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SEQUOYAH NUCLEAR PLANT UNDERWATER DAM DYE STUDY

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The authors are grateful to Chris Nubbe, Julie Young, and Bani Husin, students at the Tennessee Technological University Center for the Management, Utilization and Protection of Water Resources (Water Center) for their help in this study. The Water Center planned and directed the dye study, in cooperation with the Engineering Laboratory and Field Operations branches of TVA. A brief proposal to study the mixing caused by the dam was prepared and approved by the director of the Nonradiological Aquatic Monitoring Program. A study plan was prepared and distributed to the TVA participants. All TVA participants cooperated extremely well with the Water Center, and the ultimate success of the study was the result of the persistence and determination of the field crews to inject and locate the dye!

EXECUTIVE SUMMARY

A dye study was conducted to determine the effects of the underwater dam on flow and mixing patterns in the vicinity of the Sequoyah Nuclear Plant (SQN). The underwater dam was constructed to divert cool bottom water into the SQN condenser cooling water system submerged weir intake structure. The diffuser pipes for the discharge of the heated effluent from the SQN cooling water system are located downstream from the underwater dam. Three possible effects of the dam relative to the diffuser were considered: 1) The dam may enhance the diffuser mixing by increasing the turbulence of the water column; 2) The dam may induce mixing in the lower layers of the reservoir, whereas the diffuser mixing is dominant in the upper layers; and 3) The dam may retard flows and decrease mixing in the lower layers and thereby contribute to the dissolved oxygen (DO) depletion observed upstream of the dam. The dye study was conducted to determine the influence of the underwater dam on mixing and vertical water quality patterns in the vicinity of SQN.

Dye was injected continuously through a 16 foot long diffuser device placed perpendicular to the flow at a depth of 30 feet so that a ribbon of dye was released into the reservoir approximately 1000 feet upstream of the dam. The vertical spreading of this dye ribbon was measured with pumping samplers attached to fluorometers at several downstream locations. The downstream movement of the dye was tracked with current drogues which were released periodically at a depth of 30 feet. Two sampling boats were used; one anchored before sampling and the other sampled while drifting with the flow.

Sufficient data were obtained to show the vertical patterns of temperature, velocity, dye, and dissolved oxygen. A vertical temperature

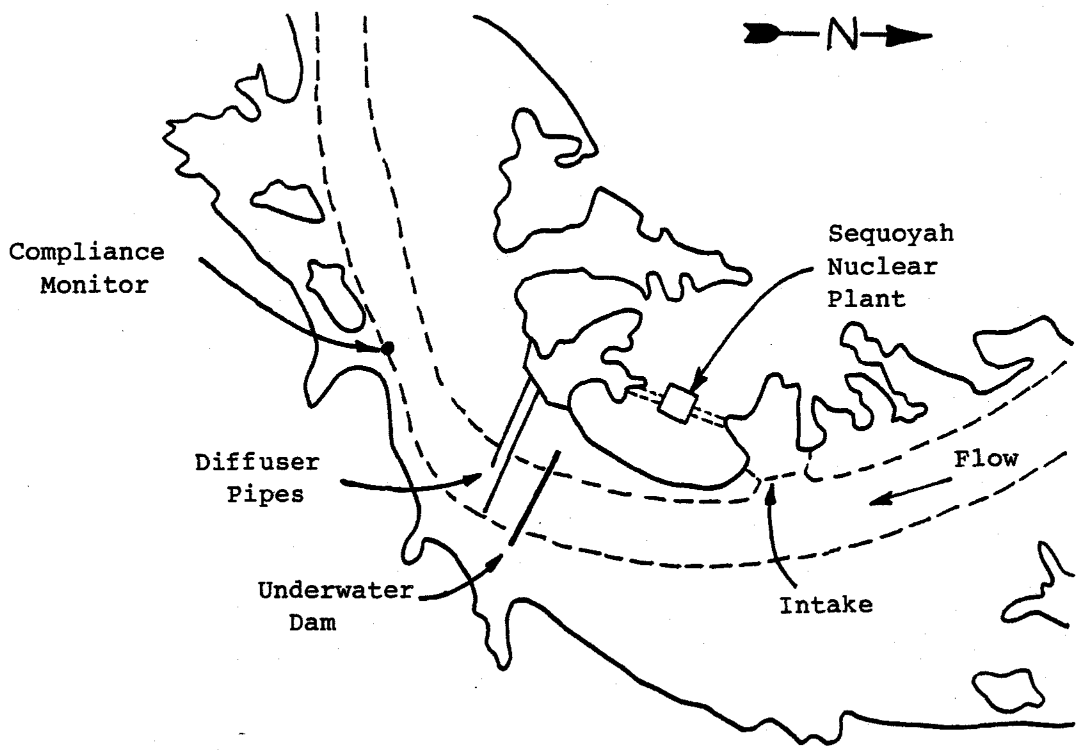
stratification of 1 degree C existed in the upper 6 meters. This was not completely mixed away after passing over the dam. Flows were approximately 30,000 cfs during the study with upstream velocities of about 0.5 ft/sec. The constriction of the conveyance area above the dam was evident with velocities between 1.2 and 1.4 ft/sec. The dye concentration measurements indicated that the dye mixed with the isothermal water between the injection device and the reservoir bottom upstream of the dam, but did not mix with the upper layers of the reservoir until after passing over the dam. Vertical mixing of the dye was almost completed at the downstream compliance location which is 2000 feet downstream of the dam. Surface layer DO concentrations varied from 6 to 8 mg/l during the day, while the lower layer DO concentrations decreased slightly with depth from about 5 mg/l below the surface layer to 4 mg/l near the bottom. There was some indication from the DO data that the surface layer was eroded and mixed with underlying layers as the water flowed over the dam.

Observations made during the test suggested that the 45 degree bend in the main channel may also have a significant effect on vertical circulation patterns in the vicinity of the SQN. A large spiraling of the flow occurs in the vicinity of SQN, with the bottom water moving towards the outside of the bend and the surface water moving towards the inside of the bend. An upwelling is created along the outside of the bend, especially near the bluff downstream of the dam and diffuser. The upwelling caused by the underwater dam complicates, the analysis of natural and plant induced temperature and mixing patterns in the vicinity of the SQN. This dye study contributes to an understanding of these flow and mixing patterns.

INTRODUCTION

Evidence of vertical mixing of the water column in the vicinity of the Sequoyah Nuclear Plant (SQN) underwater dam and diffuser has been observed during water quality surveys in Chickamauga Reservoir. These structures are part of the SQN cooling water intake and discharge system. Vertical mixing in the vicinity of SQN is the result of: 1) the underwater dam which was installed to divert cool bottom water into the SQN intake and prevent warm surface water from moving upstream towards the intake structure; 2) the diffuser which is used to discharge and mix heated condenser cooling water into the reservoir; and 3) natural turbulence and circulation processes caused by flows through this section of the reservoir which happens to be a major channel bend of approximately 90 degrees. A dye study was conducted to determine the magnitude of vertical mixing caused by flows passing over the underwater dam, which is located approximately 500 feet upstream of the diffuser.

The condenser cooling water intake structure is a skimmer wall located on the right side of the channel at Tennessee River Mile (TRM) 484.7 as shown in Figure 1. The opening height is approximately ten feet with the top of the opening at elevation 641 feet msl, which is 34 feet below minimum (winter) pool level of 675 ft. msl. and 42 feet below the maximum (summer) pool level of 683 ft. msl. The underwater dam is located approximately one mile downstream of the intake at TRM 483.7, and fills the main channel to elevation 654 ft. msl. The dam was constructed from quarry rock dumped from barges.



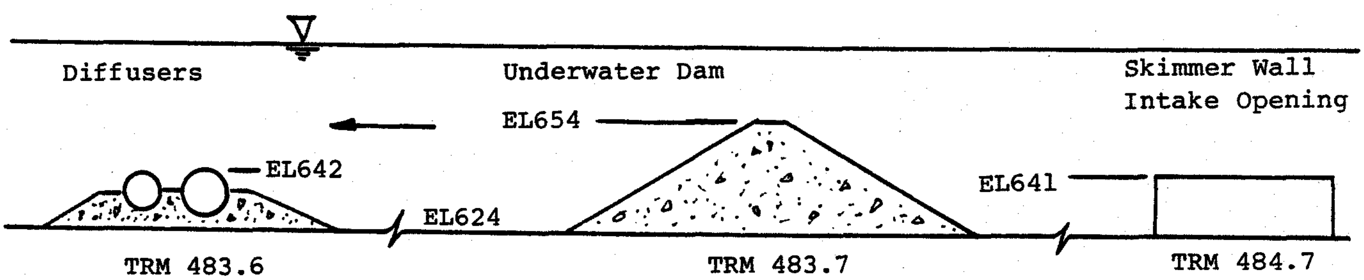


FIGURE 1. LOCATION OF SQN INTAKE, UNDERWATER DAM, AND DIFFUSERS (FROM MCINTOSH, JOHNSON, SPEAKS, 1983)

Surface velocities are increased by this constriction in the conveyance area so that warm surface water has more difficulty moving upstream towards the intake. The dam may also assist in diverting cool bottom water into the skimmer wall intake. The diffuser is buried in a riprap foundation, with the top of the diffuser pipes exposed at elevation 642 ft. msl. The SQN intake, underwater dam, and diffuser structures complicate the natural flow and mixing patterns in this portion of Chickamauga Reservoir.

The results of the dye study will help to understand the effects of the dam on vertical mixing. This understanding of mixing processes will be useful for several purposes including: 1) interpreting the near field temperature and DO patterns observed in the vicinity of the dam and diffuser to support an assessment of the impacts of water column mixing by the dam and diffuser on the aquatic biota of Chickamauga reservoir; 2) improving the routine thermal compliance monitoring requirements at SQN which involve modeling the vertical temperature profile at the downstream compliance station based on measured upstream temperatures; and 3) modeling dam mixing effects for a range of seasonal temperature and flow conditions with a two-dimensional water quality model (BETTER) being developed for Chickamauga reservoir by the Engineering Lab. The water quality model will then be used to integrate and interpret field data and make projections of water quality patterns for a range of reservoir flow and SQN operating conditions.

DYE INJECTION DEVICE

The dye injection device consisted of: 1) a water pump that brought reservoir water up into the dye boat from the depth of dye injection, 2) a rack of five peristaltic pumps that pumped concentrated dye solution (20%) from a 15 gallon tank, 3) a manifold device which mixed the dye with the reservoir water, and 4) a 16 foot long pipe diffuser which distributed the diluted dye solution into the reservoir. The general arrangement of the dye injection device is illustrated in Figure 2. This injection device design allowed a range of possible dye injection rates to be distributed uniformly in a ribbon, using ambient reservoir water from the injection depth to dilute the dye and was independent of any large volume tank or hoses on shore.

The Engineering lab built the apparatus using existing peristaltic pumps and manifold device. Five peristaltic pumps with maximum pumping rates of 0.2 l/min (3.2 gal/hr) were connected to a manifold. A 5/8 inch hose and pump with a pumping rate of 240 gal/hr (at 10' head) were connected to pump water from the injection depth into the manifold, where it was mixed with the dye, and return the mixture to the diffuser pipe.

The Water Center built the 16 foot long diffuser pipe from 3/4 inch steel pipe with 1/8 inch holes at 12 inch centers along the middle of the diffuser pipe, and 6 inch centers on the ends of the pipe to get a more uniform distribution of dye along the pipe. The

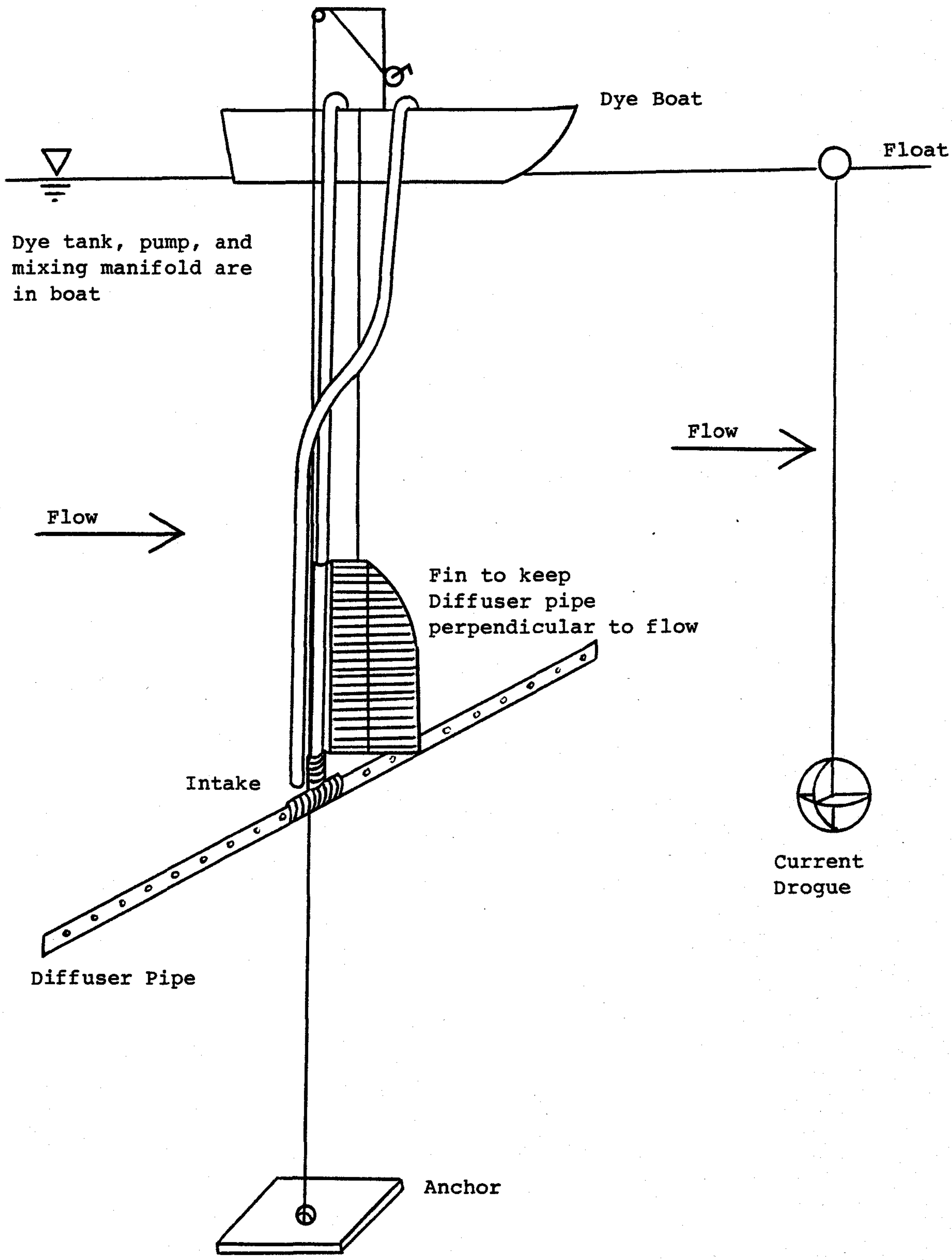


FIGURE 2. DYE INJECTION DEVICE AND CURRENT DROGUE

diffuser was lowered on a anchor line attached to a weight. A fin was attached to the vertical section of the diffuser to keep the diffuser perpendicular to the flow and release a constant "ribbon" of dye. The dye injection device operated well.

VELOCITY MEASUREMENTS

Two techniques were used to obtain velocity profiles during the dye study. Previous velocity measurements had been obtained using an electromagnetic field (EMF) probe in the vicinity of SQN during similar flow conditions in 1975 (Johnson and Waldrop, 1978) and are shown in Figure 3. An EMF probe was used to obtain velocity profiles at the dye injection site, midway to the dam, on top of the dam, and midway from the diffuser to the downstream compliance monitor.

Water current drogues, which are floats with a drag device attached at a specified depth, were constructed by the Water Center for tracking the movement of the dye ribbon. These were also used to obtain estimates of average flow velocities at various depths. These drogues were constructed from three 12 inch aluminum disks intersecting at right angles and welded together. A surface float and line kept the drogues at predetermined depths. An illustration of the device is shown in Figure 2.

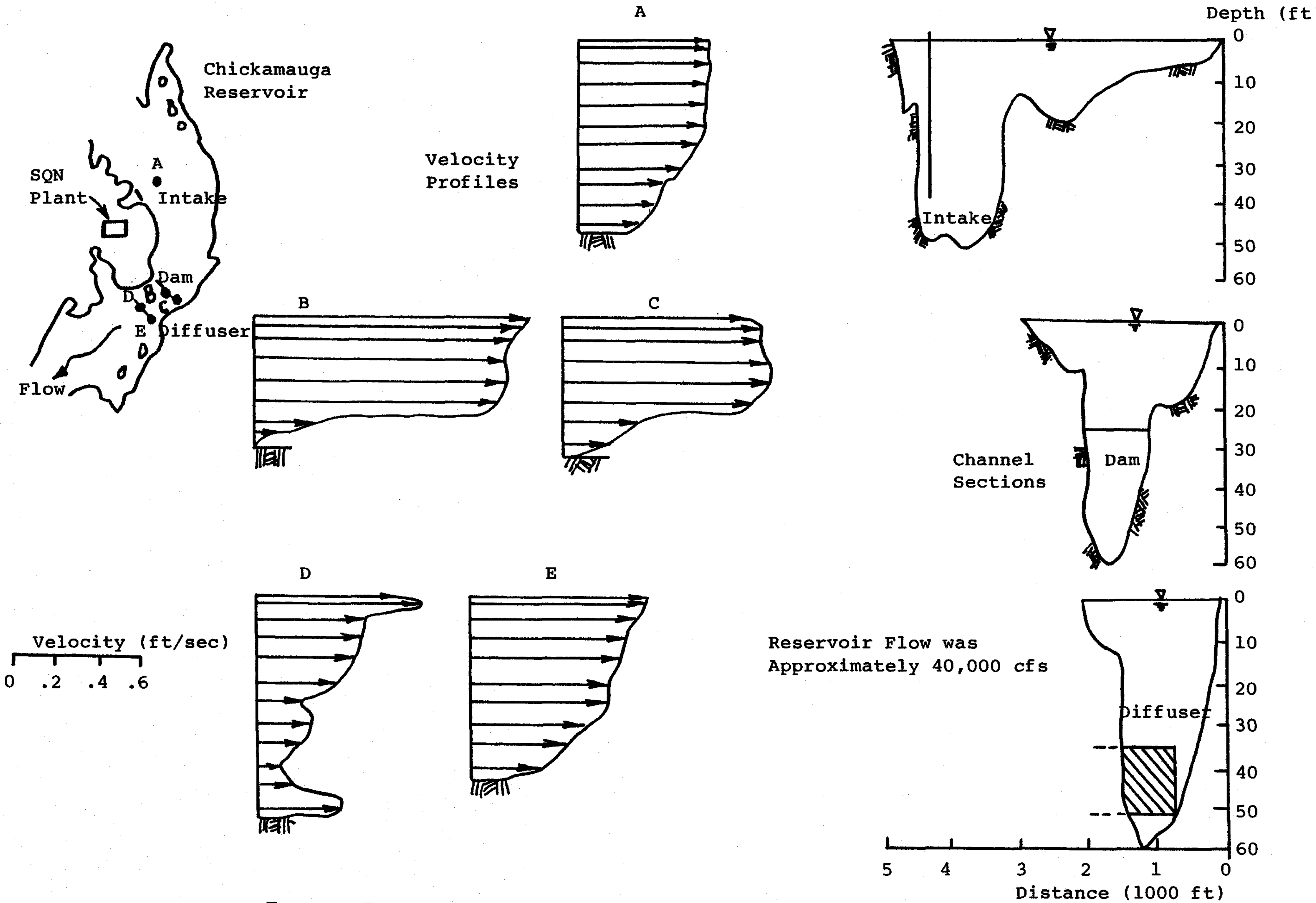


FIGURE 3. VELOCITY PROFILES IN THE VICINITY OF SQN, 1975
(FROM JOHNSON AND WALDROP, 1978)

DYE MEASUREMENTS

Fluorometers and pumps were connected to sampling hoses which were attached to Hydrolab sampling devices so that depth, temperature, and DO measurements could be made simultaneously with dye concentrations. The Engineering lab calibrated three Turner Fluorometers (2 TVA and 1 Water Center) so that dye concentrations could be read directly in the field and were within 5% of each other for the range of standards used (20 ppb and 85 ppb). This sampling technique was limited by the unknown location of the dye. Only one point in the water column could be sampled at a time, and there was a minute delay while the water moved through the hose to the fluorometer. This made it difficult to locate the dye ribbon and then stay positioned long enough in the dye ribbon to obtain a vertical dye profile. We decided to try two methods; the Water Center (WC) boat anchored to sample vertically after locating the dye at a particular location, while the Field Operations (FO) boat drifted and moved laterally to locate the peak dye concentration and then sample vertically.

FIELD STUDY LOG

The Water Center, Field Operations, and Engineering Lab crews assembled on Monday afternoon June 15, 1987 at Bass Bay marina, approximately a mile downstream of the SQN diffuser. The field Operations crew assisted the other boats in locating the underwater dam, diffuser, and dye injection station. The Water Center and Engineering lab personnel anchored the dye injection boat near mid channel at a depth of approximately 60 feet and hooked up the dye injection apparatus for a test. The dye injection diffuser pipe was lowered to a depth 40 feet and dye was injected using two of the five available peristaltic pumps at a nominal pumping rate of 0.4 l/min (6.4 gal/hr) for approximately one half hour. The other Water Center boat then released drogues at a depth of 40 feet and attempted to follow the dye cloud downstream. Sampling with a fluorometer attached to a pump and hose at a depth of 40 feet in line with the drogues was unsuccessful farther than 150 feet downstream of the injection point. Sampling at shallower depths also failed to locate the missing dye ribbon. The sampling hoses were only 50 feet long, so deeper sampling was not possible. The dye concentration near the injection boat was several hundred ppm, so that this initial dye injection rate was more than sufficient to produce a measurable dye ribbon. A decision was made to use just one peristaltic pump with an injection rate of 0.2 l/min(3.2 gal/hr) during the actual test the next day. This would conserve dye and allow a longer injection period, if necessary.

Flows were relatively high during the test and the drogues, which were released at 10 minute intervals, moved downstream in a straight line toward the dam where they were caught on the riprap face of the dam. It was apparent that the drogues would be helpful in locating the dye ribbon the next day. The test injection provided some helpful orientation and experience with the study plan, even though we had been unable to find the dye in the vicinity of the dam.

On Tuesday June 16, 1987 the three crews launched four boats and equipment. The dye boat was anchored at the dye injection station and the sampling boats were ready by 9:30 AM (Central Time). Dam releases of 30,000 cfs were scheduled for 9:00 AM, and we expected significant flows near SQN by about 10:00 AM. While waiting, a downstream barge tow interrupted us. We had to pull up the dye injector diffuser anchor and move off to the side. Significant flows were not observed until nearly 11:00 AM. This remains hard to understand since the release schedule for the study date shows that Chickamauga flows were high all morning and Watts Bar releases began around 9:00 AM. These releases are shown in Table 1.

The velocity probe was deployed from one of the survey boats to measure vertical velocity profiles. A 500-foot long floating measurement line was extended downstream from the injector boat and drogues were released on either side of the dye boat at depths of 10, 20, 30, and 40 feet. The time of travel to the end of the measurement line were recorded for each drogue to obtain a crude vertical velocity profile. The surface drogues moved faster than the deeper drogues, especially after the 30-foot and 40-foot drogues were caught behind a trotline! They were released downstream of the trotline and reasonable travel time measurements were obtained.

Table 1. Chickamauga Reservoir Elevation and Flows During SQN Underwater Dam Dye Study.

	Monday, June 15			Tuesday, June 16		
Ending Hour	Chickamauga Elevation	Chickamauga Releases	Watts Bar Releases	Chickamauga Elevation	Chickamauga Releases	Watts Bar Releases
	ft mg/l	cfs	cfs	cfs	ft. mg/l	cfs
1	682.69	0	0	682.66	8900	0
2	682.65	0	0	682.42	17400	0
3	682.34	9300	0	682.19	17400	0
4	682.21	9300	0	682.27	17400	0
5	682.20	17900	0	682.21	25800	0
6	682.21	26800	0	682.21	26200	0
7	682.29	26700	0	682.27	26300	0
8	682.24	26900	1200	682.25	26700	0
9	682.22	27300	9200	682.14	27000	14700
10	682.09	27100	25800	681.95	29700	41800
11	681.97	26500	33300	681.86	30300	42200
12	681.95	26500	41700	681.82	30700	42200
13	682.06	27300	41400	682.12	30500	42700
14	682.16	27300	42000	682.28	30500	42700
15	682.24	27100	43000	682.23	30500	42600
16	282.30	27000	43000	682.29	26900	42600
17	682.32	26700	42200	682.36	26600	42600
18	682.35	26600	42200	682.38	26600	42600
19	682.38	26700	42200	682.40	26800	40600
20	682.42	26700	37100	682.47	26800	28200
21	682.45	26800	25200	682.52	27000	16300
22	682.50	26500	12400	682.56	27000	5500
23	682.60	18000	0	682.57	26600	0
24	682.70	9000	0	682.50	26600	0

The 40-foot drogue was caught on the underwater dam, providing a target for tracking the dye ribbon. The drogues indicated that water at all depths moved rapidly towards the underwater dam without being greatly retarded. The drogues were collected and the two dye measurement boats returned upstream to the dye injection boat.

Dye was injected at a depth of 12m (40 feet) beginning at approximately 12:00 Central Time and the dye measurement boats started searching for the dye behind the drogues that were released with the dye. The Field Operations (FO) boat drifted with the current and moved back and forth laterally to find the dye. The Water Center (WC) boat anchored in the dye ribbon and obtained measurements just downstream of the injector. Soon it was discovered that the dye was sinking below the 12m (40 ft) injection depth, and the FO hose was only capable of sampling to 13m (43 ft). The WC hose was able to sample to 15m (50 ft), and this was where they were finding the peak dye concentrations of nearly 500 ppb. A decision was made to move the dye injection depth to 9m (30 ft) so that the measurement boats could more easily sample the vertical dye profiles. Just as things looked promising a very threatening thunderstorm developed, and the field study was interrupted at about 1:30 PM. All personnel safely sought shelter on shore.

After bailing the boats and cleaning up the mess, the dye injector was tested and found to be still operational. It was decided to try once more to locate and measure the dye ribbon. The dye injection at a depth of 9m began again at about 3:00 PM Central Time. Both boats were able to locate and measure dye profiles; although the maximum dye concentrations were at 12m, making it difficult for the FO boat to obtain measurements below the dye ribbon. Once again the drogues were released to help locate the dye ribbon. Dye measurements were made for about one and a half hours and were adequate to document the basic features of the vertical upwelling and mixing caused by the dam. The last dye passed the dam at 4:30 PM and the crews headed back to Bass Bay to unload the boats and pack the trucks.

FIELD DATA

There were four important variables sampled during the dye study; dissolved oxygen (DO), temperature, velocity, and dye concentration. Sufficient data were obtained for each of these to show the vertical patterns in the vicinity of the underwater dam. Dissolved oxygen concentrations are of ultimate interest in the assessment of aquatic effects due to vertical mixing by the dam and diffuser. Temperature stratification causes the bottom layers of the reservoir to be isolated from the surface water. Stratification of the water column inhibits mixing between adjacent layers and allows DO in the lower layers to decline. Changes in vertical temperature profiles between upstream and downstream of the dam may indicate vertical mixing. Velocity patterns indicate the downstream movement of water and any stagnation of water behind the dam. They also show circulation effects from the 45 degree bend in the reservoir main channel that occurs in the vicinity of the dam and diffuser. Dye concentrations show the extent of vertical mixing as the water approaches and moves over the dam and past the diffuser towards the compliance monitor station.

The temperature and DO measurements obtained during the dye study are shown in Figure 4. Surface temperatures were only 1 degree C warmer than the bottom temperature of 24.6 degree C. This slight stratification was confined to the upper twenty feet. The dye test was performed during a period when vertical mixing would be relatively uninhibited by stratification, providing a good indication of the maximum mixing effects from the dam. If stratification were stronger, mixing from the underwater dam might be less effective in redistributing the vertical profile of temperature, DO, or other water quality variables. However, mixing effects might be more apparent if stronger water quality gradients were present upstream of the dam.

The temperature measurements were nearly identical throughout the day both upstream and downstream of the dam and diffuser. Two Hydrolabs were used, so the direct temperature comparisons are probably only good to within 0.1 degree C. The slightly warmer surface layer of approximately 6m (20 ft) depth passed over the dam and diffuser without being completely mixed with the lower layers. Mixing from the dam was not strong enough to produce completely mixed conditions downstream, even at the peaking release flow of 30,000 cfs and with only a 1 degree C stratification.

The measured vertical DO patterns were similar, although the WC Hydrolab DO values declined slightly throughout the day; so the

Depth (M)	WC:9 AM T	WC:9 AM DO	FO:12N T	FO:12N DO	FO:4 PM T	WC:4 PM T	WC:4 PM DO	WC:3 PM T	WC:3 PM DO	FO:3 PM T
1	25.8	8.3				25.6	6.7	25.6	6.9	
2	25.7	7.9	25.5	6.8	25.6	25.4	6.2	25.5	4.6	25.7
3	25.4	7.1				24.9	4.9	24.7	4.4	
4	25.3	6.6	25.2	6.2	25.3	24.8	4.6	24.7	4.3	25.5
5	25.1	6.0				24.7	4.5	24.6	4.3	
6	25.0	5.9	24.9	5.2	24.7	24.6	4.3	24.6	4.4	24.9
7	24.9	5.3				24.6	4.3	24.6	4.5	
8	24.6	4.9	24.7	4.8	24.6	24.6	4.2	24.6	4.4	24.8
9	24.6	4.9				24.6	4.2	24.6	4.4	
10	24.6	4.8	24.6	4.6	24.6	24.6	4.2	24.6	4.4	24.7
11	24.6	4.7				24.6	4.2	24.6	4.4	24.7
12			24.6	4.5	24.6	24.6	4.1	24.6	4.4	24.7
13						24.6	4.1	24.6	4.5	
14			24.6	4.4		24.6	4.1	24.6	4.4	
15						24.6	4.1	24.6	4.3	
16										
17										
18										

FIGURE 4. TEMPERATURE AND DO MEASUREMENTS DURING DYE STUDY

apparent spatial patterns may not be reliable. The vertical DO patterns at each measurement location provided another indication of stratification and mixing. Saturation DO concentrations were approximately 8.5 mg/l, while actual DO values were approximately 4.5 mg/l at the bottom. Surface concentrations were between 6 and 8 mg/l. There was an indication of a slight vertical gradient of DO, decreasing in the isothermal portion of the reservoir towards the bottom. It is common to observe a decreasing DO gradient without a corresponding temperature gradient in the lower layers of reservoirs like Chickamauga. Comparing the DO profiles obtained above and below the dam, it appears that the surface layer of relatively high DO (6 mg/l) was 2m deep upstream of the dam, but was reduced to only 1m deep downstream of the dam. This may have been the situation observed during previous water quality surveys, when the 1.5m (5 ft) depth DO measurements were slightly greater than 5 mg/l upstream, but slightly less than 5 mg/l downstream.

The velocity measurements obtained with the EMF probe and with the drifting drogues are shown in Figure 5. Velocities and the direction of the flow in degrees from North are given. At the dye injection station the surface velocity was low (0.16 ft/sec), and the maximum velocity was 0.68 ft/sec at 6m depth. Velocities gradually decreased to 0.35 ft/sec at 15m, slightly off the bottom. There did appear to be some retardation of the lower layers which may have been caused by the dam or may just be a natural channel velocity profile. At the station mid-way to the dam, velocities were slightly

Depth (M)	V (ft/sec)	Direction	Drogue Measurements		V (ft/sec)	Direction	V (ft/sec)	Direction	V (ft/sec)	Direction	V (ft/sec)	Direction
			WC	FO		∇						
1	.16				.53	221	1.3	217	1.00	264	.82	275
2	.37				.57	220	1.3	217	.99	266	.82	270
3	.61	209	.33	.46	.67	216	1.4	206	.99	261	.82	265
4												
5	.57	212			.77	213	1.3	206	1.03	256	.76	265
6	.68	211	.64	lost	.80	213	1.2	207	.99	246	.73	255
7												
8	.52	207			.66	219	1.2	207	.97	250	.68	241
9	.54	239	.56	.59	.62	216			.99	249	.68	241
10												
11	.49	205			.56	219			.89	254	.58	239
12	.38	220	.43	.46	.51	213			.84	259	.50	230
13												
14	.37	210			.51	219			.77	258	.50	239
15	.34	209			.46	199			.71	257	.61	239
16	.19	226			.27	232			.54	250	.57	247
17											.52	252
18												

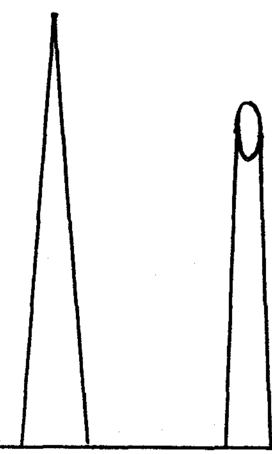


FIGURE 5. VELOCITY MEASUREMENTS DURING DYE STUDY

greater throughout the water column with an almost identical vertical pattern. The maximum velocity of 0.80 ft/sec was at 6m depth, and velocities decreased to about half the maximum near the bottom and at the surface. This may have been the result of a smaller cross section, or perhaps the flows were still increasing in the reservoir during this measurement period. Velocities over the dam were almost twice as great since the area for flow was reduced by the underwater dam. Maximum velocity was 1.4 ft/sec at 3m depth, but the vertical profile was almost uniform, with 1.3 ft/sec at the surface and 1.2 ft/sec near the top of the dam. No velocity profile was obtained between the dam and the diffuser. Velocities downstream of the diffuser were nearly uniform at 1.0 ft/sec from the surface to a depth of 9m and decreased to about 0.5 ft/sec at the bottom. The downstream velocity profile at the compliance monitor station was highest (0.8 ft/sec) in the top 4m and decreased slightly to 0.5 ft/sec at the bottom. The vertical velocity profiles were more pronounced upstream of the dam, although movement in the lower layers upstream of the dam was still approximately 0.5 ft/sec. These data suggest that stagnation of flows by the dam was a relatively minor influence in the vicinity of SQN.

The drogue measurements were made in the 500 feet between the injection site and second velocity profile. The two dye measurement boats released drogues at depths of 10, 20, 30, and 40 feet. These provided replicate measurements of the average velocity over the 500 foot longitudinal section. These average velocities were expected to be somewhat less than the actual velocity, since the drogues lag behind the flow slightly. The drogue velocity estimates were quite similar to the EMF velocity measurements, being apparently within 10% of the actual velocities. The drogues were invaluable for helping the boat crews locate the ribbon of dye downstream from the injection boat.

An interesting result from these velocity measurements was an indication that the 45 degree bend in the main channel had some effect on the vertical circulation and presumably on the mixing in the vicinity of the dam and diffuser. The channel bend begins upstream near the SQN intake and is at an angle of 210 degrees (from North) at the dye injection point, and ends at an angle of 240 degrees at the compliance monitor. The surface dye clouds, released during cleaning up following the rain and at the end of the dye injection, moved towards the inside of the channel bend at an angle of perhaps 20 degrees compared with the drogues released to track the injected dye at a depth of 30 feet. The velocity profiles revealed a similar pattern, with surface velocities heading at larger angles than the lower layers. The difference in flow direction was perhaps 10 or 15 degrees at most of the stations, but was a full 30 degrees at the downstream station where a bluff on the left bank strongly deflects the flow. These indications are consistent with the general behavior of flows through bends where the surface layers move toward the inside of the bend and the bottom layers move toward the outside. An upwelling is created along the outside of the bend, with a downwelling along the inside. Thus, a large spiraling flow pattern develops in the vicinity of SQN, further complicating the analysis of natural and plant induced mixing.

The dye measurements were intended to provide a clear and direct indication of the vertical mixing caused by the dam compared to that occurring naturally upstream of the dam. The actual dye concentration data are shown in Figure 6. The dye patterns generally demonstrated the vertical mixing caused by natural river turbulence and upwelling as the flow moved up and over the dam. The dye ribbon apparently sank 3m below the diffuser injection depth due to the slightly heavier dye mixture, even though we pumped water up from the intended injection depth to mix with dye in the manifold device. The relative pumping rates of the peristaltic and hose pumps provided a manifold dilution of approximately 75, and with an initial jet dilution of perhaps 100 at the dye diffuser, would produce a dye mixture with a concentration of 32,000 ppb and a specific gravity difference equivalent to 0.1 degree C. This was perhaps enough to allow the dye ribbon to sink and mix with the isothermal water in the lower layers of the reservoir. This apparently produced an additional near field dilution of 50, corresponding to the maximum dye measurements of 600 ppb. Since we did not obtain dye measurements from the lowest 3m of the water column, some dye may have mixed all the way to the bottom at 18m.

Maximum dye concentrations upstream of the dam were found below 9m depth; below the top of the dam. The data suggest that the dye

DEPTH (M)	WC	FO	WC	FO	FO	FO	WC	FO	FO	WC	FO	FO	FO	FO
1							0			0				
2							0				2		3	3
3							0			1				
4							0				3	4	4	4
5							0			4				
6						4	0	20			15	5	5	7
7			0			15	0		5	15				
8			1			80	20		4		17	6	5	6
9	1		0	15	40	60	20		6	10		7		
10	1		5	40	150	100	50		5	6	20	7	7	7
11	50	20	100	80	100	100	1		15	15		12	6	
12	300	500	400	80	80	100	10		15	15	20	10	7	5
13	20	10	200	150	50	100	1			20	15	18	8	5
14	40		200				0			30				
15	80		40				0							
16	40									15				
17														
18														

FIGURE 6. DYE CONCENTRATION MEASUREMENTS (PPB)

ribbon moved vertically upward as the flow approached the dam, and that some clean water did remain below the dye ribbon. The velocity data indicated that all layers were moving towards the dam and so these deeper layers must accelerate and be lifted up and over the dam. There was apparently significant mixing during this upwelling, and the dye profiles downstream of the dam showed a much more uniform vertical distribution of dye. The maximum dye concentrations were still observed below 9m depth between the dam and the diffuser. Vertical mixing continued to redistribute dye throughout the water column as the water flowed downstream, except in the slightly warmer surface layer where dye concentrations remained low. It should be noted that the diffuser structure itself represents a flow obstruction, and that a secondary upwelling must occur as the bottom water flows up and over the diffuser structure. These observations suggest that upwelling caused by the dam and diffuser structure increased the vertical mixing as compared to the normal channel mixing processes. However, these data were not sufficiently detailed to assign a magnitude to either the channel mixing or the dam and diffuser mixing.

The maximum concentrations decreased downstream from the injection site due to both vertical mixing and lateral spreading of the dye ribbon. It is not possible to separate these two effects, although the 16 foot diffuser pipe was intended to reduce the observed lateral spreading. Dye concentrations were on the order of 1000 ppb at the injection site, and were measured at 500 ppb 100 feet downstream in a 1 to 2m deep layer, with concentrations of greater than 50 ppb spread into a layer 4 to 6m deep. Peak concentrations were approximately 100 ppb just upstream of the dam, but were only 25 ppb downstream of the dam and less than 10 ppb downstream of the diffuser. Much of this decrease must have been due to lateral spreading, as the water column average decreased moving downstream. Dye was generally absent from the upper 9m depth (above the top of the dam) until immediately upstream of the dam. Vertical mixing in the vicinity of the dam resulted in some dye being distributed throughout the upper 9m depth as well as in the lower 9m depth.

CONCLUSIONS AND RECOMMENDATIONS

All of the measurements were generally consistent with the hypothesis that the dam produced significant upwelling with increased vertical mixing, especially in the layers between the top of the dam and the water surface. However, this vertical mixing was not sufficient to eliminate the relatively weak thermal stratification of 1 degree C that existed in the upper 6m depth. Both the dam and diffuser structures provide significant perturbations in the flow patterns of the lower layers of the reservoir, and the natural bend in the main channel may cause a significant circulation pattern. The dye measurements indicated that natural vertical mixing upstream of the dam was significant, distributing dye over a depth of 6m within 1000 feet of the injection point. This conceptual description of mixing in the vicinity of the SQN dam and diffuser is illustrated in Figure 7.

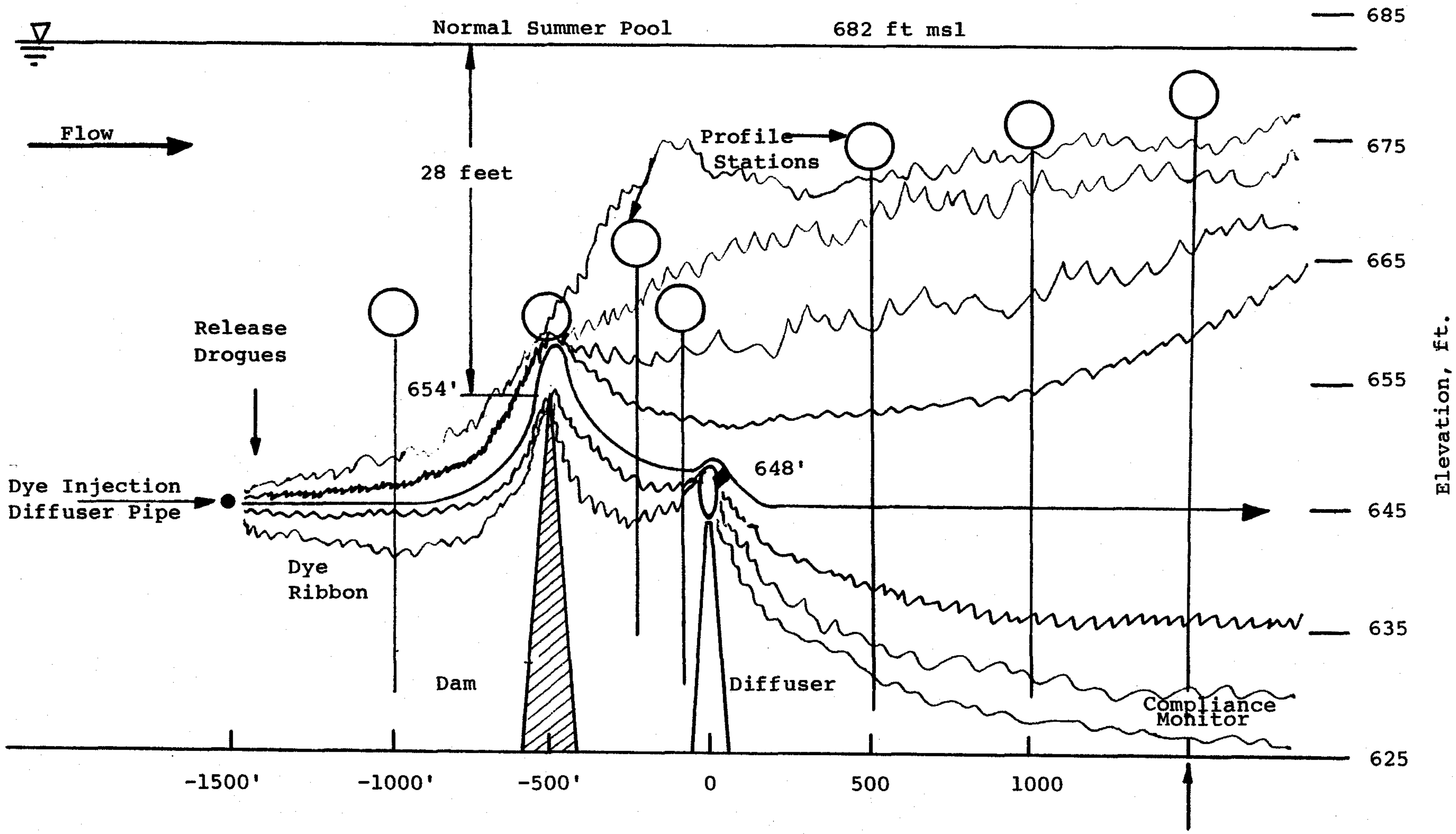


FIGURE 7. VERTICAL MIXING IN THE VICINITY OF SQN DAM AND DIFFUSER

If another dye study is attempted in the vicinity of the underwater dam, it might be advantageous to release dye from two different sites. One upstream of the dam would be tracked for just 500 feet to show natural channel mixing, while another just 250 feet upstream of the dam would be tracked 250 downstream of the dam to better characterize the localized dam mixing. A third short 500 foot section could be used to show the effects of the diffuser, once SQN is operating again. These separate dye traces would allow the relative magnitudes of mixing from the natural channel and the dam upwelling to be quantified.

Additional investigations may provide more information on the relative magnitude of these mixing influences, mixing effects may never be known with certainty. The operation of the diffusers with the discharge of heated effluent will add yet another source of mixing. The mixing induced by upwelling at the dam was not extraordinary as compared with normal vertical mixing observed upstream and downstream of the dam. The vertical profiles of temperature and DO were not greatly affected by passing over the dam; even at relatively high flow conditions, which would presumably allow the greatest mixing by the dam.

The detailed hourly temperature monitoring records from the intake and compliance stations should be examined during periods when; 1) significant temperature stratification existed upstream; 2) significant reservoir flows occurred and; 3) SQN diffusers were discharging at minimum flow and without heat. During these periods, there may be opportunity to observe effects of the upwelling and mixing caused by the dam. A similar analysis of the Hydrolab profiles obtained in the vicinity of the SQN dam during 1987 should be made to identify any observed upwelling and mixing effects.

The effects of the upwelling and mixing caused by the dam should be included in the two models which are being used to describe and evaluate the impacts of SQN operations on Chickamauga reservoir temperature and water quality patterns. The computed compliance model (McIntosh, et al., 1978) uses the measured intake station temperature profile as the upstream conditions at the diffuser. Perhaps this profile should be modified slightly to account for the upwelling and mixing caused by the dam and diffuser structures. The reservoir water quality model, being developed to represent natural conditions in Chickamauga and the effects from operation of SQN, may require special treatment of mixing in the vicinity of SQN. Results from the SQN dam dye study can improve these ongoing modeling efforts.

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