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NMFS - SEFC - 268

Effects of Aligning Waterfront Housing Development Canals with Prevailing Summer Winds and Installing a Circulating Canal and Culverts

SEPTEMBER 1990

GALVESTON LABORATORY
SOUTHEAST FISHERIES CENTER
NATIONAL MARINE FISHERIES SERVICE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
DEPARTMENT OF COMMERCE

NOAA TECHNICAL MEMORANDUM
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EFFECTS OF ALIGNING WATERFRONT HOUSING DEVELOPMENT CANALS WITH PREVAILING SUMMER WINDS AND INSTALLING A CIRCULATING CANAL AND CULVERTS

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ABSTRACT

Waterfront housing developments are becoming more and more prevalent along the Gulf of Mexico (Gulf) coast. With increased development, estuarine biota are adversely affected by loss of habitat and reduced water quality. In 1973, the National Marine Fisheries Service (NMFS) reviewed and recommended changes to the development plan of a waterfront subdivision called Omega Bay near Galveston, Texas. NMFS recommended that canal excavation be designed to maintain adequate oxygen levels by eliminating dead-end canal construction and aligning canals north-south in a direction to receive maximum turbulent mixing from prevailing summer winds and that canal depths not exceed those of the bordering Highland Bayou. This study, conducted in 1977 following the completion of the canal system, indicated that alignment of canals parallel to the prevailing summer winds, elimination of dead-end canals, and the intersection of an entrance canal with other canals enhanced circulation and provided adequate water quality essential for estuarine-dependent fauna.

KEY WORDS:

Waterfront Housing Development
Circulation Canals
Galveston Bay, Texas
Estuarine
Oxygen

INTRODUCTION

In 1973, the National Marine Fisheries Service (NMFS) reviewed an application for a Department of the Army/Corps of Engineer's permit submitted by a waterfront housing developer to construct a residential subdivision called Omega Bay near Galveston, Texas. The construction would include dredging, filling, and bulkheading an area on the east shoreline of Highland Bayou in La Marque, Texas (Figure 1). The planned subdivision, with a network of 12 dead-end canals 3.04 m (10 ft) deep, was to be located on approximately 49 hectares (120 acres) of land, one-quarter of which was tidal salt marsh.

The initial studies of canals in West Galveston Bay (Moore and Trent, 1971; Trent et al. 1972, 1976; Gilmore and Trent, 1974; Lindall and Trent, 1975) suggested that oxygen concentrations in bottom waters of dead-end canals are often insufficient to maintain marine life. Based on these studies, NMFS recommended that the Omega Bay canals be designed to maintain oxygen levels equal to or higher than those established by State and Federal regulations by eliminating dead-end canal construction to provide adequate water exchange with Highland Bayou. NMFS further suggested that canals be aligned north-south to receive maximum aeration from prevailing summer winds and that canal depths not exceed those of Highland Bayou.

Some of the recommendations were adopted by the developer in a modified proposal (Figure 1) that was subsequently approved by NMFS. The approved proposal included 10 rather than 12 canals. Six canals would be aligned north-south parallel to the prevailing summer winds. Of the four canals not so aligned, two would be oriented northeast-southwest and a third, the entrance canal, would cut through 8 of the canals and terminate in Highland Bayou. The fourth, a culverted circulation canal, would connect to the end of each canal (entrance canal excepted) and terminate in Highland Bayou. A plan view and a typical cross-section view of the modified proposal is shown in Figure 2. The entrance and circulation canals would thus provide potential circulation to the entire canal system. In addition, the circulation canal would eliminate 50% of the dead end construction. The width of the entrance canal would be 30.3

m (100 ft), the circulation canal 9.1 m (30 ft), and all others, 27.4 m (90 ft) wide. The proposed canal depths would be approximately 1.8 m (6 ft) below mean low water (mlw).

On the basis of past studies, NMFS believed that implementation of the modified plans would increase the probability that adequate water quality would be maintained in the canals of the developed area. To confirm this, a study was conducted in 1977 following completion of the canal system. The results and recommendations presented in this report are significant because they represent a baseline for current and future evaluations of other waterfront housing projects.

Study Area and Conditions Following Construction

The entrance canal extended several hundred feet into Highland Bayou at canal depths (1.8 m) before sloping up to the shallower depth of the bayou. The end of the circulation canal was also connected to a shallow area 0.4 to 0.6 m (1.5 to 2 ft) of Highland Bayou called Omega Lake. The 8 bridge culverts in the circulation canal varied in diameter from 0.9 m (3 ft) at culvert A to 1.2 m (4 ft) at culvert H (Figure 1). During August and September, however, their effective cross-sectional areas were reduced by siltation. Culverts D and E were completely clogged and the rest were occluded approximately 30 to 50 percent. The obstructions were cleared during the first two weeks of October 1977.

The maximum and average tidal range observed during monitoring trips, were 8.9 to 4.6 cm (3.5 and 1.8 in), respectively. These values were based on 14 weekly measurements from July 5 to September 26.

The Texas Highway Department's drainage easements from Interstate Highway 45 discharge into the circulation canal, the canal system, and Omega Lake.

METHODS AND VARIABLES

Monitoring of canal and Highland Bayou water commenced on May 19, 1977, and ended September 26, 1977. Phase A consisted of seven stations in the canals and one control in Highland Bayou (Figure 3). These were monitored weekly for seven weeks. During Phase B (Figure 4) two additional stations were added and several Phase A stations were repositioned (Figure 4). The Phase B station plan was monitored once weekly for 13 weeks. Station depths based on 13 consecutive weekly measurements varied from 2.3 m to 2.6 m (7.5 to 8.5 ft). The exception was the Phase A control station (8), which was about 1.4 m (4.5 ft) deep and comparable to the depth of water at the Highland Bayou entrance end of the entrance canal. During Phase B, the control station (10) was about 2.4 m (8 ft) deep to provide better comparisons with other stations.

Water samples were collected in B.O.D. bottles approximately 13 cm (5 inches) below the surface, at mid-depth, and approximately 15 to 20 cm (6 to 8 inches) above bottom. Collections were made weekly between 0930 and 1530 hrs. Oysters were used for biological monitoring because they were attainable, sessile, and are considered an appropriate test animal for water quality assessment.

Each station was monitored for:

1. Dissolved oxygen (Strickland and Parsons, 1972).

2. Indication of biological stress to caged oysters near-bottom waters (Phase B only).

3. Salinity (Strickland and Parsons, 1972).

4. Air and water temperature (mercury thermometer).

5. pH (portable pH meter).

6. Current flow (with an ice meter). In addition, current measurements were made at each culvert using the ice meter and Rhodamine WT dye.

7. Wind direction and speed (hand held wind gauge).

Site water levels were measured from a gauge erected at station 9, and precipitation data for Galveston, Texas, were obtained from the National Weather Service.

RESULTS

Dissolved Oxygen

A comparison of the Phase A canal and control station data shows that 78% of the surface and 57% of the bottom oxygen concentrations of the canal stations exceeded corresponding control station oxygen concentrations (Table 1). A similar comparison of Phase B data shows that 94% of surface, 73% of mid-depth, and 20% of bottom oxygen concentrations exceed corresponding control station oxygen concentrations (Table 2).

From May 18 through July 11, 68% of the canal station bottom water samples had greater dissolved oxygen levels than the corresponding control samples. From July 18 through September 26, however, only 11% of the canal station bottom water samples contained higher oxygen levels than the corresponding control samples (Tables 1 and 2).

The average dissolved oxygen concentration during the first monitoring period (Phase A) was more than 2 ppm higher than during the second (Table 3). During Phase A, station 2, an open-end station, had the highest oxygen concentration (5.37 ppm). The average dissolved oxygen at the remaining stations was within 1 standard deviation of the mean. Interestingly, the mean and control station values were the same.

During the Phase B, the highest dissolved bottom oxygen was recorded at the control station. Stations 8, 9, and 1 located in the entrance canal and station 7 (a dead-end station) had higher dissolved oxygen concentrations than stations 2, 3 and 4 located near the circulation canal.

On September 26, 1977 a surface phytoplankton bloom was observed at station 1. Dissolved oxygen concentration of surface water measured during the bloom was 13.2 ppm, the highest level determined during the study.

Bioassay of Bottom Waters

Evaluation of water quality (Phase B only) was based on the mortality of caged oysters (10/cage) placed several inches above the bottom of stations 1, 3, 4, 6, 8 and 10. The percent mortality occurring between monitoring trips is shown in Table 4. During each observation period dead oysters were replaced with live ones. With a few exceptions, percent mortality within the canal system was relatively low between July 5 and July 25. Percent mortality increased to a high level on subsequent sampling dates, and remained elevated for the duration of the study. An exception occurred between August 29 and September 6 when high tides apparently exchanged the oxygen-depleted water with oxygenated water which reduced mortality. No oyster mortalities were recorded at the control site. Based on mortality averages, the highest mortality (65%) occurred at station 4 located close to the access end of the circulation canal. Stations 3 and 6 were next highest (59% each) and located on an open-end and closed-end of the same canal. Lowest mortalities were found at stations 1 (55%) and 8 (34%) in the entrance canal.

Precipitation and Salinity

Precipitation during the study was atypical. Rainfall was below the historical averages in May, June, July and September, with May and July means being extremely low (Table 5).

Salinity increased steadily from 15-16 ppt in May to a maximum of 30 ppt in early August. During this period bottom salinities were slightly higher than surface salinities, but not significantly different from the control area. (Tables 6 and 7). As rainfall increased from early August to the end of the study, salinities decreased erratically.

Temperature and pH

Water temperature ranged from 25°C in May to 32.8°C in August (Tables 8 and 9). The temporary decrease noted on September 12 probably resulted from high tides and water exchange similar to that discussed in the bioassay section. Bottom temperatures during Phase B were usually slightly less than surface temperatures. Air temperatures (Table 10) were generally about a degree higher than surface temperatures.

pH measurements can be indicative of phytoplankton blooms, pollutants, calcium precipitation or solution, biodegradation, respiration, etc. The pH measurements recorded during this study showed little variation and fell well within the pH range for salt water (7.5 to 8.4) and for pH guidelines established by the State of Texas for this particular area (6.0-8.5). The pH showed little variation between stations (Tables 11 and 12). The greatest variation between canal stations (1.1 units) was observed on July 11. Bottom pH values were generally within a tenth of a unit of surface pH levels.

Current Measurements

The lowest velocity that could be detected with the ice meter was 5.5 m (18 ft) per minute. This value was not attained during current measurement attempts within the canal system; however, measurable values were recorded in Culvert G (Table 13).

After the completion of the study on September 26, the culverts were cleaned and current flow rates were again checked. On October 28, the flow rate through Culvert H was determined, and on December 6 the flow rates through all culverts were checked (Table 13).

During the approximately 6 hours it took to obtain the December 6 data, the tide rose 20 cm (8 inches) which is nearly twice the maximum rise observed during the May 19-September 26 monitoring period. Also on December 6 it was observed that as the tide rose, water was discharged through the circulation canal into Omega Lake. This was a result of the lake being first isolated from Highland Bayou and then being completely drained through the canal system by the previous outgoing tide.

DISCUSSION AND CONCLUSIONS

The dissolved oxygen and oyster mortality data indicate that bottom waters of the canal system were capable of supporting marine life at least from May 18 to the latter part of July. After July, hypoxic conditions prevailed. The general decrease in bottom oxygen concentrations most likely resulted from high oxygen demand. Additionally, the problem of reduced bottom dissolved oxygen within the canal system was compounded by low dissolved oxygen levels in Highland Bayou. These were often below the minimum concentration (4 ppm-surface water) established by the State for Highland Bayou (unclassified stream).

A phytoplankton bloom observed on

September 26th most likely caused the high dissolved oxygen concentration (13.2 ppm) at station 1. These blooms can have a devastating effect on oxygen concentrations, especially in canal situations with slow water exchange (Moore and Trent, 1971; Trent et al., 1972; Lindall et al., 1973; Hicks et al., 1975). It appears that the September 26 phytoplankton bloom had little measurable affect on the study area, suggesting that conditions were not conducive for large-scale phytoplankton production (Lindall and Trent, 1975).

Our data suggest that the circulation canal had little beneficial effect on bottom water dissolved oxygen concentration during periods of biological stress (Table 2). This was not unexpected, however, in view of the following:

1. The circulation canal and the main entrance canal were not of uniform depths.

2. The circulation canal had numerous exits and entrances (e.g. six canals and an Omega Lake access canal). The cross-sectional areas of the connections were large and unrestricted so that water in the circulation canal rose and fell, for all practical purposes, at the same rate as that in the Omega Bay canals. This was especially true during low tides. It was difficult for currents to be generated under these conditions.

3. Clogged and partially restricted culverts within the circulation canal decreased water circulation.

Alignment of six of the canals parallel to the prevailing summer wind (Table 14) is believed to have improved aeration of surface waters. Apparently, mixing of the oxygenated surface waters resulted in relatively high oxygen concentration of mid-waters. To a lesser degree, mid-depth oxygen mixed further to the bottom minimizing the extent and duration of hypoxic conditions there.

A beneficial feature incorporated into the canal construction was the intersection of the entrance canal with other canals. Overall, stations located at the intersections had the highest average bottom dissolved oxygen concentrations and lowest average percent oyster mortality.

The greater difference between surface and bottom salinity and dissolved oxygen measurements from mid-August through September strongly suggest stratification and incomplete mixing. These sub-optimal biological conditions might have been less severe if the canals were shallower as recommended by NMFS. Had this been the case, the denser waters at the bottom of the canals would have been more easily circulated and mixed.

A brief mention should be made of water quality problems existing in the adjacent waterfront development, Bayou Vista (Figure 5). Prior to 1968, developers were not required to obtain a permit from the U.S. Army Corps of Engineers; consequently, recommendations from NMFS were not voiced. Both Bayou Vista, built in 1962, and Omega Bay border Highland Bayou. According to the Galveston County Health Department, Bayou Vista has had several poor water quality complaints while Omega Bay has had none. The Texas Parks and Wildlife Department, reports four fish kills from 1977 to present in the Bayou Vista area. Three of these kills were attributed to low dissolved oxygen, and the cause of the fourth kill was not investigated. In contrast, there were no documented fish kills in the Omega Bay complex.

Generalized guidelines have been established for the design and location of waterfront real estate. These guidelines are designed to minimize habitat loss, insure the protection of marine biota, and expedite the application/permit process (Lindall and Trent, 1975; NMFS, 1983; NMFS, 1986). Since 1977, no other systematic surveys have been conducted in the Omega Bay development. Based on historical and current hydrological data from State and local environmental agencies, we conclude that the modified canal design did in fact increase circulation. Consequently, adequate water quality has been maintained in the Omega Bay development. We recommend, however, for future considerations that culverts of four feet diameter or less be eliminated from circulation canals in favor of box culverts and bridges.

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Table 13. Current velocities (feet/minute) measured by timing dye flow through culverts or with the ice meter (*). The hour at which the October and December measurements are shown in parentheses. October and December data represent flow through unclogged culverts.

Table 14. Wind direction and average wind speed (mph) by station and date.

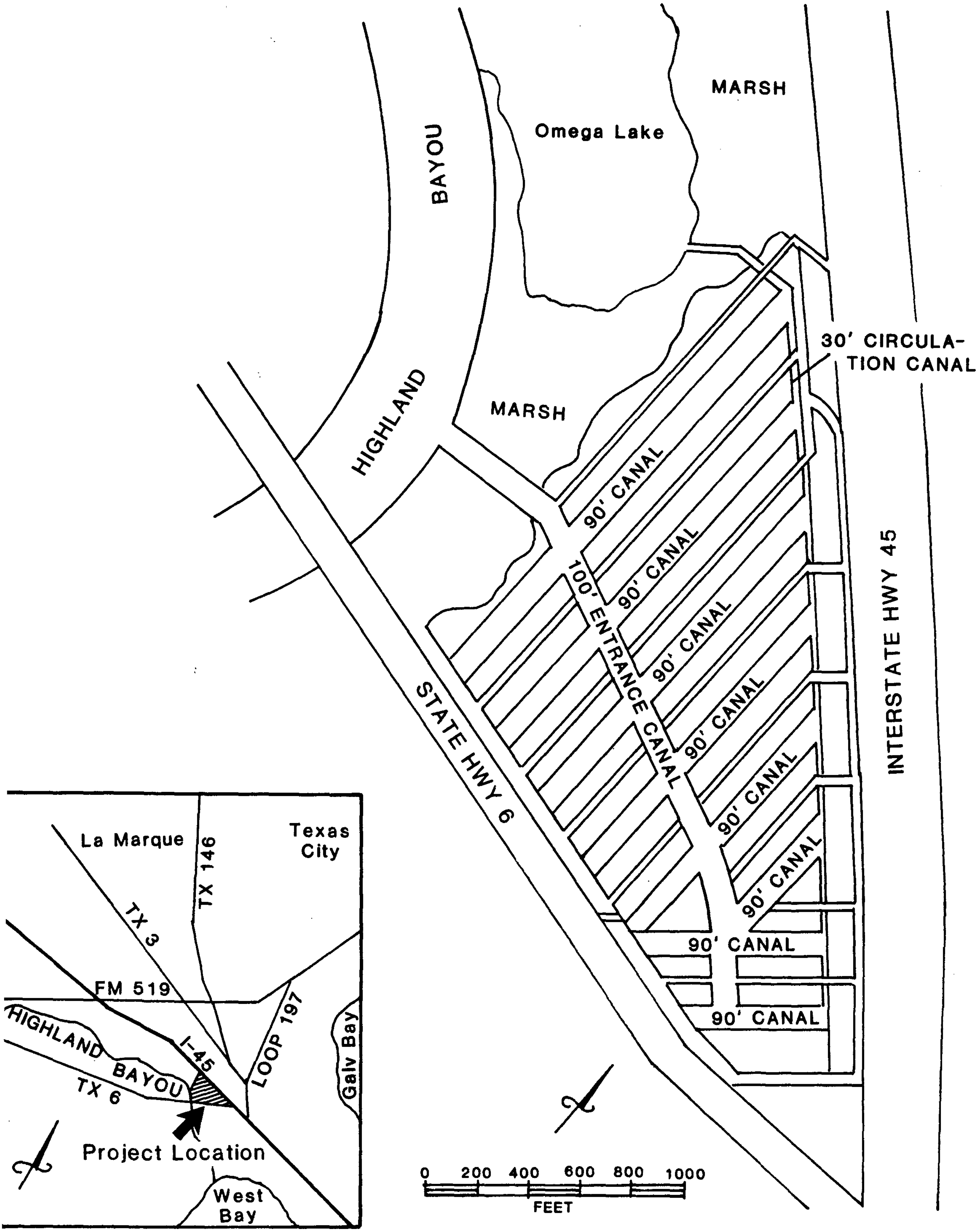

Figure 1. Proposed Omega Bay canal construction adjacent to Highland Bayou, approved by NMFS.

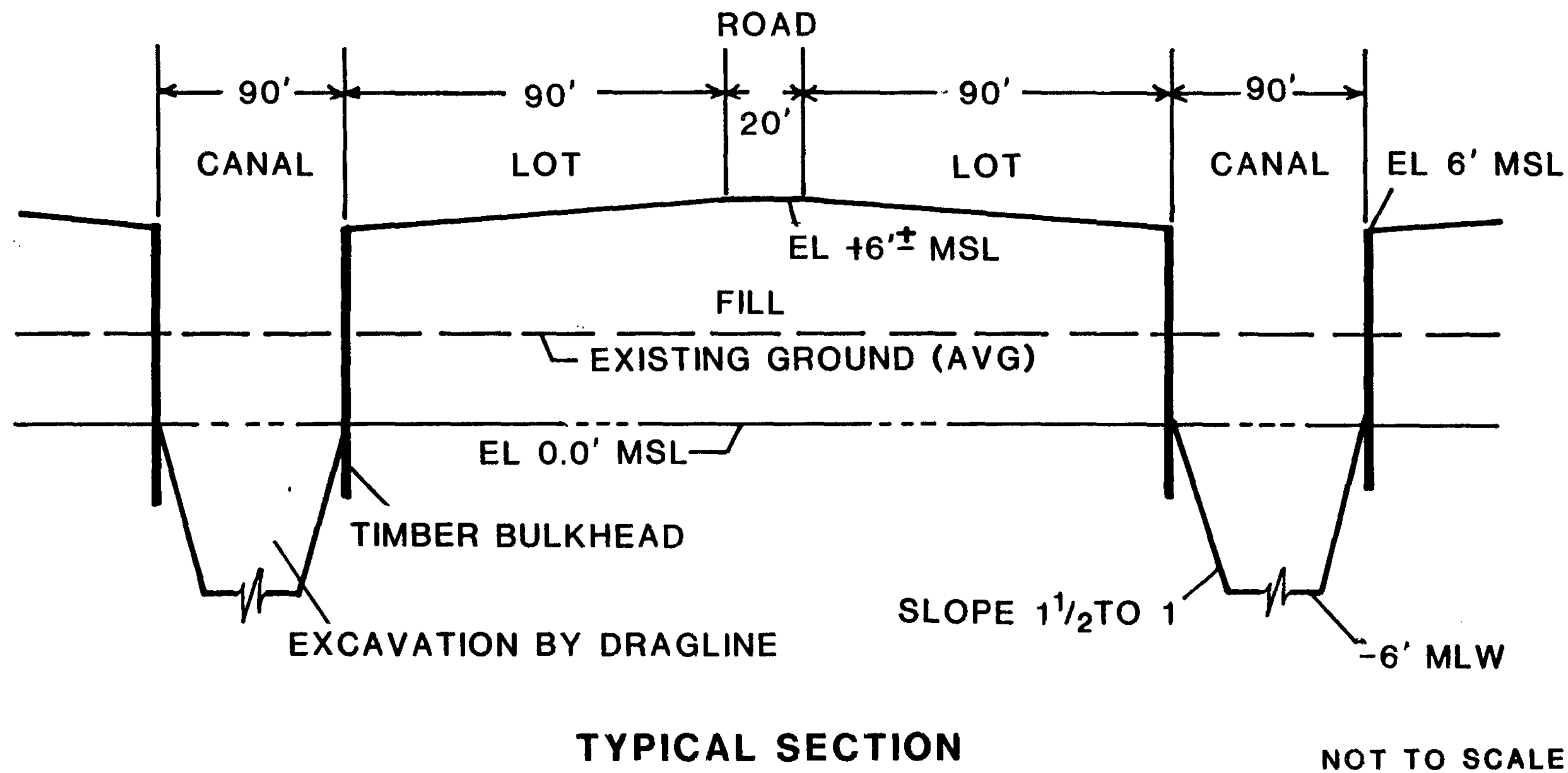

Figure 2. Typical cross-sectional view of the modified proposal.

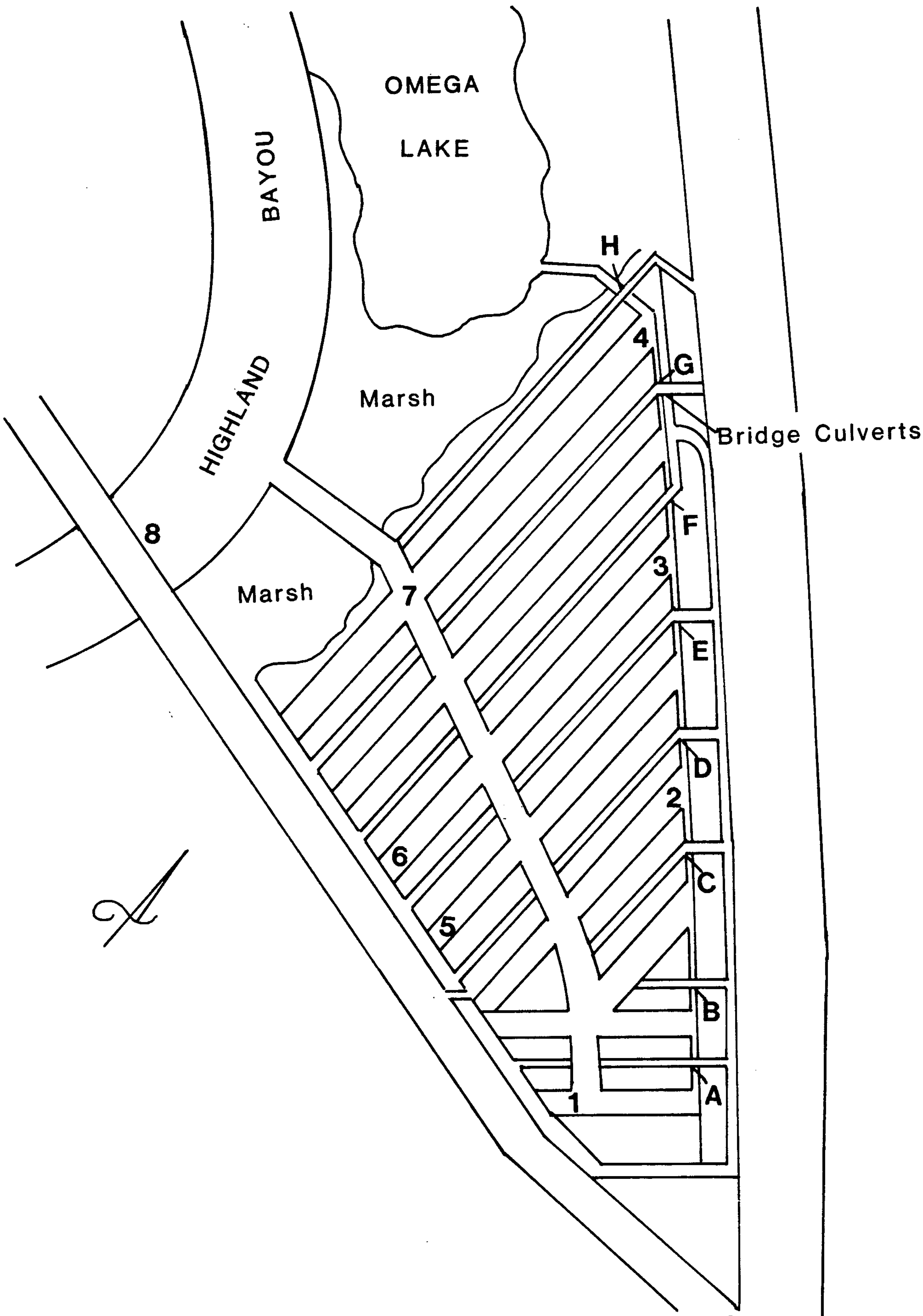

Figure 3. Phase A. Showing the locations of stations 1 through 8 and culverts A through H.

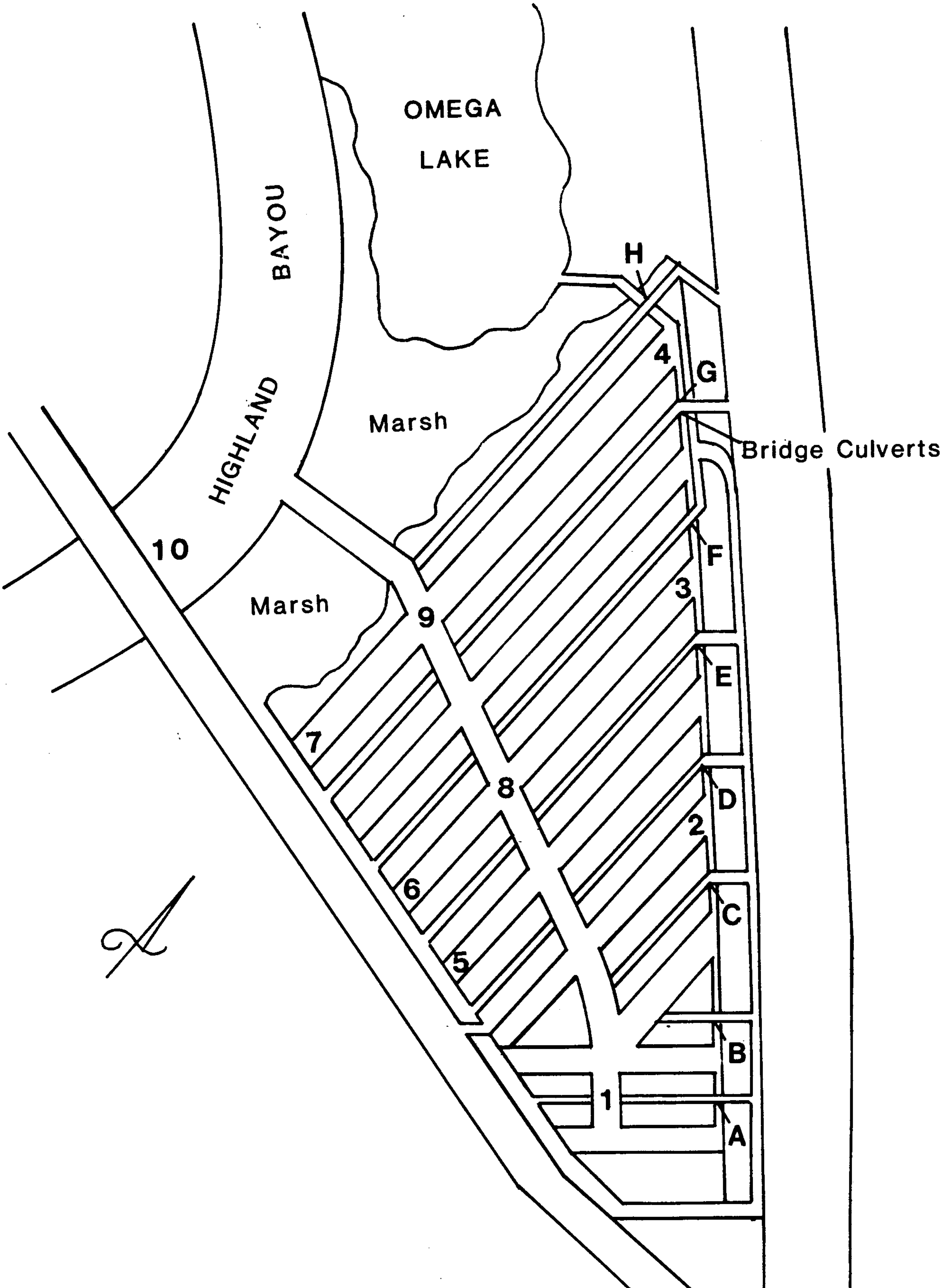

Figure 4. Phase B. Showing the locations of stations 1 through 10 and culverts A through H.

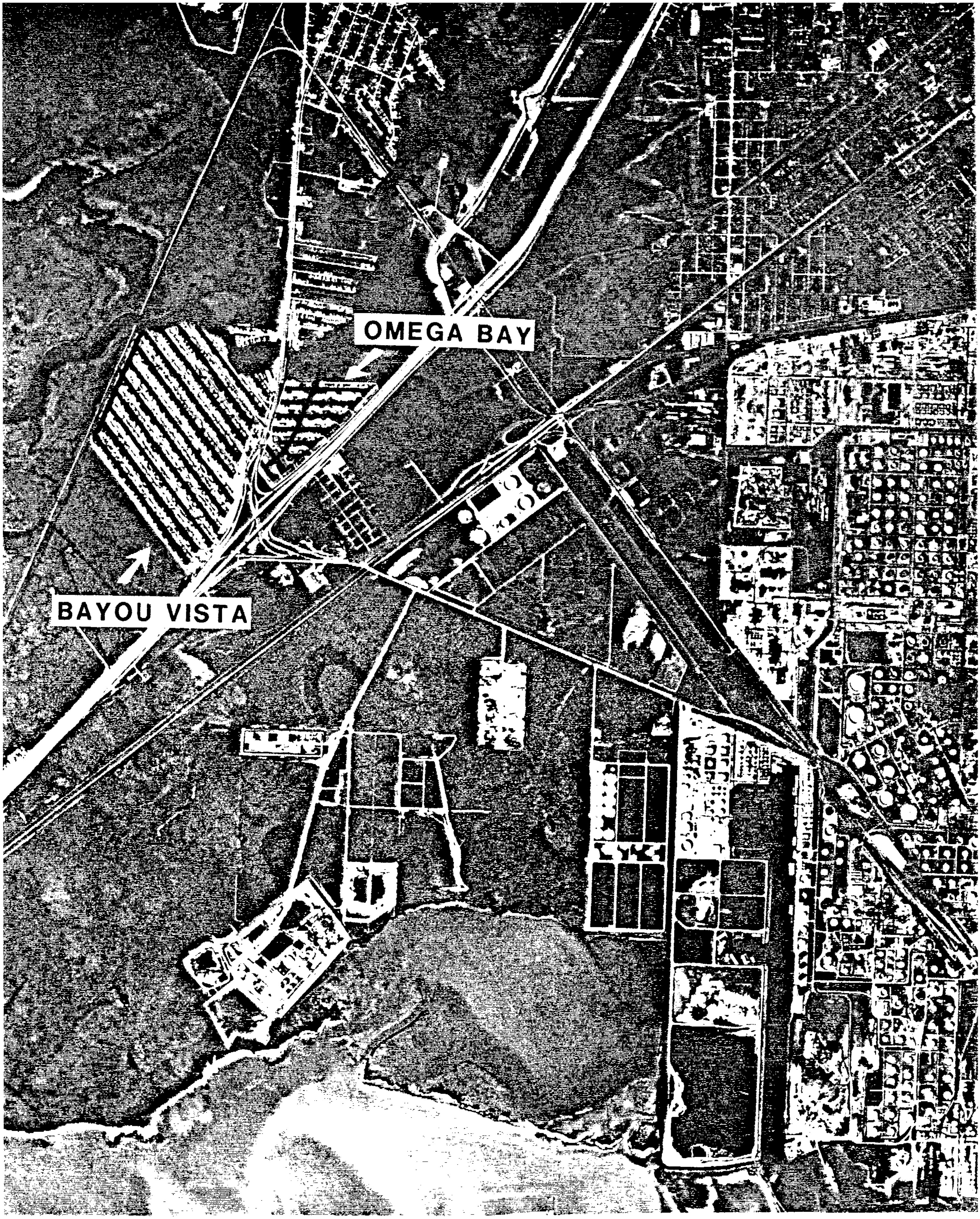

Figure 5. Showing location of Omega Bay and the adjacent waterfront development, Bayou Vista.

Table 1. Phase A - Dissolved oxygen concentrations (ppm) at surface (S), mid-depth (M), and bottom (B) by station and date.

STATION	DEPTH	MAY 18	MAY 23	MAY 31	JUNE 7	JUNE 16	JUNE 20	JUNE 27
1	S	7.08	7.18	5.69	4.77	8.69	7.64	
	M				4.90			6.11
	B	4.77	6.60	1.59	5.06	5.46	5.18	5.02
2	S	7.11	7.39	6.84	4.60	7.30	7.51	
	M				4.28			7.32
	B	7.08	7.22	1.26	4.34	7.16	4.43	6.09
3	S	6.70	7.11	7.07	4.22	7.57	7.02	
	M				4.13			7.39
	B	6.69	7.14	1.93	3.09	7.43	2.95	5.51
4	S	6.46	7.32	7.30	4.49	7.46	6.72	
	M				4.95			7.61
	B	5.37	4.81	1.30	3.16	7.21	2.28	7.18
5	S	6.41	7.00	6.04	5.32	7.07	6.84	
	M				5.40			5.20
	B	5.40	7.16	1.48	5.29	4.39	3.05	4.35
6	S	6.06	6.77	5.86	5.86	6.93	5.99	
	M				5.74			7.25
	B	5.29	6.25	2.00	5.83	3.59	2.07	6.25
7	S	6.13	6.67	7.18	6.48	7.07	6.09	
	M				5.41			6.34
	B	5.25	4.35	4.85	4.69	5.51	3.08	6.31
8	S	4.83	6.13	6.91	5.33	5.11	4.21	
CONTROL	M				4.73			
	B	4.88	4.31	5.25	4.64	5.36	4.11	

Table 2. Phase B - Dissolved oxygen concentrations (ppm) at surface (S), mid-depth (M) and bottom (B) by station and date.

STATION	DEPTH	JULY 5	JULY 11	JULY 18	JULY 25	AUG 1	AUG 8	AUG 15	AUG 22	AUG 29	SEPT 6	SEPT 12	SEPT 19	SEPT 26
1	S		7.41	6.75	7.05	6.45	5.70	7.31	8.96	6.15	6.52	8.56	7.31	13.22
	M	5.33	5.95	4.05	5.33	6.24	5.09	6.73	9.93	3.48	5.34	5.94	4.73	4.64
	B	5.22	5.47	3.44	2.58	5.30	3.70	1.18	1.22	2.51	1.86	1.51	1.90	1.02
2	S		7.48	8.06	7.28	6.12	5.87	8.49	8.49	5.96	6.80	9.37	7.03	7.38
	M	7.30	7.52	7.88	7.05	5.90	5.98	6.17	7.07	3.36	3.80	6.61	4.27	6.52
	B	4.38	6.13	2.92	2.06	2.62	3.18	1.29	2.11	1.74	1.32	1.25	0.12	1.41
3	S		7.32	7.86	5.83	4.29	4.92	8.47	8.34	5.94	6.57	8.82	6.80	6.87
	M	6.54	7.32	7.41	4.52	4.14	6.11	5.18	5.29	1.76	4.54	8.51	4.62	5.22
	B	2.89	5.52	2.26	1.78	1.63	2.24	1.10	1.16	1.97	1.72	1.46	2.32	4.55
4	S		6.31	6.70	5.31	4.27	5.37	7.76	8.06	5.43	6.29	9.14	5.73	6.38
	M	3.78	6.31	6.59	2.21	3.22	5.46	4.79	3.31	3.16	5.45	4.08	4.01	5.38
	B	3.49	3.65	4.03	2.30	1.65	2.47	0.90	1.03	2.25	1.44	1.55	1.25	0.76
5	S		6.09	6.68	6.30	5.81	4.73	7.05	9.78	6.73	6.77	8.14	7.26	9.05
	M	5.31	3.78	6.23	4.32	5.47	3.57	3.16	3.93	2.48	6.15	6.36	2.32	5.47
	B	3.95	3.74	3.87	1.54	1.33	2.06	1.01	1.18	1.32	2.18	2.02	0.21	5.50
6	S		5.97	5.64	6.12	5.28	4.58	6.79	9.14	7.13	6.50	7.93	6.89	8.93
	M	4.09	4.33	4.91	2.85	5.00	2.60	4.45	3.14	3.36	6.12	5.64	4.59	4.89
	B	3.31	3.83	2.72	1.69	1.48	1.89	1.01	1.16	1.72	1.62	1.39	2.44	1.04
7	S		5.36	5.25	5.69	5.79	2.41	6.75	7.59	5.41	5.73	7.05	6.89	6.91
	M	5.95	5.02	3.53	3.98	5.39	2.58	4.15	3.48	1.39	6.03	5.80	4.06	5.67
	B	5.88	4.33	3.40	2.35	2.36	3.31	1.18	0.86	1.58	2.00	1.16	1.14	5.43
8	S		6.61	6.84	6.08	5.47	5.55	7.52	7.72	5.59	3.96	8.68	6.50	7.17
	M	4.88	6.22	6.66	4.84	5.32	5.01	3.76	3.61	3.32	6.73	6.15	4.76	5.68
	B	3.72	5.43	5.10	3.05	1.29	4.04	1.07	0.99	3.87	1.92	1.51	0.58	1.37
9	S		6.04	6.45	5.54	4.23	5.48	8.30	7.05	5.80	5.34	8.51	5.17	6.89
	M	3.67	6.00	6.30	4.25	3.65	5.35	4.92	3.46	3.22	5.24	6.17	4.64	4.76
	B	4.65	5.17	4.78	3.32	2.15	4.30	0.79	1.18	4.04	3.71	1.58	3.43	2.02
10	S		4.70	4.17	5.08	2.75	3.96	6.92	6.88	4.85	5.27	8.19	4.64	5.22
CONTROL	M	3.05	4.79	4.30	3.66	2.70	3.78	3.50	3.85	3.85	3.27	5.10	4.87	2.74
	B	3.01	4.33	4.62	3.19	2.70	3.78	3.55	3.30	4.18	2.27	4.29	4.71	4.06

Table 3. Bottom mean dissolved oxygen concentrations (ppm) by station type and station number. Mean values are listed in descending order of magnitude.

Phase A (May 18 - June 27)

Station	Type	Mean dissolved oxygen	Mean dissolved oxygen by station type	
2	open-end	5.37	open-end	4.90
3	open-end	4.96	connecting	4.86
7	connecting	4.86	control	4.76
1	open-end	4.81	dead-end	4.46
8	control	4.76		
4	open-end	4.47		
6	dead-end	4.47		
5	dead-end	4.45		

mean = 4.77, s.d. = 0.313.

Phase B (July 5 - September 26)

Station	Type	Mean dissolved oxygen	Mean dissolved oxygen by station type	
10	control	3.69	control	3.69
9	connecting	3.16	connecting	2.87
1	connecting	2.84	dead-end	2.31
7	dead-end	2.69	open-end	2.25
8	connecting	2.61		
2	open-end	2.35		
3	open-end	2.35		
5	dead-end	2.30		
4	open-end	2.06		
6	dead-end	1.95		

mean = 2.60, s.d. = 0.534

Table 4. Oyster mortality in percent by station and date.

STATION	JULY 5	JULY 11	JULY 18	JULY 25	AUG 1	AUG 8	AUG 15	AUG 22	AUG 29	SEPT 6	SEPT 12	SEPT 19	SEPT 26
1	10	0	0	0	100	30	70	100	100	10	100	100	100
3	100	0	0	10	100	20	100	100	100	0	50	90	100
4	-	-	30	40	100	60	100	90	100	30	100	100	100
6	10	0	0	10	90	70	90	100	100	20	100	80	100
8	10	10	0	10	60	0	40	90	20	0	10	100	100
10 CONTROL	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5. Total precipitation (inches) in Galveston, Texas, by month for May through September (1977) with comparative historical monthly means (1957-1976).

YEAR(S)	*MAY*	*JUNE*	*JULY*	*AUG*	*SEPT*	*ANNUAL*
1977	0.67	2.83	0.68	6.45	4.91	42.07
1957 - 76	3.47	4.24	3.31	4.69	6.44	42.32

Table 6. Phase A - Salinity (ppt) at surface (S), mid-depth (M), and bottom (B) by station and date.

STATION	*DEPTH*	*MAY 18*	*MAY 23*	*MAY 31*	*JUNE 7*	*JUNE 16*	*JUNE 20*	*JUNE 27*
1	S		16.6	15.3	19.1	20.8	21.6	
	M							24.1
	B	16.4	16.5	17.1	19.4	21	21.6	23.8
2	S		16.6	15.4	19.7	20.3	20.3	
	M							23.4
	B	16.1	16.5	16.8	19.6	20.5	21.7	23.7
3	S		16.5	15.5	19.8	19.8	20.4	
	M							22.8
	B	15.5	16.4	17.2	20	19.8	21.9	23.4
4	S	15.0	15.9	15.7	19.7	19.5	20.4	
	M							22.6
	B	15.3	16.4	17.5	20.4	20.2	21.5	24.5
5	S		16.6	16.1	19.7	20.7	21.4	
	M							23.6
	B	16.2	16.6	17.5	19.7	20.7	21.9	24.6
6	S		16.6	16.5	19.4	20.5	21.7	
	M							23.7
	B	16.0	16.6	17.6	19.6	20.7	21.9	24.7
7	S	15.6	16.6	15.8	16.8	20.2	20.4	
	M							25.3
	B	15.9	16.5	17.5	19.6	20.8	22.2	25.7
8	S	16.4	16.7	16.7	18	21.1	22.2	
	M							
CONTROL	B	16.5	16.4	18.6	18.5	21.3	23.1	

Table 7. Phase B - Salinity (ppt) at surface (S), mid-depth (M) and bottom (B) by station and date.

STATION	DEPTH	JULY 5	JULY 11	JULY 18	JULY 25	AUG 1	AUG 8	AUG 15	AUG 22	AUG 29	SEPT 6	SEPT 12	SEPT 19	SEPT 26
1	S		26.7	29.1	28.9	28.3	29.7	12.3	12.2	21.1	14.1	22.2	11.8	15.8
	M	25.8	27.1	29.4	28.7	28.1	29.9	18.3	17.3	24.6	21.4	22.9	17.8	19.0
	B	25.9	28.0	29.6	29.6	28.3	29.8	26.6	25.8	25.5	21.6	25.6	19.2	20.9
2	S		26.6	29.1	28.8	28.2	29.3	9.1	10.7	21.9	14.3	18.5	11.4	14.2
	M	25.7	26.7	29.1	28.9	28.4	29.5	16.0	18.7	24.6	21.9	22.8	17.4	18.1
	B	25.5	26.7	29.5	29.4	28.9	29.6	26.2	21.6	25.3	22.5	23.8	19.6	19.5
3	S		26.3	29.1	29.0	28.8	28.6	9.5	11.1	20.9	14.2	18.4	11.3	14.0
	M	25.4	26.3	29.0	29.3	29.3	28.8	16.7	16.8	24.3	17.9	20.0	18.3	17.6
	B	24.7	26.3	29.5	29.3	29.8	29.6	27.1	22.9	25.3	20.8	25.1	19.4	19.5
4	S		25.9	29.0	29.3	28.4	29.1	9.7	9.5	21.7	14.0	18.1	11.0	13.4
	M	25.4	26.1	28.9	29.5	29.2	29.1	14.1	15.0	25.3	20.3	22.0	17.9	14.0
	B	25.8	27.6	29.3	30.2	29.9	29.6	27.5	27.3	25.5	23.6	25.0	21.1	18.7
5	S		27.1	29.2	29.0	27.8	29.7	12.3	14.0	15.9	14.2	22.3	11.9	16.8
	M	25.9	27.6	29.3	29.2	28.1	29.9	18.1	16.5	24.1	14.0	23.2	18.4	18.7
	B	25.8	27.8	29.5	29.6	29.7	30.0	26.4	26.3	24.8	22.3	25.5	21.1	20.6
6	S		27.2	29.2	28.9	27.5	29.7	12.3	13.6	17.9	14.1	22.2	11.4	16.9
	M	25.9	27.6	29.2	29.1	28.0	29.8	14.8	20.1	24.0	21.4	23.2	18.4	17.4
	B	26.0	27.8	29.5	30.9	29.1	30.0	26.7	27.8	25.1	21.3	25.7	19.9	20.4
7	S		27.8	29.1	28.6	27.3	29.9	11.4	15.2	16.7	13.7	22.1	10.7	16.9
	M	25.7	28.1	29.3	29.2	28.0	30.0	15.2	19.0	25.2	22.2	22.7	17.6	18.3
	B	26.0	28.0	29.4	30.2	29.2	30.2	27.1	23.4	25.5	22.6	25.0	19.6	20.2
8	S		26.8	29.0	28.9	28.1	29.6	10.4	11.8	20.7	13.8	20.5	9.7	15.1
	M	25.8	26.9	29.2	29.1	28.3	29.6	15.6	18.4	24.2	19.6	22.7	18.3	18.6
	B	25.7	28.5	29.4	29.9	29.2	30.1	26.7	27.4	25.6	22.0	24.4	21.6	20.7
9	S		26.7	28.9	28.8	27.8	29.4	8.0	11.2	19.3	13.5	19.7	9.1	14.7
	M	25.9	27.3	29.3	28.8	29.0	29.5	15.3	19.3	24.1	20.6	21.9	16.6	17.5
	B	25.7	28.8	29.8	30.6	29.5	30.1	24.9	26.6	25.4	23.6	24.8	18.7	19.5
10	S		29.5	30.1	29.7	28.8	30.4	11.4	11.5	15.9	13.3	21.0	9.4	15.1
	M	26.5	29.6	30.2	31.0	29.2	30.4	19.8	22.0	27.2	18.3	23.0	17.7	19.4
CONTROL	B	26.4	29.5	30.2	31.3	29.3	30.5	20.5	24.1	27.7	20.6	23.2	19.6	22.3

Table 8. Phase A - Surface water temperatures (°C) by station and date.

STATION	MAY 18	MAY 23	MAY 31	JUNE 7	JUNE 16	JUNE 20	JUNE 27
1	27.0	25.5	28.0	28.0	27.5	29.5	29.0
2	25.0	26.0	28.0	28.0	27.5	29.5	29.5
3	25.0	25.5	29.0	29.0	27.0	29.0	29.0
4	25.0	25.0	30.0	29.0	27.0	28.5	28.5
5	25.0	25.5	28.5	28.0	27.0	29.0	29.0
6	25.0	25.5	29.5	29.0	27.0	29.0	29.0
7	25.5	25.5	30.0	29.0	27.0	29.0	28.5
8 CONTROL	25.0	25.5	31.0	29.0	27.5	28.0	- -

Table 9. Phase B - Water temperature (^{o}C) at surface (S), mid-depth (M), and bottom (B) by station and date.

STATION	DEPTH	JULY 5	JULY 11	JULY 18	JULY 25	AUG 1	AUG 8	AUG 15	AUG 22	AUG 29	SEPT 6	SEPT 12	SEPT 19	SEPT 26
1	S	29.4	29.5	30.2	31.2	32.0	32.6	31.6	30.2	28.3	30.6	29.5	30.3	29.4
	M									28.5		29.2	30.7	28.7
	B			29.0	29.8	29.5	31.4	30.7	29.7	28.7	29.9	29.0	29.7	28.8
2	S	30.4	30.9	30.9	32.8	31.8	32.1	32.2	29.9	28.4	32.1	30.3	30.8	28.8
	M									28.7		29.2	31.0	29.5
	B			29.4	30.1	30.1	31.8	31.2	29.5	28.6	30.4	28.9	30.3	29.3
3	S	30.2	30.6	31.2	31.9	30.6	31.3	31.9	31.1	27.9	31.0	29.8	30.6	28.7
	M									28.9		29.9	30.5	29.1
	B			29.5	29.9	29.9	31.2	31.4	31.3	28.4	30.4	29.1	29.8	29.1
4	S	29.9	29.7	30.3	31.8	30.0	31.5	30.8	29.1	28.4	30.0	29.3	29.4	28.6
	M									29.3		31.1	30.3	28.7
	B			28.8	30.1	30.2	31.0	31.1	30.2	28.6	29.5	29.7	28.3	29.0
5	S	29.6	29.8	30.8	31.7	31.8	32.0	31.3	30.1	27.5	32.4	29.5	30.3	29.5
	M									28.6		29.1	31.0	29.4
	B			29.1	29.8	29.5	31.4	30.9	29.9	28.5	30.7	28.8	29.9	29.3
6	S	29.4	29.7	30.3	31.0	30.2	31.5	31.5	30.7	27.1	31.6	29.8	29.9	29.3
	M									28.2		30.1	30.5	29.4
	B			29.1	29.8	29.7	31.3	31.1	30.4	28.2	30.3	29.5	30.0	28.9
7	S	29.6	29.2	29.8	30.8	29.8	31.3	30.2	29.9	27.2	30.4	29.5	28.9	28.9
	M									28.5		28.5	30.2	29.5
	B			28.8	30.0	29.7	31.0	30.3	30.1	28.2	29.9	28.0	29.8	29.0
8	S	30.0	29.7	30.8	31.5	30.5	31.1	31.6	30.3	27.7	30.1	30.0	29.7	28.9
	M									28.6		29.4	30.6	29.8
	B			29.1	30.0	29.8	31.2	31.1	30.3	28.5	29.9	28.9	28.6	28.6
9	S	29.7	29.6	30.2	30.4	30.0	30.6	30.2	30.4	27.6	29.8	29.2	28.6	28.6
	M											29.0	29.4	29.1
	B			29.0	29.8	29.8	31.0	30.1	30.5	28.3	29.5	28.6	29.3	28.9
10	S	29.9	28.9	30.1	30.2	29.2	30.7	28.6	28.8	28.1	29.3	29.2	28.5	28.8
CONTROL	M											28.7	28.7	28.9
	B			29.2	29.9	29.0	30.3	28.1	29.1	28.7	29.9	28.4	28.9	28.5

Table 10. Phase A (June only) and Phase B - Air temperature (°C) by station and date.

STATION	June 16	July 5	July 11	July 18	July 25	Aug 1	Aug 8	Aug 15	Aug 22	Aug 29	Sept 6	Sept 12	Sept 19	Sept 26
1	30.5	32.7	31.5	31.4	35.5	33.4	32.8	32.5	30.3	26.7	29.2	30.0	35.3	33.5
2	30.0	32.5	30.1	31.4	32.6	33.3	32.7	32.5	28.5	27.1	31.9	31.2	35.0	32.7
3	30.0	32.0	34.0	32.4	32.3	31.7	32.1	32.3	31.8	25.6	31.6	30.1	35.5	29.8
4	29.5	31.8	31.2	30.5	32.0	31.0	32.0	32.1	31.0	26.5	32.2	30.3	32.1	31.6
5	30.0	32.2	33.3	31.4	32.3	31.8	32.5	32.2	30.5	26.5	32.0	30.1	35.4	31.4
6	30.0	32.9	31.5	31.3	31.9	31.2	31.9	32.1	31.6	25.4	31.8	31.1	36.4	30.2
7	30.0	30.6	32.2	30.5	31.3	31.1	31.8	30.9	31.0	26.2	31.9	31.1	30.2	30.4
8	29.0	32.9	29.2	31.5	32.1	31.3	32.0	32.0	31.1	26.1	32.2	32.8	36.4	34.7
9		31.1	28.9	30.6	30.7	30.2	31.6	30.8	31.1	25.5	30.5	30.3	31.2	33.5
10 CONTROL		30.6	28.6	30.2	30.8	29.7	31.6	28.4	30.1	25.1	30.1	28.1	26.5	29.4

Table 11. Phase A - pH at surface (S) and bottom (B) by station and date.

STATION	*DEPTH*	*June 16*	*June 20*	*June 27*
1	S	8.4	8.3	8.0
	B	7.9	8.0	8.0
2	S	8.4	8.3	--
	B	8.2	8.2	8.1
3	S	8.3	8.3	8.2
	B	7.8	8.5	8.2
4	S	8.4	8.4	8.2
	B	8.0	8.1	8.2
5	S	8.3	8.3	--
	B	8.1	8.2	8.0
6	S	8.2	8.3	8.1
	B	7.8	8.0	8.1
7	S	8.2	8.5	8.2
	B	7.8	8.1	8.2
8	S	7.8	8.7	--
	B	7.6	8.4	--
CONTROL				

Table 12. Phase B - pH at surface (S), mid-depth (M), and bottom (B) by station and date.

STATION	DEPTH	JULY 5	JULY 11	JULY 18	JULY 25	AUG 1	AUG 8	AUG 15	AUG 22	AUG 29	SEPT 6	SEPT 12	SEPT 19	SEPT 26
1	S	8.2	8.6	-	8.4	8.2	8.2	-	-	8.0	8.1	8.2	8.1	8.8
	M	-	8.6	8.5	8.4	8.3	8.2	-	-	-	8.0	8.0	7.9	8.3
	B	-	8.6	8.5	8.3	8.2	8.1	-	-	-	7.8	7.8	7.7	7.9
2	S	8.4	8.0	-	8.3	8.0	8.2	-	-	7.9	8.1	8.2	8.1	8.4
	M	-	8.0	8.6	8.4	8.1	8.3	-	-	-	7.9	8.0	7.9	8.2
	B	-	8.0	8.4	8.2	8.0	8.2	-	-	-	7.7	7.8	7.6	7.9
3	S	8.3	8.0	-	8.2	8.0	8.1	-	-	7.9	8.1	8.5	8.1	8.3
	M	-	8.0	8.6	8.3	8.0	8.2	-	-	-	8.0	8.3	7.8	8.1
	B	-	8.0	8.4	8.2	7.9	8.0	-	-	-	7.7	7.8	7.6	8.0
4	S	8.4	8.4	-	8.2	8.1	8.1	-	-	7.9	8.0	8.4	8.1	8.2
	M	-	8.4	7.9	8.1	8.2	8.3	-	-	-	7.8	8.2	7.8	8.2
	B	-	8.3	7.8	8.0	8.0	8.2	-	-	-	7.7	7.8	7.6	7.8
5	S	8.2	7.7	-	8.4	8.2	8.0	-	-	8.0	8.1	8.2	8.1	8.6
	M	-	7.7	8.5	8.4	8.2	8.0	-	-	-	7.9	8.0	7.8	8.4
	B	-	7.7	8.4	8.3	7.9	8.0	-	-	-	7.8	7.8	7.5	8.1
6	S	8.2	7.7	-	8.2	8.0	8.1	-	-	8.0	8.0	8.2	8.0	8.4
	M	-	7.7	7.9	8.4	8.1	8.0	-	-	-	7.9	8.0	7.9	8.4
	B	-	7.8	8.0	8.2	8.0	8.0	-	-	-	7.8	7.7	7.6	8.1
7	S	8.3	8.1	-	8.4	8.2	8.1	-	-	8.0	7.8	8.1	8.1	8.2
	M	-	8.1	7.6	8.4	8.3	8.1	-	-	-	7.8	8.0	7.7	8.2
	B	-	8.2	7.6	8.3	8.1	8.1	-	-	-	7.7	7.9	7.5	8.1
8	S	8.2	8.4	-	8.4	8.2	8.1	-	-	8.0	7.9	8.4	8.1	8.4
	M	-	8.4	8.0	8.3	8.2	8.2	-	-	-	7.9	8.2	7.8	7.6
	B	-	8.4	7.9	8.3	7.9	8.0	-	-	-	7.8	8.0	7.6	7.6
9	S	8.2	8.4	-	8.4	8.4	8.1	-	-	8.0	7.8	8.3	8.1	8.3
	M	-	8.4	8.1	8.4	8.3	8.3	-	-	-	7.8	8.1	7.9	8.2
	B	-	8.3	8.3	8.3	8.2	8.2	-	-	-	7.7	7.9	7.7	8.1
10	S	8.0	7.5	-	8.2	8.2	8.3	-	-	7.8	7.9	8.2	8.3	8.0
CONTROL	M	-	7.2	7.8	8.3	7.8	8.3	-	-	-	7.7	8.1	7.8	8.0
	B	-	7.5	7.7	8.2	8.2	8.3	-	-	-	7.5	8.0	7.2	7.9

Table 13. Current velocities (feet/minute) measured by timing dye flow through culverts or with the Ice meter (*). The hour at which the October and December measurements were made is shown in parentheses. October and December data represent flow through unclogged culverts.

	CULVERTS							
DATE	A	B	C	D	E	F	G	H
9/5/77	<18*	<18*	<18*	<18*	<18*	<18*	<18*	<18*
10/28/77								25*(1000)
10/28/77								23*(1020)
12/6/77	0(1000)	0(1200)	0(1115)	0(1100)	4.6(1045)	8(1030)	16(1015)	19*(1000)
12/6/77	0(1415)	0(1420)	0(1440)	0(1547)	0(1545)	3(1240)	5(1525)	32(1530)

Table 14. Wind direction and average wind speed (mph) by station and date.

STATION	MAY 18	MAY 23	MAY 31	JUNE 7	JUNE 16	JUNE 20	JUNE 27	JULY 5	JULY 11	JULY 18	JULY 25
1	SE 8-12	SE 12-16	W 0-4	NW 3-8	SE 8-12	S 8-10	S 10-12	S 5-8	S 12-15	SE 5-8	S 5-8
2	SE 10-14	SE 10-14	W 0-4	N 5-8	SE 8-12	S 5-10	S 12-18	S 5-8	SE 15	S 5-10	S 8-12
3	SE 12-16	SE 10-15	W 0-2	NE 7-10	S 5-10	S 10-12	S 10-15	S 5-8	E 8-10	S 5-8	SW 2-3
4	SE 10-18	SE 12-16	W 0-5	NE 7-10	S 8-12	S 10-12	S 10-15	S 5-8	S 8-12	S 2-5	W 2-3
5	SE 10-12	SE 8-10	W 0-2	N 5-8	S 8-10	S 8-10	S 10-15	S 5-8	S 8-10	S 8-10	S 8-10
6	SE 10-12	SE 8-10	W 2-4	NE 8-10	S 8-10	S 8-10	S 5-8	S 5-8	S 5-8	S 5-8	SW 1-2
7	SE 6-8	S 12-16	W 0-2	NE 5-7	S 5-8	S 5-8	S 10-15	S 5-8	S 5-8	S 2-5	W 2-3
8	SE 12-14	S 12-16	SW 2-6	NE 5-8	S 5-10	S 5-8	--	S 2-5	S 15	S 5-8	W 2-3
9	--	--	--	--	--	--	--	S 2-4	SW 5-10	S 2-5	W 2-3
10	--	--	--	--	--	--	--	S 2-5	S 5-8	S 2-5	W 2-3

STATION	AUGUST 1	AUGUST 8	AUGUST 15	AUGUST 22	AUGUST 29	SEPTEMBER 6	SEPTEMBER 12	SEPTEMBER 19	SEPTEMBER 26
1	W 8-10	S 5-6	S 6-8	W 8-10	NE 8	S 2-4	S 10-15	W 5-8	S 12-14
2	NW 5-8	S 6-8	S 4-6	SW 8-10	NE 8	S 2-4	S 10-15	W 3-5	S 10-12
3	NW 8-10	S 6-8	S 6-8	S 8-10	NE 5-10	--	S 10-15	W 8-10	S 10-12
4	NW 2-5	S 6-8	S 2-5	SW 8-10	E 6	W 1	E 5	W 5-8	S 12-15
5	NW 5-8	S 6-8	S 2-5	SW 8-10	NE 8	SE 6-8	S 10-15	W 3-5	S 10-12
6	NW 5-8	S 8-10	S 4-6	S 6-8	E 5	--	S 10-15	NW 3-5	S 5-10
7	NW 2-5	S 4-6	S 4-6	S 6-8	NE 2	W 2	E 5	W 0-5	S 12-14
8	NW 8-10	S 8-10	S 4-6	SW 8-10	E 5-10	--	S 5-10	NW 8-10	S 12-15
9	NW 2-5	S 4-6	S 4-6	S 6-8	E 5	W 2-4	S 5-10	W 8-10	S 10-14
10	NW 2-5	S 4-6	W 2-5	S 8-10	NE 5	W 2-3	S 5	W 2-5	S 5-8