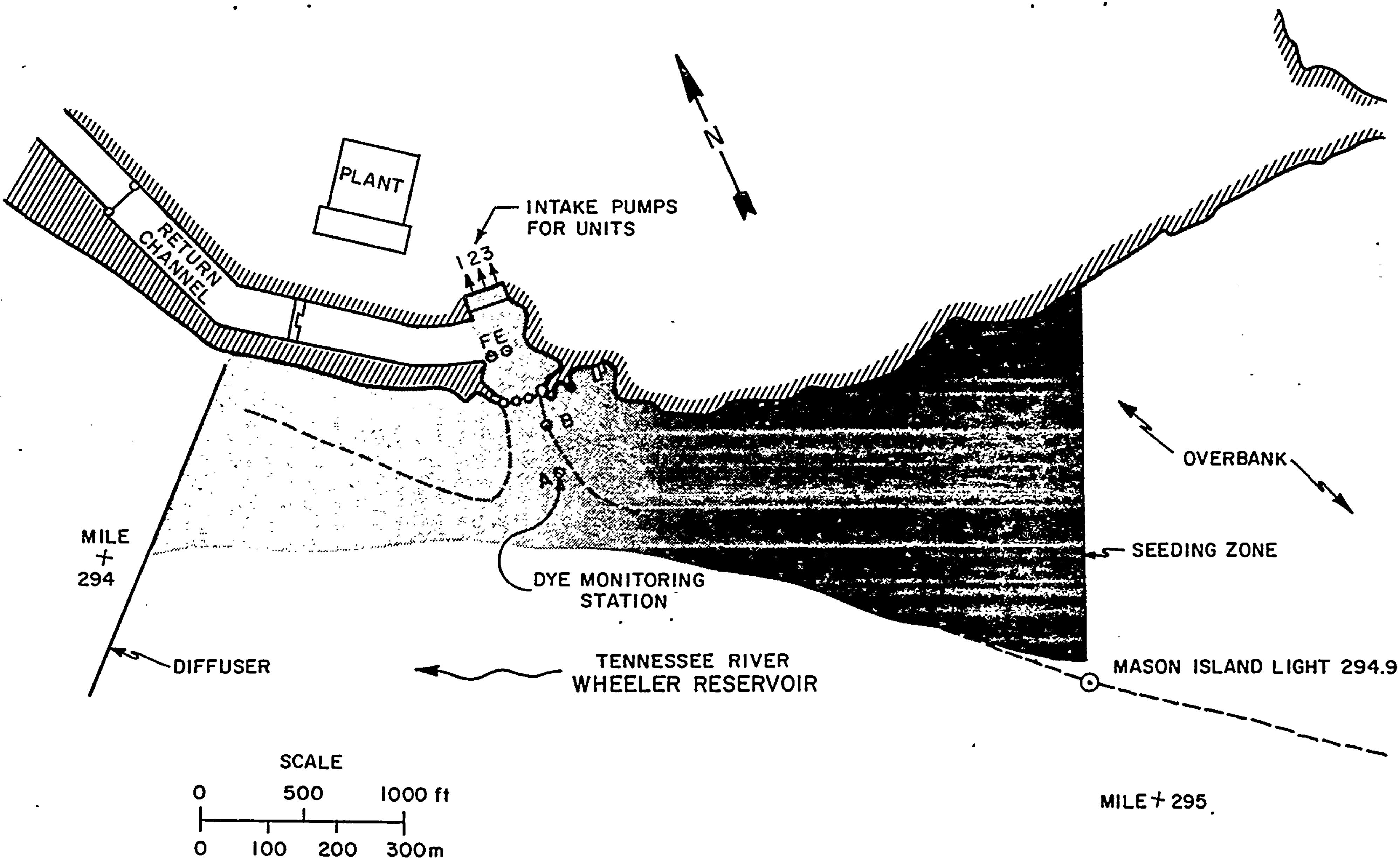


Figure 20: Seeding Zone, Monitoring Stations
And Observed Behavior of Dye Cloud
May 18, 1977

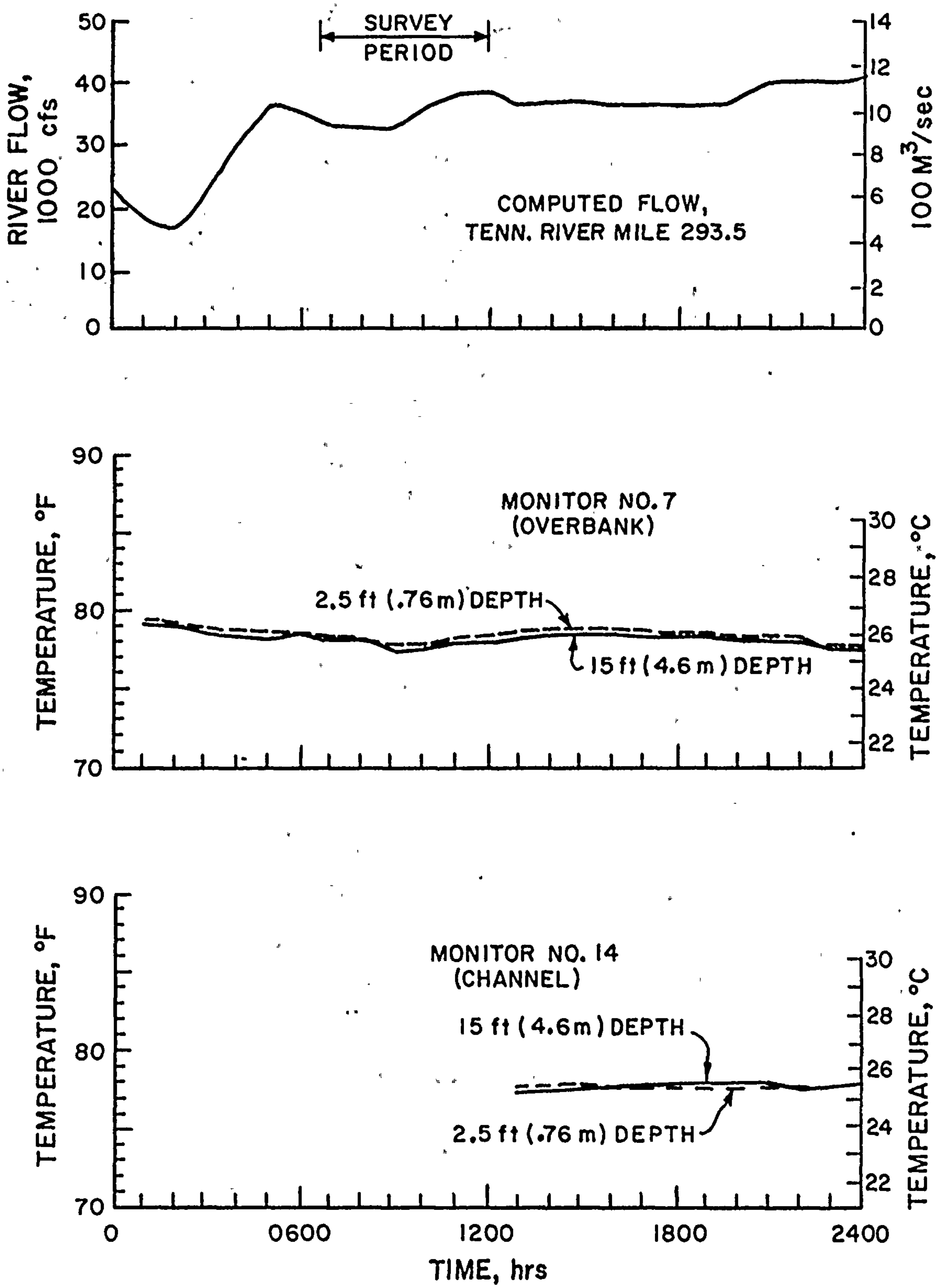


Figure 21: River Flow and Temperature vs Time
June 7, 1977

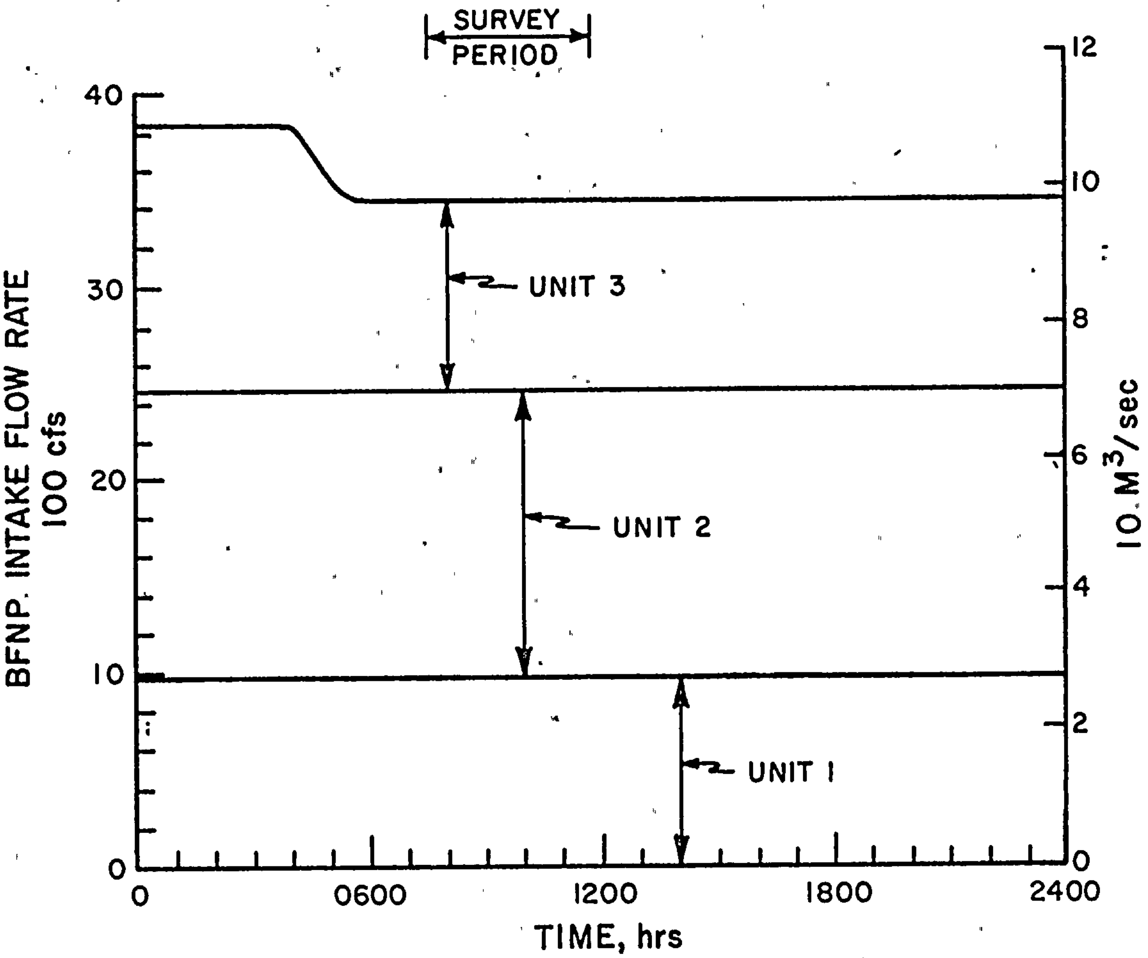


Figure 22: Condenser Cooling Water Flow For June 7, 1977

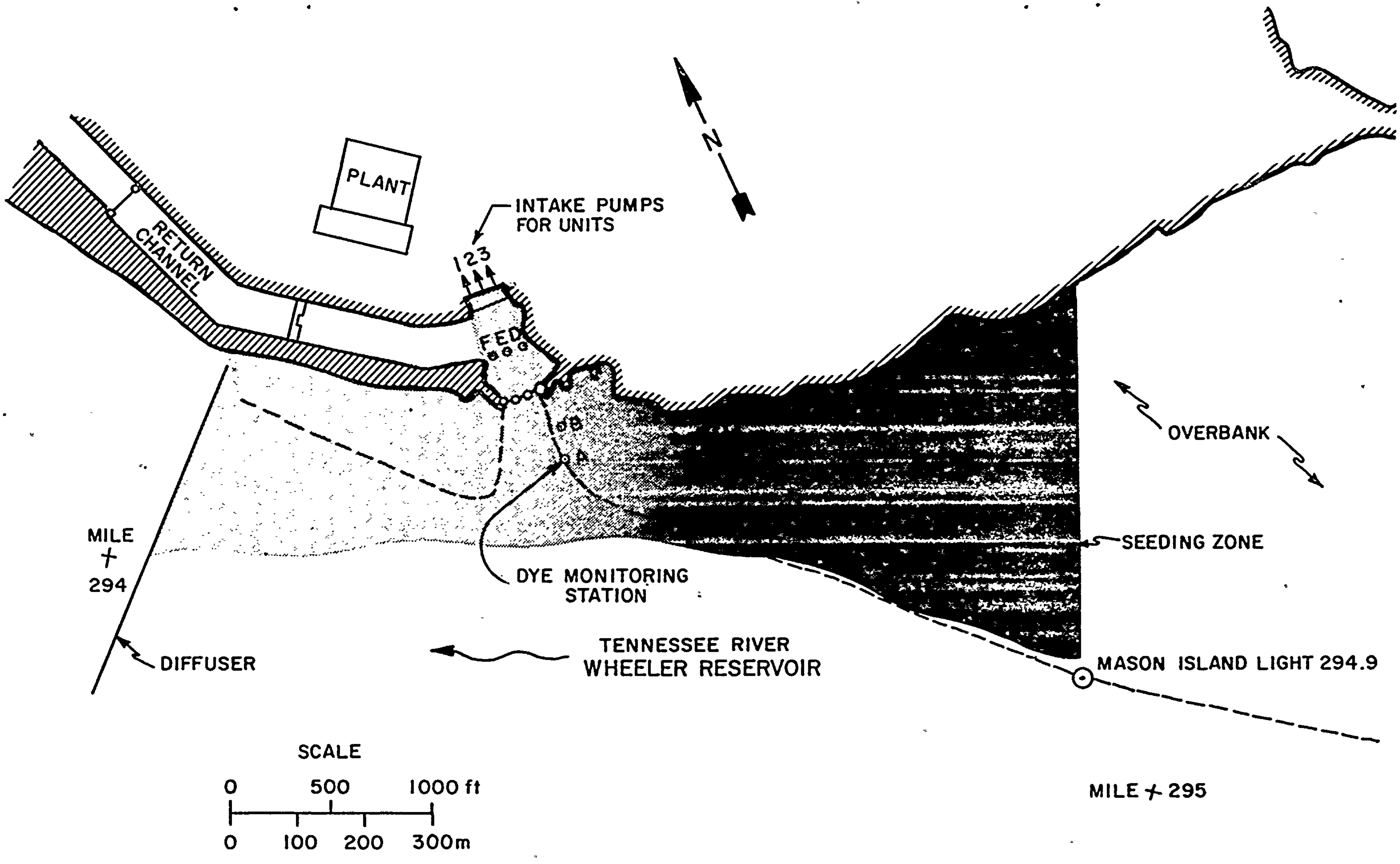


Figure 23: Seeding Zone, Monitoring Stations And Observed Behavior of Dye Cloud June 7, 1977

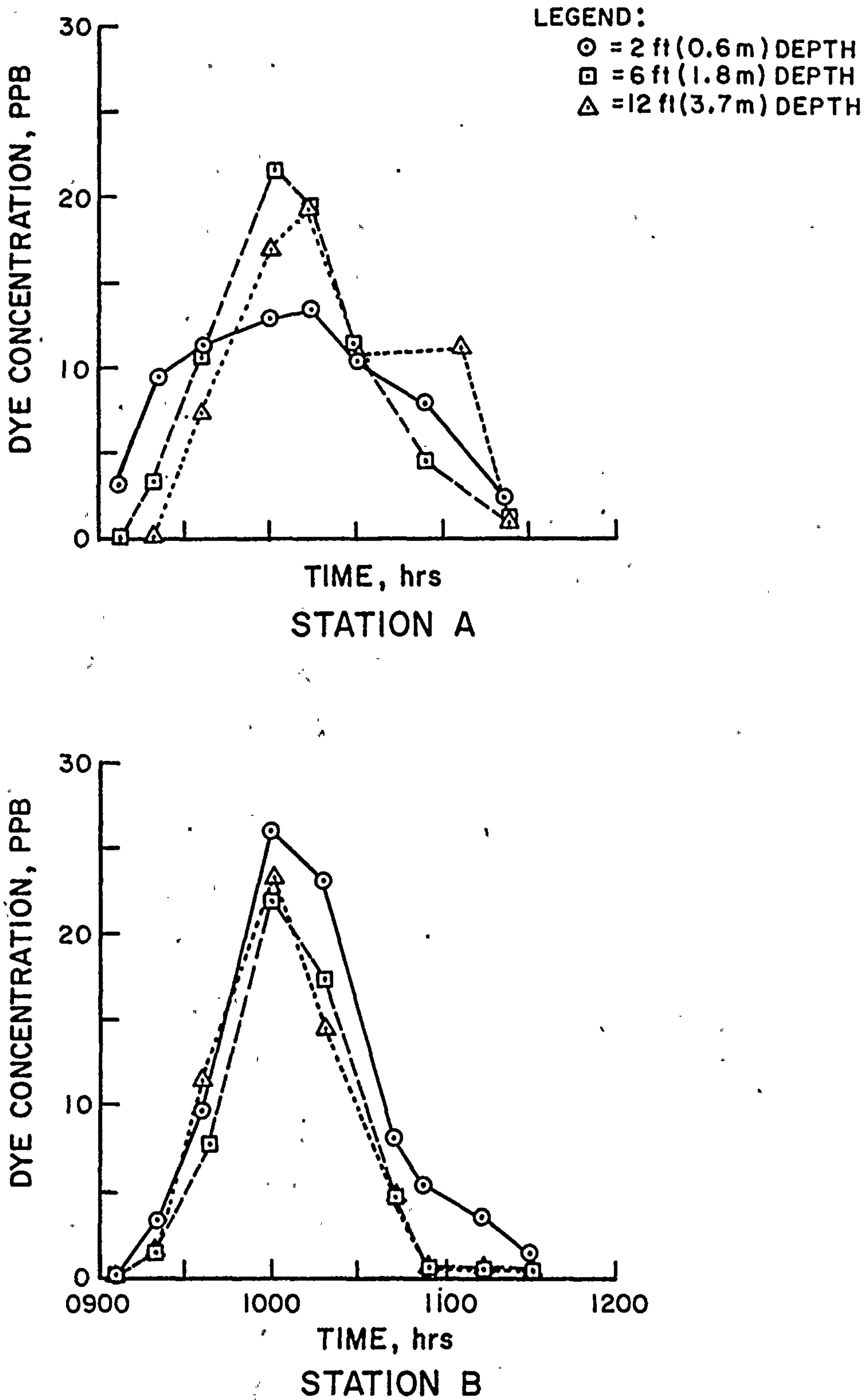


Figure 24: Dye Concentration Outside of Skimmer Wall
June 7, 1977

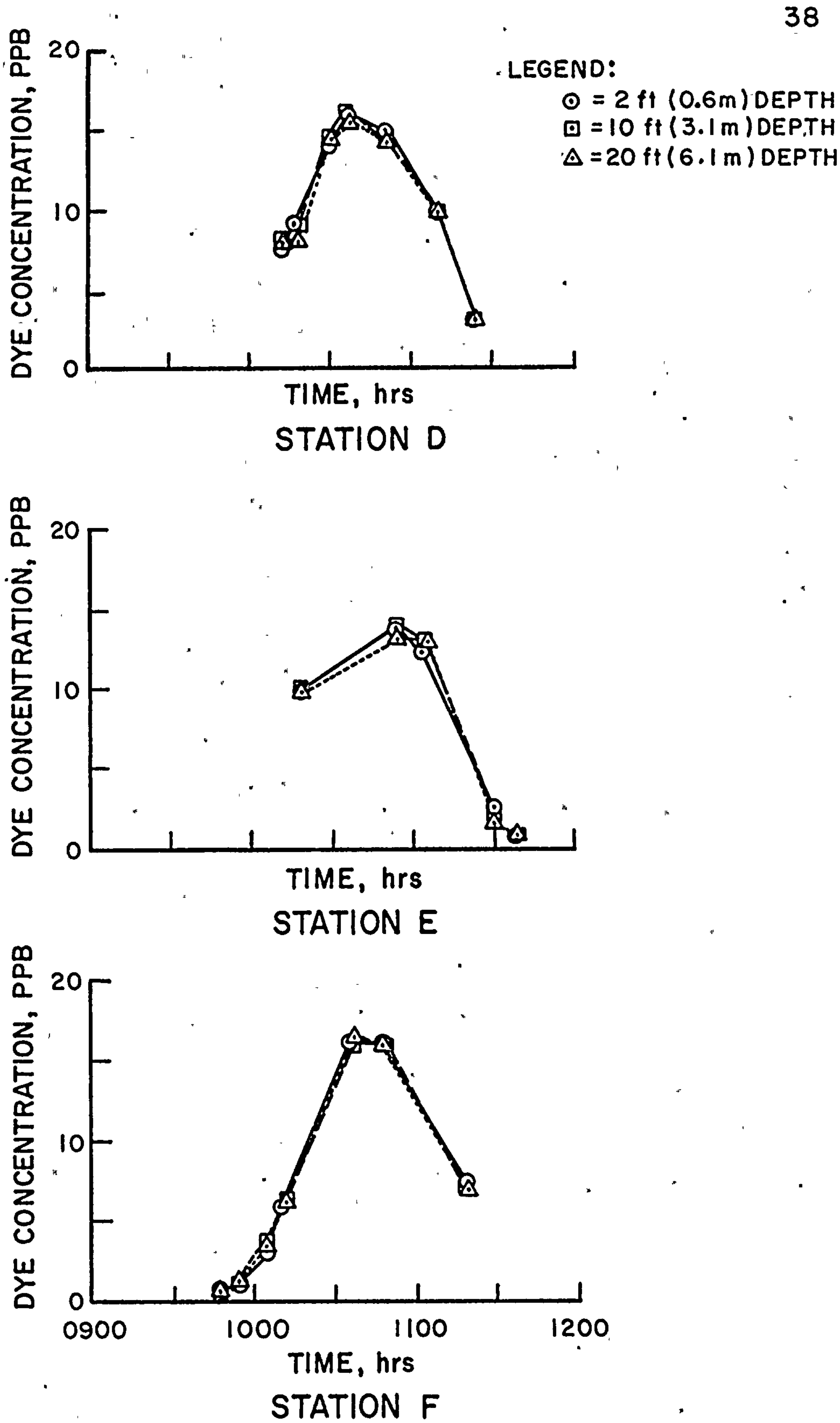


Figure 25: Dye Concentration in Intake Channel
June 7, 1977

reflected some mixing with flow from the main channel. Hence, Station B was used to determine a depth-averaged peak overbank dye concentration of 22 ppb. Comparing this concentration with the maximum concentration determined by averaging across the cross-section of the intake channel, 13.8 ppb, it was determined that approximately 63 percent of the intake flow came from the overbank.

June 19, 1977--River flows were significantly lower than during any of the other three tests, averaging about 11,000 ft^3/sec (310 m^3/sec). There was no appreciable difference in water temperatures in the region surveyed (Figure 26) and the intake flow was constant at 3420 ft^3/sec (97 m^3/sec) (Figure 27). For these conditions, the qualitative picture of the surface (Figure 28) reveals a different flow pattern as all of the overbank flow seemed to be drawn into the intake. Data from the reservoir monitoring stations (Figure 29) were used to estimate an average overbank dye concentration of 23 ppb.

Dye concentrations recorded in the intake channel (Figure 30) show that during these low river flows, flow from the overbank was confined to the right side of the intake channel with water from the main river channel on the left side. These data produced a maximum cross-sectional average concentration of 12.7 ppb, which indicated that 55 percent of the intake flow came from the overbank (Table 1).

July 20, 1977--Both the river flow (Figure 31) and the intake flow (Figure 32) were somewhat unsteady, averaging 21,000 ft^3/sec (596 m^3/sec) and 35,500 ft^3/sec (1005 m^3/sec), respectively. Because the reservoir had begun its annual was in a cooling phase, the overbank temperatures were slightly cooler than those of the main channel (Figure 31 and Table 1). Where the two water masses met, the main

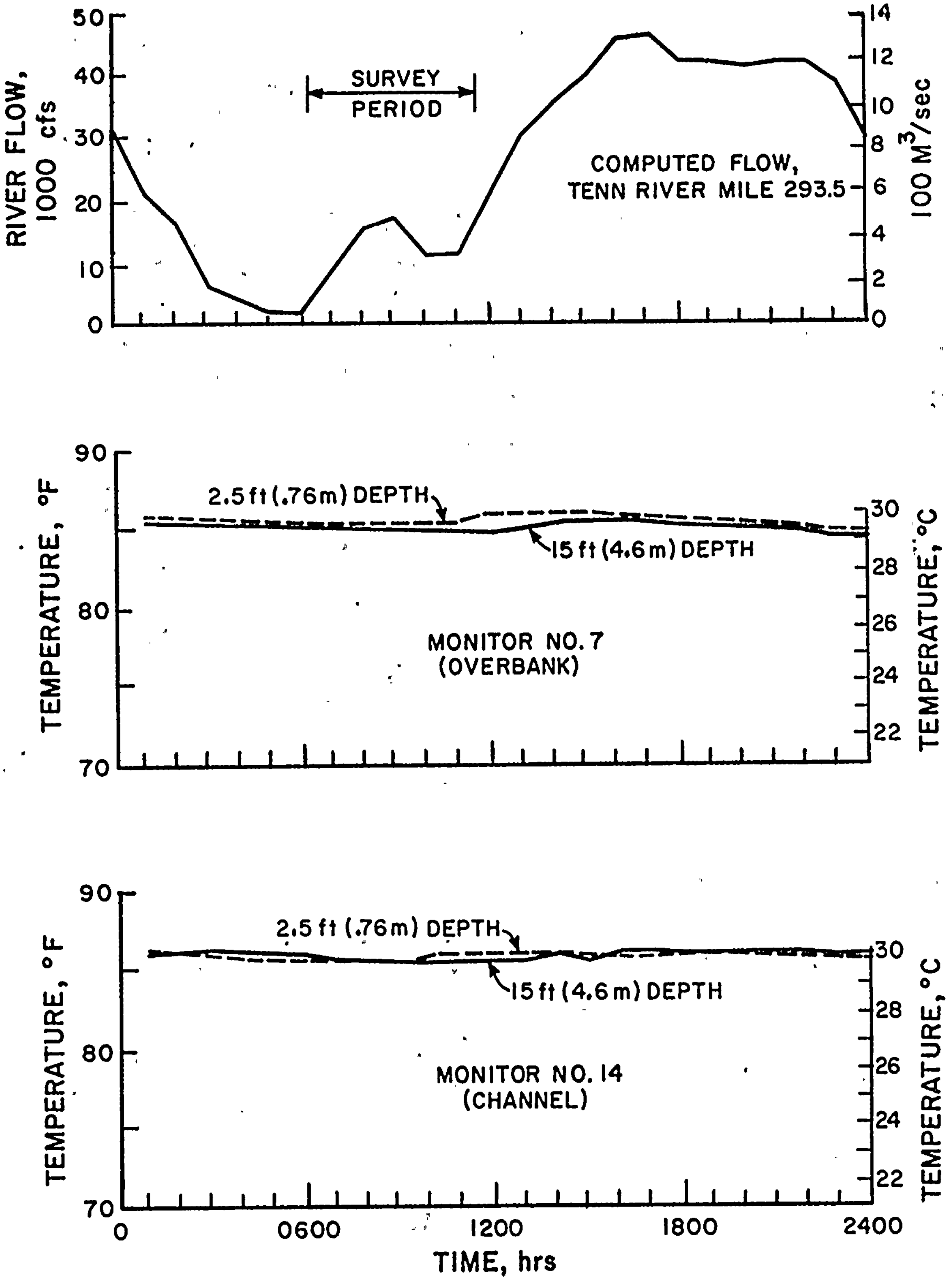


Figure 26: River Flow and Temperature vs Time
July 19, 1977

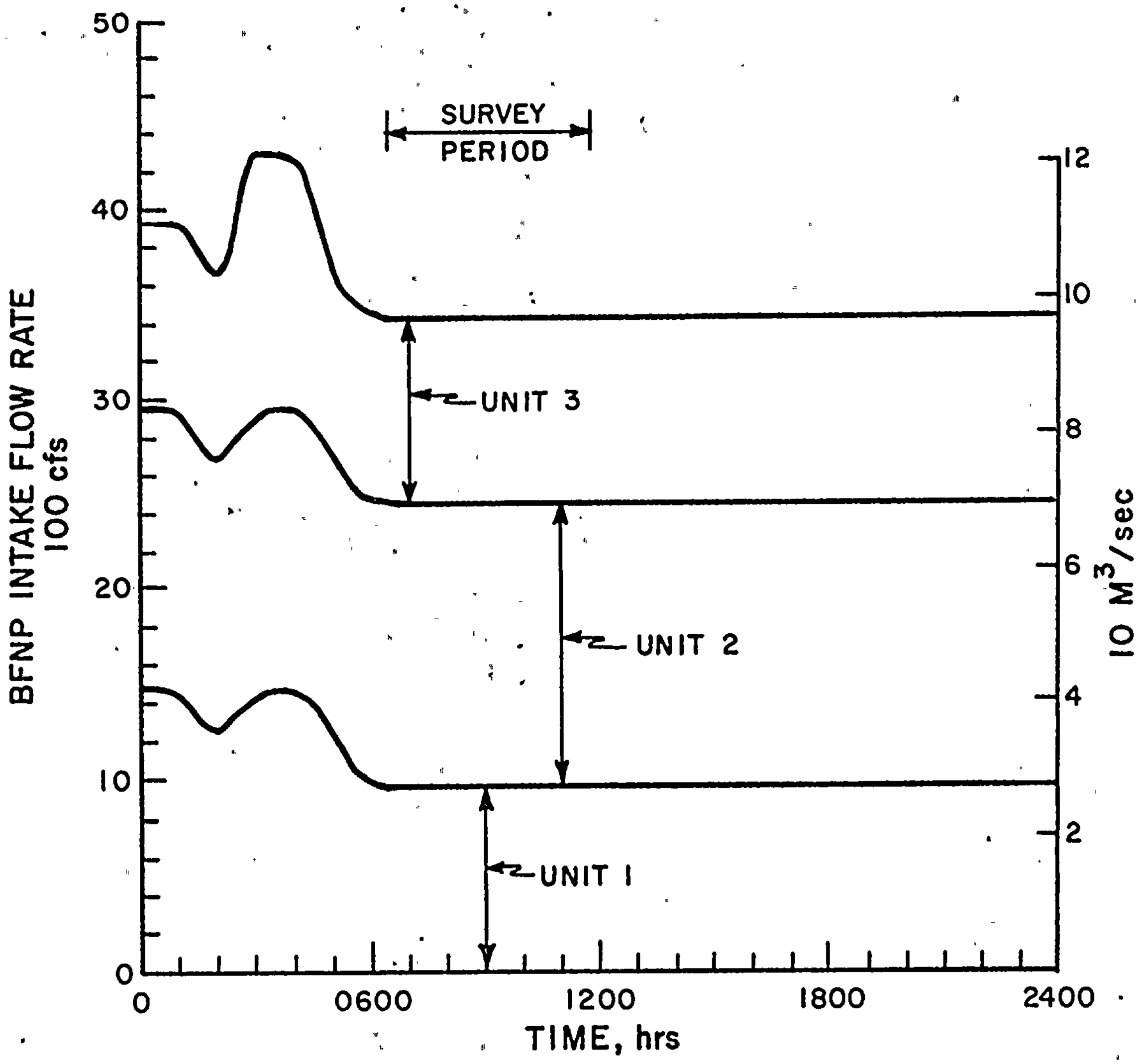


Figure 27: Condenser Cooling Water Flow For July 19, 1977

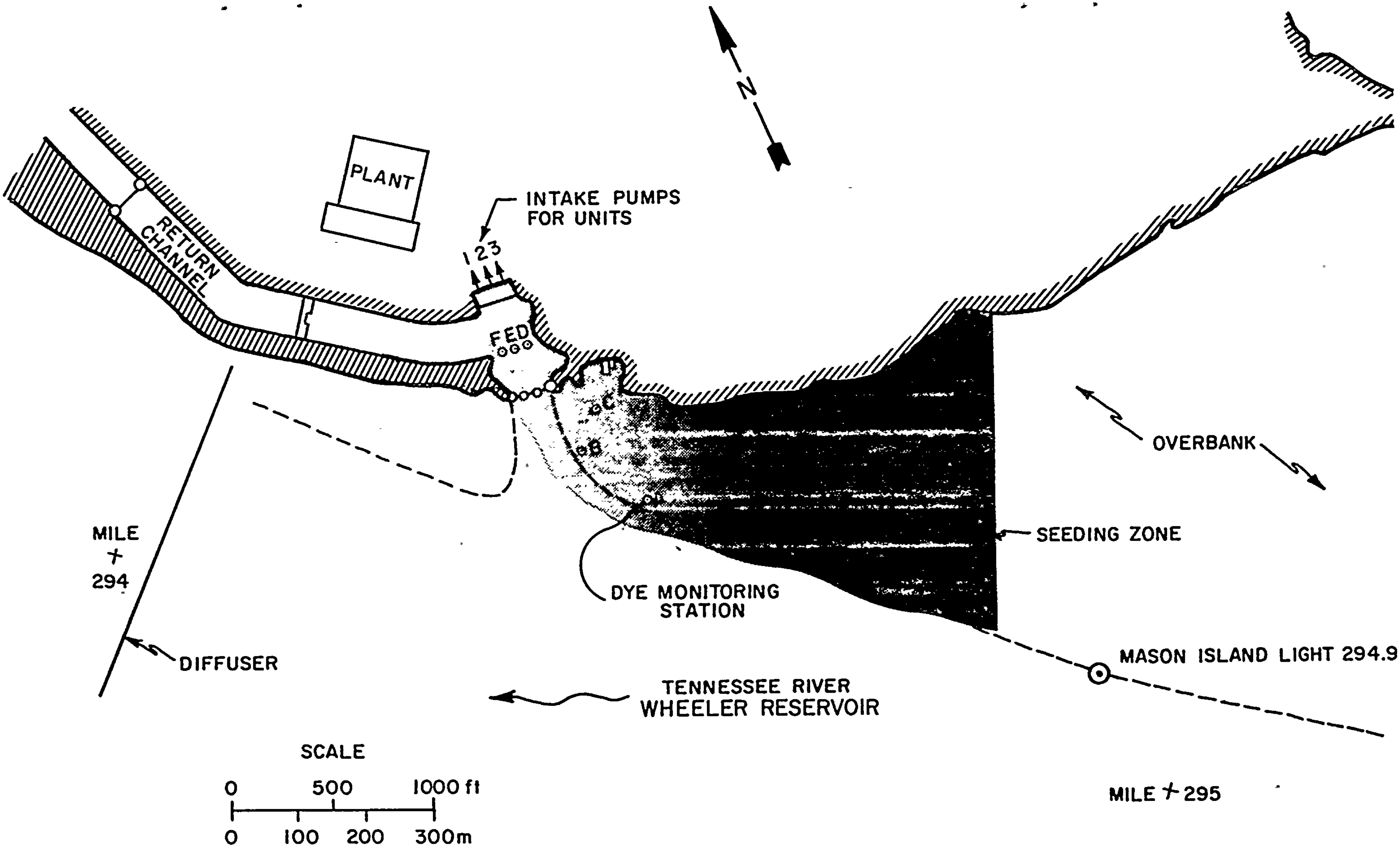


Figure 28: Seeding Zone, Monitoring Stations And Observed Behavior of Dye Cloud July 19, 1977

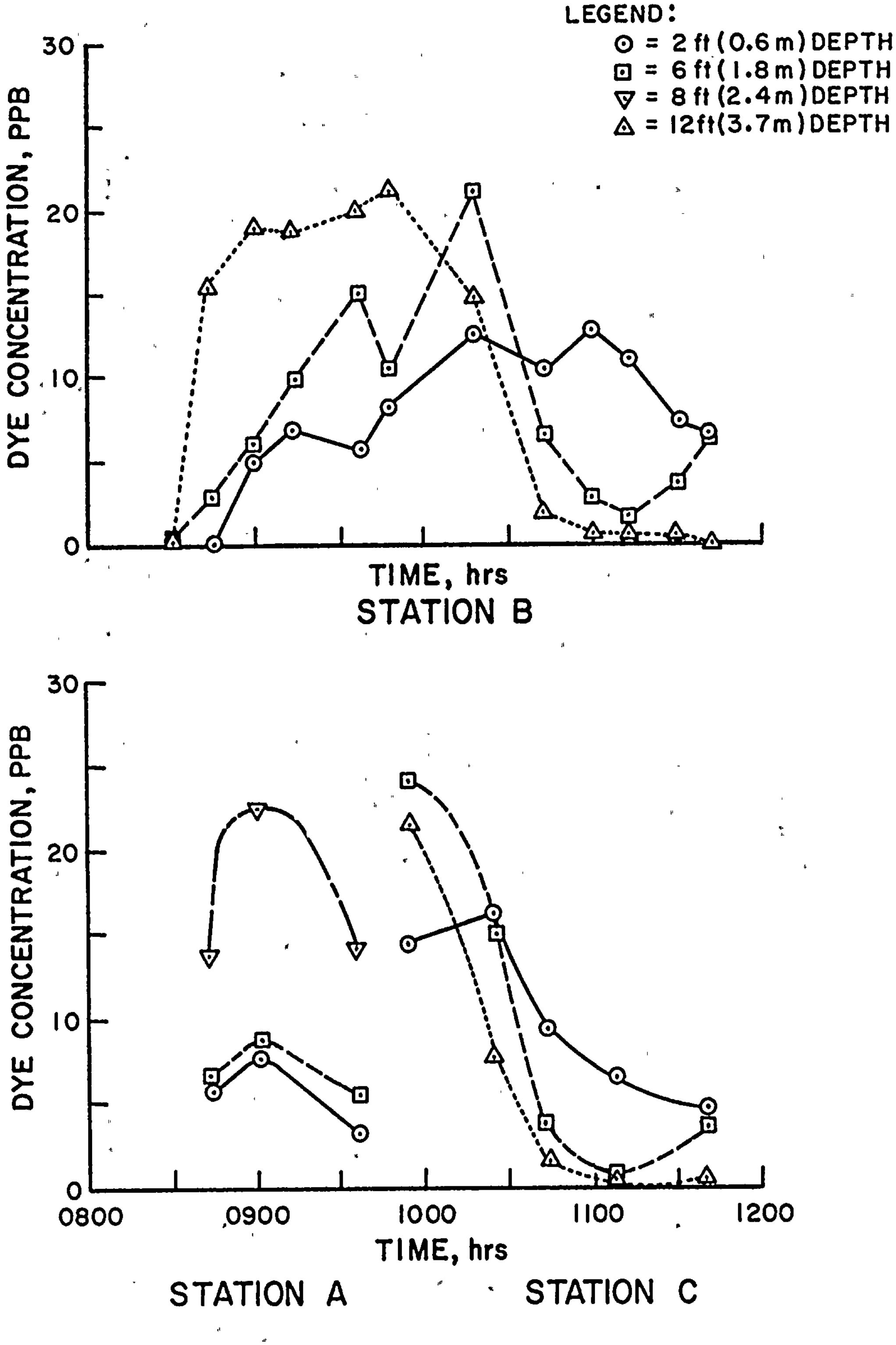


Figure 29: Dye Concentration Outside of Skimmer Wall
July 19, 1977

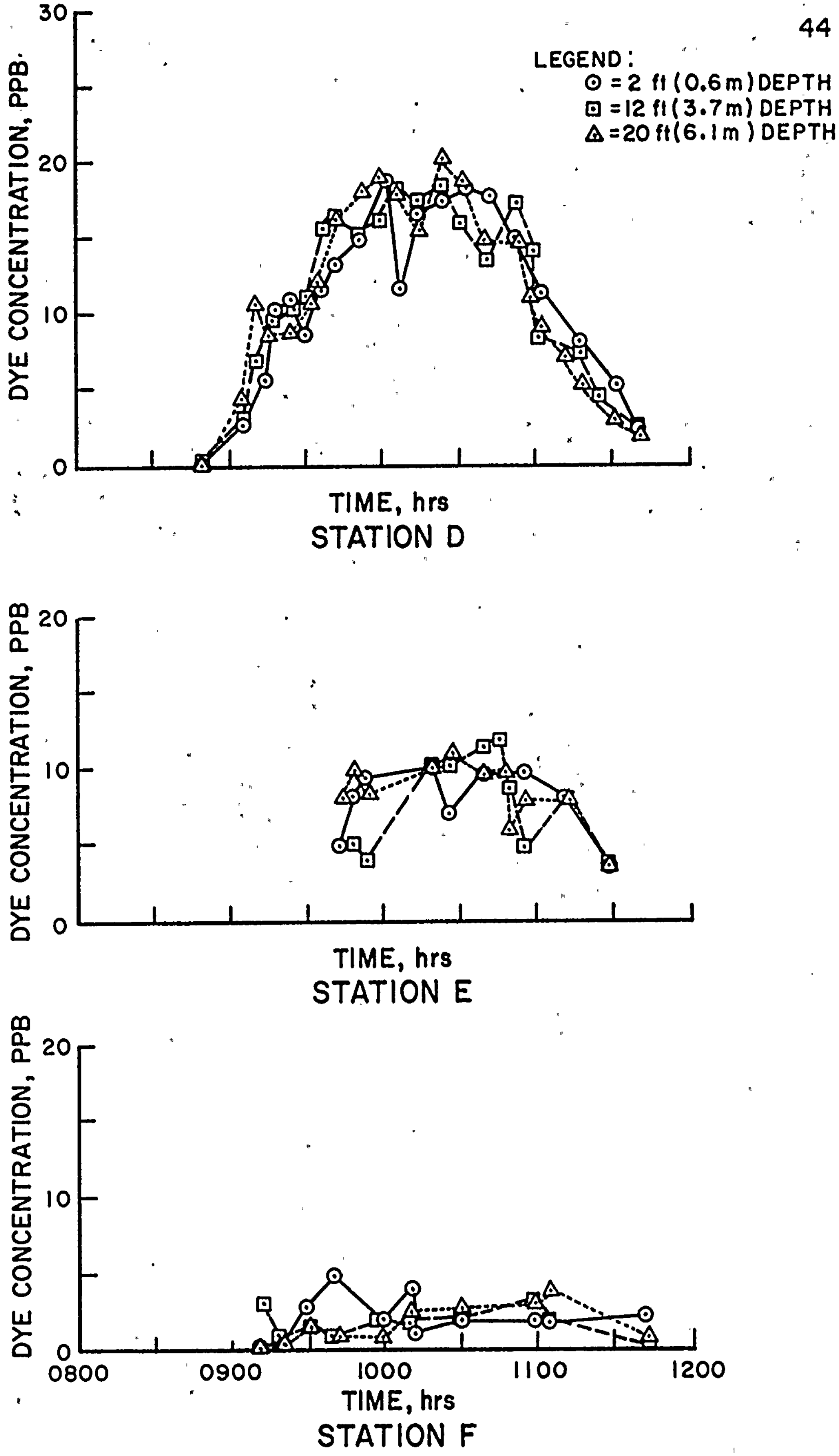


Figure 30: Dye Concentration in Intake Channel
July 19, 1977

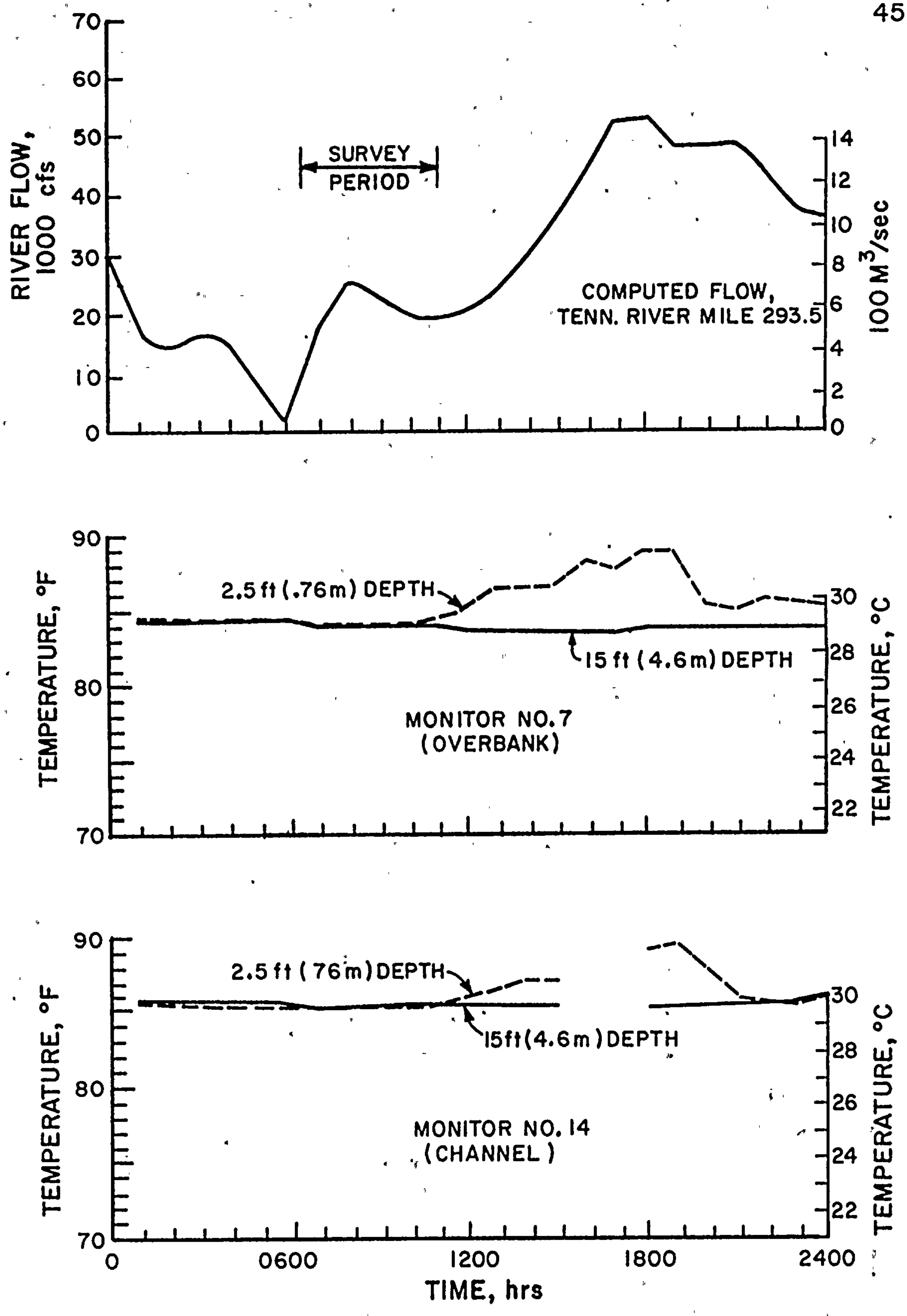


Figure 31: River Flow and Temperature vs Time
July 20, 1977

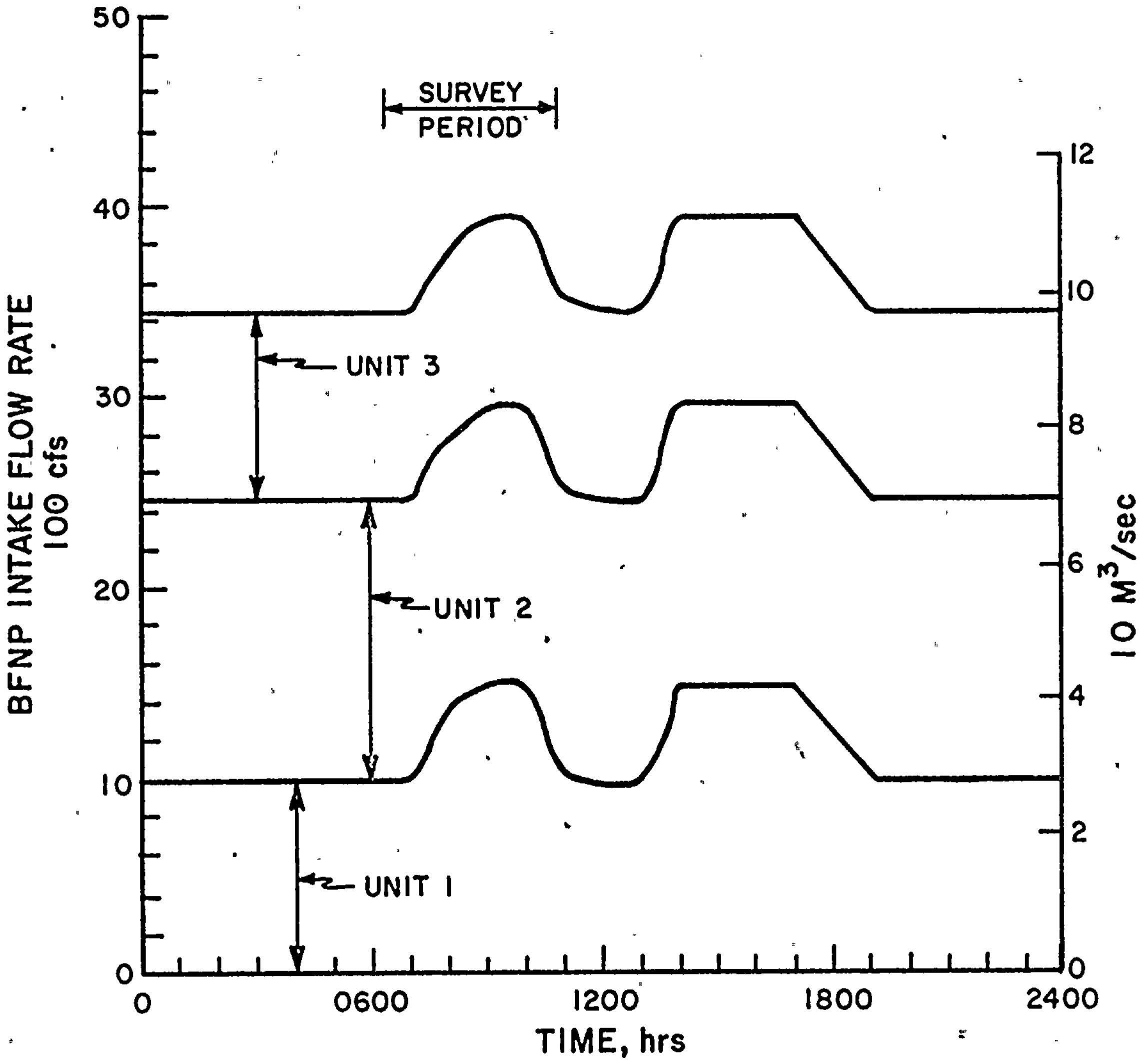


Figure 32: Condenser Cooling Water Flow For July 20, 1977

TABLE 1

SUMMARY OF TEST CONDITIONS AND RESULTS FOR BROWNS FERRY NUCLEAR PLANT INTAKE STUDIES

Test Date	Test Condition *Q_c (cfs)	River Flow **Q_R (cfs)	Temperature From Monitor*** No. 7	Temperature From Monitor*** No. 14	Percentage of Flow in Intake from Overbank
May 18	4410	38,000	75.6	73.6	56
June 7	3420	35,000	77.8	77.0	63
July 19	3420	11,000	85.3	85.7	55
July 20	3550	21,000	84.0	85.4	53

*Intake flow.
**Average river flow at Tennessee River Mile 293.5 during test period.
***Temperature recorded at depth of 5 feet at 1000 hrs.

channel spread over the cooler overbank water which plunged underneath. Figure 33 shows the qualitative description of the water surface on July 20. Although some of the dyed water was observed downstream of the intake, it seems likely that the source of that water was from the overbank near the edge of the channel.

For this survey, the overbank dye concentration was approximately 10 ppb and the maximum cross-sectional average of the intake channel was 5.3 ppb, which implies that 53 percent of the intake flow came from the overbank.

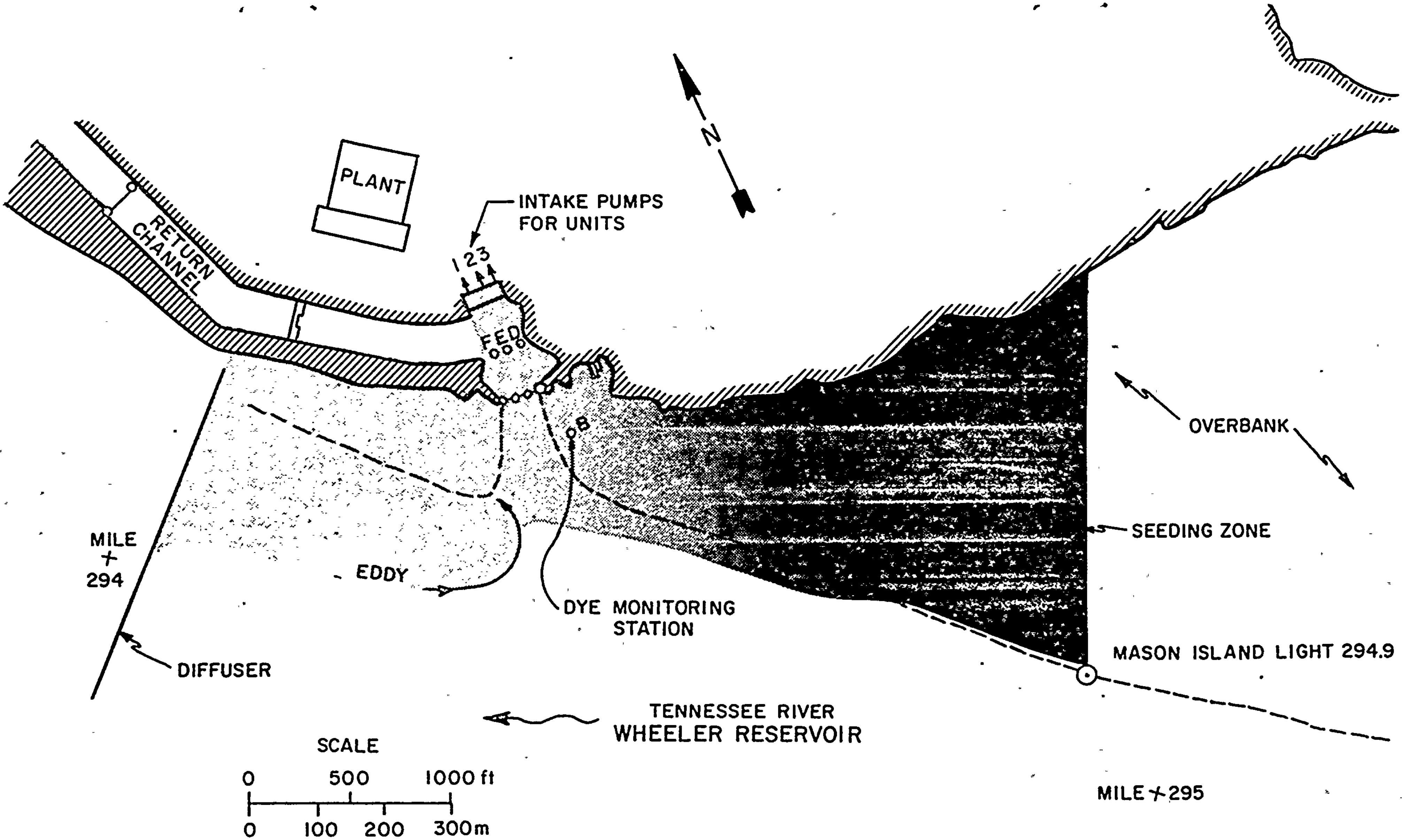


Figure 33: Seeding Zone, Monitoring Stations And Observed Behavior of Dye Cloud July 20, 1977

CONCLUSIONS

A relatively wide overbank area is situated immediately upstream of the intake of the BFNP. The quantity of flow along this overbank varies with reservoir stage and flow. Prior to spring filling of the reservoir, the shallow depths will prohibit much flow over the overbank, but after the reservoir has been raised to near the maximum level, usually in April, the depths of the overbank will permit more flow. A velocity survey conducted in May 1977 during a river flow of 38,000 ft^3/sec (1075 m^3/sec) revealed that about 3000 ft^3/sec (85 m^3/sec) was flowing over the overbank.

Most of the flow over the overbank is being drawn into the BFNP intake when the plant is operating in Open or Helper Modes of condenser cooling. During Open Mode, the design intake flow rate for all three units in operation is 4410 ft^3/sec (125 m^3/sec), and for Helper Mode, design flow rate is 3675 ft^3/sec (104 m^3/sec). These flow rates are proportionally decreased when units are not in service.

In the spring, when the reservoir is gradually warming, the large surface areas and shallow depths of the overbanks provide little thermal inertia; hence, the overbank areas are generally warmer than the main channel. Under these conditions, buoyancy of the warmer overbank water is sometimes sufficient to prevent water in the upper three feet (one meter) from being entrained into the plant intake. This was demonstrated with a velocity survey and a dye study. However, studies conducted during the summer which also included a trajectory analysis using drogues showed that this phenomenon was nominal.

Four field surveys using fluorescent dye were performed to determine the percentage of BFNP intake flow which originated from the overbank. These tests, which were conducted during near maximum surface elevations for a wide range of typical reservoir flow and plant operational conditions, revealed that between 53 and 63 percent of the BFNP intake flow comes from the overbank when the plant is operating three units in Open or Helper Modes.