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Preface

The work reported herein was conducted as part of the Water Operations Technical Support (WOTS) Program. The WOTS Program is sponsored by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL). Funding was provided under Department of the Army Appropriation 96X3123, Operations and Maintenance. Dr. John W. Barko was Program Manager for the WOTS Program, and Mr. Robert C. Gunkel, Jr. was Assistant Manager. Program Monitors during this study were Mr. Frederick B. Juhle and Mr. Lewis Smith, HQUSACE. This study was also conducted in response to a request from the Huron-Clinton Metropolitan Authority (Detroit, MI).

The study was conducted and the report written by Dr. Craig S. Smith of Professional Lake Management, and Mr. William F. James, Mr. Harry L. Eakin, and Dr. Barko of the Ecosystem Processes and Effects Division (EPED) of the EL, ERDC. We gratefully acknowledge the assistance of Ms. Colette Luff of the USACE District, Detroit, for logistical support, Mr. Steven Ashby for review of this report, Ms. Michele Huppert and Mr. Dale Dressel of AScI Corp., and Mss. Laura Blegen, Brenda Lamb, Emily Schnieder, and Holly Wallace of the Eau Galle Aquatic Ecology Laboratory, ERDC, Spring Valley, WI, for the execution of water movement studies.

This investigation was conducted under the general supervision of Dr. John W. Keeley, Acting Director, EL, and under the direct supervision of Dr. Richard E. Price, Chief, Environmental Processes and Effects Division.

At the time of publication Dr. Lewis E. Link was Acting Director, ERDC, and COL Robin R. Cababa, EN, was Commander.

1 Introduction

In 1994, frequent periods of unacceptably high fecal coliform levels in the Metro Beach and Memorial Beach areas of Lake St. Clair, coupled with thick floating mats of decomposing aquatic vegetation, led to beach closures and the loss of millions of dollars in recreational revenue. Since then, beach closures have continued to be a problem at Metro Beach and several other nearby beaches. Although the origin of the waterborne fecal coliform bacteria has not been identified, it has been postulated that combined sewer overflows (CSO) into the Clinton River during storm events result in a plume of contaminated water that enters the lake through the Clinton River cutoff (located ~ 3 km to the west of the Metro Beach area). When these flows occur during periods of southwesterly or westerly winds, water circulation from the cutoff to Metro Beach could result in bacterial contamination of the beach. Based on plant populations observed in 1994 and 1995 (U.S. Army Corps of Engineers 1996) , it has also been suggested that dense submersed aquatic plant growth may restrict water movement in the Metro Beach area, thereby increasing water residence times in sheltered shoreline regions and retaining contaminated water in these areas.

The objectives of this investigation were to determine (1) the source of fecal coliform bacteria contaminating the Metro Beach area and (2) how likely it is that water currents could move contaminated water from the Clinton River cutoff into the Metro Beach Area rapidly enough and with sufficiently limited dilution that bacteria from this source would exceed state standards for body contact recreation. To address these connections, investigations of bacterial concentrations and water movements were conducted seasonally by employing fluorescent dye as a tracer of water movement.

2 Methods

Water Movement

Rhodamine WT, a red fluorescent dye, was used as a tracer for monitoring water movement near the Metro Beach area of Lake St. Clair. Dye tracer studies were conducted during the weeks of 1 June, 13 July, 3 August, 24 August, and 7 September 1998. On all dates, dye was injected into the upper 1 m of the water column along transects established near the Clinton River cutoff and the Metro Beach area (Figure 1). The injection transects were perpendicular to the shoreline and approximately 600 m in length. During the dye tracer study conducted during the week of 1 June, an additional transect was established between the Clinton River cutoff and the Metro Beach area (Figure 1).

During the morning of each dye study, approximately 3.25 L of concentrated dye (2.4×10^8 ppm) were diluted with 200 L of lake water prior to injection for each transect. Using an impeller pump, the dye slurry was injected into the water through a 1-m-long dye injector hose that had a series of holes interspersed throughout it. The dye was injected into the upper 1 m of the water column at a constant rate by making three to four passes over the transect with a boat traveling at 5 km/h (i.e., 7 minutes per pass). During each pass, the dye cloud was gently mixed by the boat motor action to homogenize the dye throughout the upper 1 m of the water column. Injection of all of the dye along a transect was achieved in less than 30 min. Immediately after injection, each dye cloud was approximately 600 m long by 10-20 m wide. The target concentration of dye after injection was ~ 100 ppb. Thus, the dye cloud was clearly visible for a number of hours after injection.

Dye cloud movement from each transect was tracked at ~2 hr intervals over a 12- to 24-hr period. To characterize the size and movement of the dye cloud as a function of time, a series of sampling transects were established through the dye cloud, based on visual approximation of the size of the cloud. Two transects were located along the leading edges of the cloud, and one transect was established through the approximate center of it (Figure 2). Two additional transects were established just beyond the visible bounds of the cloud to characterize the extent of the leading edges. Along each sampling transect, five to seven stations were sampled for determination of dye concentrations. The location of each sampling station was determined using a differential global positioning system (dGPS; Micrologic Model ML-250).

At each station, a sample of the upper 1 m of the water column was collected using an integrated sampler (Barko et al. 1981), which consisted of a 1.5-in. (0.0381-m) PVC pipe with a one-way check valve attached to the base of the pipe. When the pipe was lowered into the water column down to the 1-m depth, the check valve remained open, allowing water to pass freely through the pipe. When the sampler was raised from the water column, the check valve closed, trapping a water sample integrated over the upper 1-m depth. Samples were carefully poured into a rinsed bucket, gently mixed, and subsampled for fluorometric analysis.

Dye concentrations were measured using a Turner Designs Fluorometer (10-005R) that was calibrated using known dye standards. The position, extent, and movement of dye clouds through time were graphically determined using the contour mapping software SURFER (Golden Software 1997).

In addition to dye tracer studies, dye dissipation (residence time) studies were conducted for water located along the Metro Beach during the weeks of 3 and 24 August and 7 September. A dye streak measuring approximately 800 m long by 5 m wide was injected along the beach area on these dates. Reference points were established along the beach at 100-m intervals for dye concentration and bacteria determinations (Table 1). The Universal Transverse Mercator (UTM) coordinates of the reference points were determined by dGPS, and water samples for dye concentration determination were collected just offshore from these reference points (at about 2 m offshore). Short-term (hourly) changes in concentration were monitored over a 6- to 24-hr period on each date.

.

Table 1
Locations of Beach Sampling Reference Points for Bacterial Sampling

	UTM Coordinates[1]	
Location	**East**	**North**
C0	352280	4714664
C1	352375	4714670
C2	352470	4714680
C3	352559	4714666
C4	352687	4714553
C5	352754	4714520
C6	352846	4714490
C7	352939	4714462
C8	352998	4714437

[1]1927 North American Datum

Wind speed and direction were monitored continuously during each study using a logging weather station deployed at Metro Beach. A 3-cup anemometer and wind vane (DataLoggers Model ES-055; range=0-175 mph; Threshold=1.1 mph; Accuracy=2%) were positioned on a pole approximately 2 m in elevation above the beach. Wind speed and direction were averaged over 5-min intervals every 15 min for the duration of each study using a data logging system (DataLoggers Model ES-824).

Fecal Coliform Bacteria Sampling

Lake St. Clair transects

Based on an initial sampling grid established for dye studies, bacterial sampling transects perpendicular to the shore were located at intervals from just west of the Clinton River spillway to just east of Black Creek (Figure 3). Along each transect, samples were collected at distances of approximately 100, 300, and 700-1000 m from shore. Bacterial sampling stations were located in the field by their UTM coordinates (Table 2) using dGPS. A sample was also taken from the mouth of the Clinton River spillway. Beginning in August, as mounting evidence indicated that bacterial contamination might be a localized nearshore phenomenon, an additional nearshore sampling location was added to each transect. Nearshore samples were collected along the transect lines as close to shore as samples could be collected from a boat. Samples were collected from lake transects on 1 June, 30 June, 14 July, 4 August, 26 August, and 13 September 1998. Except for the 30 June sampling date, bacterial sampling was coordinated with water movement studies.

Beach transects

During water residence time studies, bacterial concentrations were sampled along a series of transects located off the Metro beach swimming area (Figure 3). These transects extended perpendicular to the shoreline just offshore from the reference points used in the dye dissipation studies. Samples were collected along each transect as described below at locations with water depths of approximately 2.5, 15 , 30, and 90 cm (1 in., 6 in., 1 ft, and 3 ft).

Coliform sampling and enumeration

Bacterial samples were collected in sterile 100-mL containers by immersing the inverted containers to elbow depth and then turning them right-side up and allowing them to fill. Where the water depth was too shallow for this technique (i.e., the 2.5-cm samples on beach transects), water was collected using a sterile 60-mL syringe, which was then used to fill the sterile sample containers. Concentrations of *Escherichia coli (E. coli)* in the samples were determined by National Environmental Testing, Inc., of Pontiac, MI.

Table 2
Locations of Lake St. Clair Bacteria Sampling Sites

Location	UTM Coordinates[1] East	UTM Coordinates[1] North
T1-0		
T1-1	348500	4713201
T1-2	348700	4713000
T1-3	349100	4712601
T2-0		
T2-1	348900	4713600
T2-2	349100	4713400
T2-3	349500	4713000
T3-0		
T3-1	350200	4714400
T3-2	350200	4714200
T3-3	350200	4713800
T4-0		
T4-1	351600	4714500
T4-2	351600	4714300
T4-3	351600	4713900
T5-0		
T5-1	352800	4714400
T5-2	352800	4714200
T5-3	352800	4713800
T6-0		
T6-1	353673	4714041
T6-2	353901	4713800
T6-3	354035	4713721

[1]1927 North American Datum

3 Results

Precipitation and Wind Patterns

Mean daily flow for the Clinton River near Fraser, MI, exhibited peaks exceeding 1000 cubic feet per second (cfs) in April and early May (Figure 4). Elevated flows were also observed in late May, early and mid-July, and early August. In particular, the largest storm inflow during the summer of 1998 occurred on 6 August (2510 cfs). In contrast, flows were low for extended periods in mid- to late June, late July, and mid-August through September. Average flow for the summer period (April through September) of 1998 was 320 cfs. This value was slightly lower than average summer flows of 356 cfs, based on a 50-year record (Figure 5).

During April through September 1998, winds blew most frequently out of the northwest (NW) and southwest (SW) (Figure 6). Winds blew out of the southeast (SE) 21% of the time and out of the northeast (NE) 17% of the time. Wind speeds averaged ~ 7.5 mph over all wind directions (NW=7.1 mph, SW=7.8 mph, SE=7.3 mph, NE=7.4 mph). Mean daily wind speeds during summer 1998 fluctuated between ~ 3 and 15 mph (Figure 7).

Dye Cloud Movement and Bacterial Concentrations

1-2 June 1998

From midnight to 1100 hours on 1 June, winds blew steadily from the north-northwest (NNW) at approximately 7 mph (Figure 8). Between 1115 and 2400 hours, wind velocity increased and shifted to the east-southeast (ESE). Shortly before the study, precipitation occurred in the region, resulting in elevated flow in the Clinton River on 31 May and 1 June (Figure 4). Mean daily flows were 524 cfs on 31 May and 288 cfs on 1 June. Dye was injected along three transects in the Metro Beach area between 0700 and 0800 hours on 1 June (Figure 9). In general, all dye clouds were strongly influenced by wind-driven currents. The dye cloud deployed near the Metro Beach area moved in a SE direction between 0700 and 1300 as a result of wind shear. During this time period, the southern edge of the cloud moved more than 600 m. Dye clouds located near the Clinton River cutoff and in the middle of the study area also initially moved in a SE direction from 0700 until 1300 on 1 June. The dramatic shift in winds to the south-southeast (SSE) direction at noon caused dye clouds to reverse direction and move NW toward the shore. Sampling of dye clouds located near the Clinton River cutoff and in the middle of the study area shortly after the wind shift demonstrated movement in a NW direction toward the shore. In particular, the dye cloud located near the Clinton River cutoff moved in a southerly direction during the morning of 1 June, but then moved back to the NW by the time of sampling (1300 hours).

Bacterial concentrations were uniformly low throughout the Lake St. Clair sampling grid (Figure 10). In most locations the *E. coli* concentration was below the detection limit of 10 colony-forming units (CFU)/100 mL. A few isolated locations had *E. coli* concentrations of 10 or 20 CFU/100 mL. No location had an *E. coli* concentration above 20 CFU/100 mL.

30 June

Bacterial concentrations were measured along the Lake St. Clair transects on 30 June (Figure 11). No dye movement studies were conducted on this date. Concentrations of *E. coli* were slightly elevated (i.e., 10-50 CFU/100 mL) at the shoreward end of the transects and decreased to levels below the detection limit at the outer end of the transects. The only sample having an *E. coli* concentration above 100 CFU/100 mL was collected at the shoreward end of the transect just east of the Clinton River cutoff channel. This sample had an *E. coli* concentration of 140 CFU/100 mL

14-15 July

Between 1200 and 2000 hours on 14 July, wind speeds averaged 11 mph out of the SSE (Figure 12). Wind speed diminished to near 0 mph between 2030 and 2200 hours, increased to near 10 mph out of the south-southwest (SSW) at 2300 hours, then declined to minimal speeds after midnight on 15 July. Six days (i.e., on 8 July 1998) prior to injection of dye clouds in the Metro Beach area, a storm event resulted in a peak flow of 1040 cfs for the Clinton River (Figure 4). Flows quickly declined and returned to nominal levels several days before dye injection. Flows were nominal during the dye study on 14 July 1998.

Dye streaks were injected in the surface waters along transects established near the Metro Beach area and the Clinton River cutoff between 1130 and 1300 hours on 14 July (Figure 13). Near the Metro Beach area, the dye cloud moved along a NW trajectory away from the swimming beach, reflecting wind direction (Figures 14 through 16). Trajectory speed during the afternoon of 14 July, determined for the center of mass of the dye cloud, averaged ~ 2 cm/s.

Twenty-four hours after dye injection, the dye cloud deployed near the Metro Beach area had moved > 1000 m away from its original position (Figure 17).

The dye streak injected near the Clinton River cutoff exhibited a complex dispersion pattern during the afternoon of 14 July (Figures 14 through 17). The southern leading edge of the cloud moved in a SSW direction toward Detroit during that afternoon. At 1900 hours this edge of the dye cloud had moved nearly 500 m from its original position (Figure 16). In contrast the northern leading edge of the dye cloud moved back into shore along a NE trajectory and became trapped along a break wall that was located to the east of the mouth of the Clinton River cutoff. These patterns suggested the occurrence of some eddying of water near the cutoff region under southerly winds.

Bacterial concentrations were measured along the Lake St. Clair transects on 14 July (Figure 18). Concentrations of *E. coli* were below the detection limit everywhere except along the transect just west of the Clinton River cutoff channel. Samples collected along this transect had *E. coli* concentrations of 20 to 50 CFU/100 mL

4-5 August

On 4 August, wind speed was nearly constant at 6.3 mph out of the SE during the afternoon (Figure 19). Wind direction shifted to the E and north-northeast (NNE) between 2100 hours on 4 August and 1200 hours on 5 August. Flows via the Clinton River were < 100 cfs between 27 July and 4 August (Figure 4). Elevated flows from the Clinton River occurred on 22 July and averaged 656 cfs over a 24-hr period.

Dye clouds injected near the Metro Beach area and the Clinton River cutoff between 1130 and 1300 hours on 4 August followed trajectories similar to those observed on 14 July (Figures 20-24). Near the Metro Beach area, the dye cloud moved in a NW direction away from the beach during the afternoon of 4 August. Like dye cloud movement on 14 July, the trajectory speed on 4 August was ~2 cm/s. Sustained winds from the SSE and east (E) during the night of 4 August and morning of 5 August resulted in dispersion and movement of the dye cloud toward the Clinton River cutoff (Figure 24). The leading edge of the dye cloud moved 2100 m from its original injection transect by 1030 hours on 5 August.

The dye streak injected near the Clinton River cutoff moved in a northerly direction on 4 August. In particular, some of the dye cloud moved considerably north into the Clinton River cutoff throughout the afternoon of 4 August (Figure 22). As on 14 July, much of the dye cloud also eddied along the break wall located east of the mouth of the Clinton River cutoff during 4 August. On the morning of 5 August, the shift in wind direction during the night out of the NE appeared to be associated with movement of some of the dye cloud along a southern trajectory (Figure 24). Much of the dye trapped along the break wall moved south by the morning of 5 August. There was also considerable movement of dye upstream into the Clinton River cutoff by the morning of 5 August.

Bacterial concentrations were measured along the Lake St. Clair transects on 4 August (Figure 25). This sampling date was the first occasion when additional sampling locations close to shore were added to the transects. Concentrations of *E. coli* were slightly elevated (i.e., 10-30 CFU/100 mL) at the shoreward end of the transects and decreased to levels below the detection limit at the outer end of the transects. No sample had an *E. coli* concentration above 30 CFU/100 mL, and concentrations of 30 CFU/100 mL were encountered only in the Clinton River cutoff channel and the nearshore sample just east of the Metro Beach swimming area.

25-26 August

During the afternoon of 25 August, winds blew steadily out of the west at ~ 6 mph between 1200 hours and 1800 hours (Figure 26). Peaks in wind speed near 10 mph out of the west occurred at 1400 hours. Between 1800 hours on 25 August and 0900 hours on 26 August, wind speed decreased to a mean 2.9 out of the NNW. Shortly before noon on 26 August, wind direction shifted to the NNE and east with wind speeds averaging 5.1 mph. Before dye injection, mean daily flows from the Clinton River were < 150 cfs between 20 and 24 August. On the day of dye injection (25 August, see below), mean daily flows increased slightly to 312 cfs. Mean daily flow declined to nominal levels on 26 August.

A 600-m-long dye streak was injected near the Metro Beach area at ~1300 hours on 25 August (Figure 27). Injection of the second dye streak near the Clinton River cutoff was postponed until 26 August at 1200 hours, due to elevated wind speeds and high waves during the afternoon of 25 August.

The trajectory of the dye cloud on 25 August was clearly influenced by winds blowing out of the west, as it moved in an easterly direction, parallel to the shoreline of the Metro Beach area (Figures 27-31). By 1830 hours, its center of mass had moved directly east over 200 m (~ 2 cm/s). At 1100 hours on 26 August, the southern portion of the dye cloud moved in a southerly direction, coincident with winds blowing out of the NW and NE during the evening of 25 August. At that particular time the dye cloud was ~ 1100 m long and 600 m wide.

Due to shifts in wind direction to the NE during the afternoon of 26 August, the dye cloud deployed near the Clinton River cutoff moved in a SW direction (Figures 32-35). By 1600 hours on 26 August, the southern edge of the dye cloud had moved nearly 1000 m from its original injection point. The northern edge of the dye cloud dispersed toward the shoreline and toward the break wall located east of the mouth of the cutoff.

Bacterial concentrations were measured along the Lake St. Clair transects on 26 August (Figure 36). On this date concentrations of *E. coli* were below the detection limit everywhere except in and around the mouth of the Clinton River cutoff and near the shore at Metro Beach. The *E. coli* concentration in the cutoff channel was 880 CFU/100 mL. Concentrations between 10 and 100 CFU/100 mL were encountered in all but the outermost locations along the transects on both sides of the channel. The two locations on the shoreward end of the transect just east of the Metro Beach swimming area had *E. coli* concentrations of 170 and 20. No location between the cutoff channel and the beach had an *E. coli* concentration above the detection limit.

11-12 September

Similar to wind patterns observed during the afternoon of 25 August, winds blew from a westerly direction on 11 September (Figure 37). Wind speeds during this period averaged ~ 13 mph. Winds continued to blow from the west and SW throughout the afternoon and evening of 11 September and until ~ 1500 hours on 12 September. Wind direction shifted to the NNE over a 6-hour period during the evening of 12 September. Wind speeds out of the north declined substantially during the early morning of 13 September. During the study period, mean daily flows from the Clinton River cutoff were nominal with the exception of a minor peak of 227 cfs that occurred on 2 September (Figure 4).

A dye cloud was injected at the Clinton River cutoff region at 1130 hours on 11 September (Figure 38). During the afternoon of 11 September, movement of dye exhibited a complex spatial pattern (Figures 38-41). The southern portion of the dye cloud followed an easterly and NE trajectory, coinciding with wind direction that afternoon. However, the northern portion of the dye cloud, located near the mouth of the Clinton River cutoff, both remained near the shoreline region and dispersed south slightly along the shoreline west of the cutoff region. By 0930 hours on 12 September (Figure 42), the dye cloud had split, with one portion moving along an east and NE trajectory toward the Metro Beach area and another portion remaining near the cutoff area. These results suggest that near the shoreline on the leeward side of the wind, wind-generated currents were slight, while further out into the lake, where wind speeds and waves were noticeably stronger, wind-generated currents were resulting in water movement toward the beach.

Continued sustained winds out of the west on 12 September resulted in movement of a second dye cloud, deployed near the Metro Beach area at 1000 hours on 12 September, toward the beach area during the afternoon (Figures 43-46). The center of mass of the dye cloud moved over 300 m between 1000 and 1630 hours, for an estimated velocity of 1 cm/s. The eastern leading edge of the dye cloud reached the western edge of the beach area by 1630 hours. A shift in wind direction toward the north and NE between 1500 hours and 2100 hours on 12 September resulted in movement of the southern portion of the dye cloud along a NW trajectory back toward the original injection transect. By 0900 hours on 13 September (Figure 47), the dye cloud appeared to have split due to shifting wind direction during the previous day.

One portion of the dye cloud appeared to continue to follow a NW trajectory during that evening and was located along the shoreline to the west of the Metro Beach area on the morning of 13 September. Another portion of the dye cloud appeared to continue to move toward the NE and was tracked to the shoreline east of the Metro Beach area on the morning of 13 September.

Bacterial concentrations were measured along the Lake St. Clair transects on 13 September (Figure 48). On this date concentrations of *E. coli* were below the detection limit everywhere except in two locations along the transect just west of the Clinton River cutoff. The *E. coli* concentrations in these locations were 20 to 40 CFU/100 mL. No other locations had *E. coli* concentrations above the detection limit.

Water Residence Time Along the Metro Beach

On 5 August, dye streaks were deployed directly along the shoreline area just to the east of the beach to observe dissipation. Sampling station locations are shown in Figure 49. During the late morning and early afternoon of 5 August, winds were blowing from the east at ~ 8 mph (range=5.9 - 10.4 mph). Concentrations of dye in the middle of the transect were ~ 500 ug/L shortly after injection. The dye cloud dissipated very rapidly, as concentrations declined to near zero about 3 hours after injection (Figure 50), suggesting substantial water exchange. The dye cloud traveled rapidly along a westerly trajectory through the beach area and toward the Clinton River cutoff during the afternoon of 5 August.

Bacterial concentrations on 5 August generally decreased from west to east and outwards from the shore (Figure 51). The highest *E. coli* concentrations were observed 200 to 400 m east and slightly offshore 100 m east of the western end of the beach. In these locations, bacterial counts exceeded 2500 CFU/100 mL (Table 3). Samples collected at the two locations nearest to shore on each transect exceeded the single-sample threshold of 300 CFU/100 mL for body contact recreation (e.g., swimming) in nearly every location, and many samples exceeded 1000 CFU/100 mL.

On 25 August, a dye cloud was injected along the shoreline east of the beach area at ~ 1230 hours (Figure 52). Average wind speeds during the afternoon were ~ 6 mph (range = 3.6 - 9.6 mph) from the west. Dissipation again occurred very rapidly as dye concentrations in the middle of the transect became diluted within an hour of initial injection (Figure 53). The dye cloud moved toward the peninsula located to the east of the beach area on this date.

Bacterial concentrations on 25 August generally decreased from east to west and outwards from the shore (Figure 54). The highest *E. coli* concentrations were observed near the shore at the east end of the beach. In these locations, bacterial counts exceeded 5000 CFU/100 mL (Table 3). Some of the samples collected along the two westernmost transects were below the single-sample threshold of 300 CFU/100 mL for body contact recreation (e.g., swimming), but

Table 3
Bacterial Concentrations Measured in the Beach Area

Location	*E. coli* CFU/100 mL	
	5-Aug	**25-Aug**
C0-1	1440	20
C0-2	1770	30
C0-3	1890	10
C0-4	1220	10
C1-1	1800	260
C1-2	7100	430
C1-3	1400	250
C1-4	1800	100
C2-1	4700	600
C2-2	2100	1200
C2-3	3000	580
C2-4	1300	330
C3-1	2600	800
C3-2	2300	540
C3-3	1800	550
C3-4	900	800
C4-1	4700	1200
C4-2	1000	300
C4-3	1900	480
C4-4	700	390
C5-1	1800	2700
C5-2	1400	600
C5-3	500	1500
C5-4	50	900
C6-1	200	3500
C6-2	700	3600
C6-3	400	2400
C6-4	<10	2700
C7-1	850	8000
C7-2	770	6000
C7-3	700	3500
C7-4	<10	3200
C8-1	470	6500
C8-2	300	7000
C8-3	120	3200
C8-4	10	2300

all samples from the other transects exceeded 300 CFU/100 mL. Many samples had *E. coli* concentrations above 1000 CFU/100 mL.

On 11 September, winds were blowing steadily from the west during the dye dissipation study conducted along the beach shoreline area. Dye was injected along the shoreline at ~ 1000 hours on this date. As with other dissipation studies, the dye cloud rapidly dissipated, as concentrations in the middle of the dye cloud declined to near zero ug/L within 1.5 hours (Figures 55 and 56).

Bacterial samples were not collected in conjunction with the 11 September dye dissipation study.

4 Discussion

Based on the dye tracer studies conducted in 1998, water currents in the part of Lake St. Clair between Metro Beach and the Clinton River cutoff were predominantly driven by wind direction and speed. Winds blowing out of the north and northwest resulted in water movement toward the south, away from the beach. Easterly and southeasterly winds caused water circulation in a westerly direction, from the beach toward the Clinton River cutoff. Winds blowing out of the west and southwest resulted in water circulation that followed an easterly trajectory toward the beach area. During the summer of 1998, winds blew out of the westerly wind rose (i.e., NW and SW wind rose) 62% of the time; thus water movement from the mouth of the cutoff toward Metro Beach would have been expected to dominate circulation patterns from April until September.

Wind patterns observed in the summer of 1998 were typical of those reported for this area. Based on analysis of long-term wind data collected at Selfridge Air National Guard Base, located 10 miles north of the Metro Beach area, Fox (1998) reported that winds generally blew out of the SSW during the summer. During the summer of 1998, average wind direction was out of the SW. Monthly wind speeds during May through August 1998 ranged from 6.4 to 7.5 mph, slightly lower than the long-term average of 8.7 to 11.5 mph (Fox 1998).

One possible source of fecal coliform contamination in the Metro Beach area was contaminated Clinton River water from the cutoff, transported to the beach by water currents circulating from the cutoff toward the beach due to winds blowing out of the westerly wind rose. In order for this mechanism to operate, three conditions must be met: (1) the Clinton River cutoff must carry water with a high concentration of bacteria, (2) the flow of contaminated water from the Clinton River cutoff must be sufficient to produce a mass of contaminated water in the lake, and (3) water circulation must move the contaminated water mass from the cutoff to the beach rapidly enough so that the bacteria remain viable.

These conditions were rarely met during the summer of 1998. Bacterial concentrations in the vicinity of the cutoff were relatively low on all sampling dates. No significant plumes of bacterially contaminated water were observed in the vicinity of the cutoff or moving from the cutoff toward Metro Beach. Mean summer flow from the Clinton River in 1998 was slightly below the average determined over a 50-year period, and there were several relatively long periods of low flow (i.e., 2- to 3-week periods) in July, August, and September. Concentrations of *E. coli* measured in the cutoff by the Macomb County Health Department were also relatively low (Figure 57). The *E. coli* count exceeded 1000 CFU/100 mL on 9 and 10 March, 6 and 10 August, and 8 September. Counts exceeded 2500 CFU/100 mL only on 6 and 10 August.

Observed water movement from the Clinton River cutoff toward the beach area was rapid under westerly wind conditions, as illustrated for conditions on 11-13 September 1998 (see Figures 38-42), when water movement was traced from the mouth of the Clinton River cutoff to the Metro Beach area over a two-day period. Through a comparison of the daily wind rose with periods of elevated flow from the Clinton River and *E. coli* counts above 1000 CFU/ 100 mL in the cutoff, elevated flow and bacterial counts were found to coincide with winds blowing from the NW or SW only between 6 and 8 August. Thus, if the Clinton River cutoff were a substantial source of bacteria contamination in the beach area, a pulse of high bacterial concentration to within a day or two of the above dates would have been likely. In fact, bacterial counts measured at the beach by the Macomb County Health Department during this period were lower than in the weeks before or after this storm (Figure 58).

Despite low flows from the Clinton River cutoff and low bacterial concentrations in the area between the cutoff and Metro Beach, *E. coli* concentrations were often elevated in the immediate vicinity of the beach. Bacterial concentrations along the beach transects were consistently highest close to shore, suggesting that bacteria were entering the lake from the beach. Bacterial concentration patterns observed near the beach during dye studies indicated relatively low bacterial concentrations in the water on the upstream end of the beach, and higher concentrations toward the downstream end of the beach. This pattern suggests that relatively clean water from the lake was becoming contaminated as it passed by the beach.

Relatively high levels of bacterial contamination in the beach area were attained despite the brief residence time of water in the area, indicating that the beach must be a substantial source of bacteria. Water ponded on the beach after rainstorms contained extremely high concentrations of *E. coli* (Aquest Corporation, Flint, Michigan, unpublished data), indicating that the beach itself is highly contaminated with *E. coli*. The source of bacteria contaminating the beach was not positively identified, but large numbers of gulls and geese congregate on the beach at night, and their droppings are the most likely source.

Although the frequency of beach closings due to elevated bacterial counts became a major concern in 1994 when abundant submersed plant growth was also a problem, there is little reason to believe that submersed plant growth is currently an important factor contributing to elevated bacterial counts at Metro Beach. In 1994, large amounts of plant material accumulated in the Metro Beach area to the extent that plant biomass may have severely impeded water circulation. Submersed plant growth may also have impacted water circulation in 1995, when Eurasian watermilfoil (*Myriophyllum spicatum*) growth on the sandbar offshore from Metro Beach nearly reached the surface. In 1998, although submersed plants were abundant throughout much of the area off Metro Beach, most of the plant growth consisted of low-growing species such as wild celery (*Vallisneria americana*). Even on the offshore sandbar, little of the plant biomass extended into the upper 3 ft of the water column. Thus the impact of submersed plant growth on water circulation was probably minimal.

Below-average precipitation and extended dry periods in 1998 represent conditions that were less favorable for loading of fecal coliform bacteria via the Clinton River cutoff than in years such as 1994, when fecal coliform bacterial contamination was prevalent. During conditions leading to more frequent CSO overflows and greater flow from the Clinton River cutoff, the contribution of bacteria from the cutoff to problems at Metro Beach might be considerably greater than in 1998.

5 Conclusions

The results of this study provide very strong evidence that bacterial contamination of the beach at Metro Beach is an important source of bacterial contamination in the swimming area. During the summer of 1998, *E. coli* contamination was frequent in the beach area, despite few occasions conducive to the transport of bacteria from the Clinton River. No plumes of contaminated water were observed between the cutoff and the beach, yet *E. coli* concentrations in the Metro Beach swimming area frequently exceeded state standards for full-body contact recreation. Bacterial concentrations in the beach area were consistently highest near the shore and increased as water moved alongshore past the beach, suggesting that the beach itself is a major source of bacterial contamination. Extremely high counts of *E. coli* in water ponded on the beach following rainstorms suggest that the beach sand is highly contaminated, probably due to droppings from gulls and geese that congregate on the beach. High bacterial counts in the beach area occurred despite a relatively short water residence time in the area, thus contamination problems are more the result of high levels of contamination on the beach than inadequate water movement in the area.

During periods of sustained winds coming from the westerly wind rose (NW, W, and SW), water movement from the cutoff toward the beach was relatively rapid; thus contaminated water could potentially be transported from the cutoff to the beach rapidly enough to result in contamination of the beach. In a year when CSO overflows occur more frequently, the Clinton River cutoff could be a more important source of bacterial contamination in the beach area than it was in 1998. Measurements of water movements and bacterial distribution patterns during a year with more frequent CSO overflows will be necessary to determine whether transport of contaminated water from the cutoff actually results in significant contamination of the beach.

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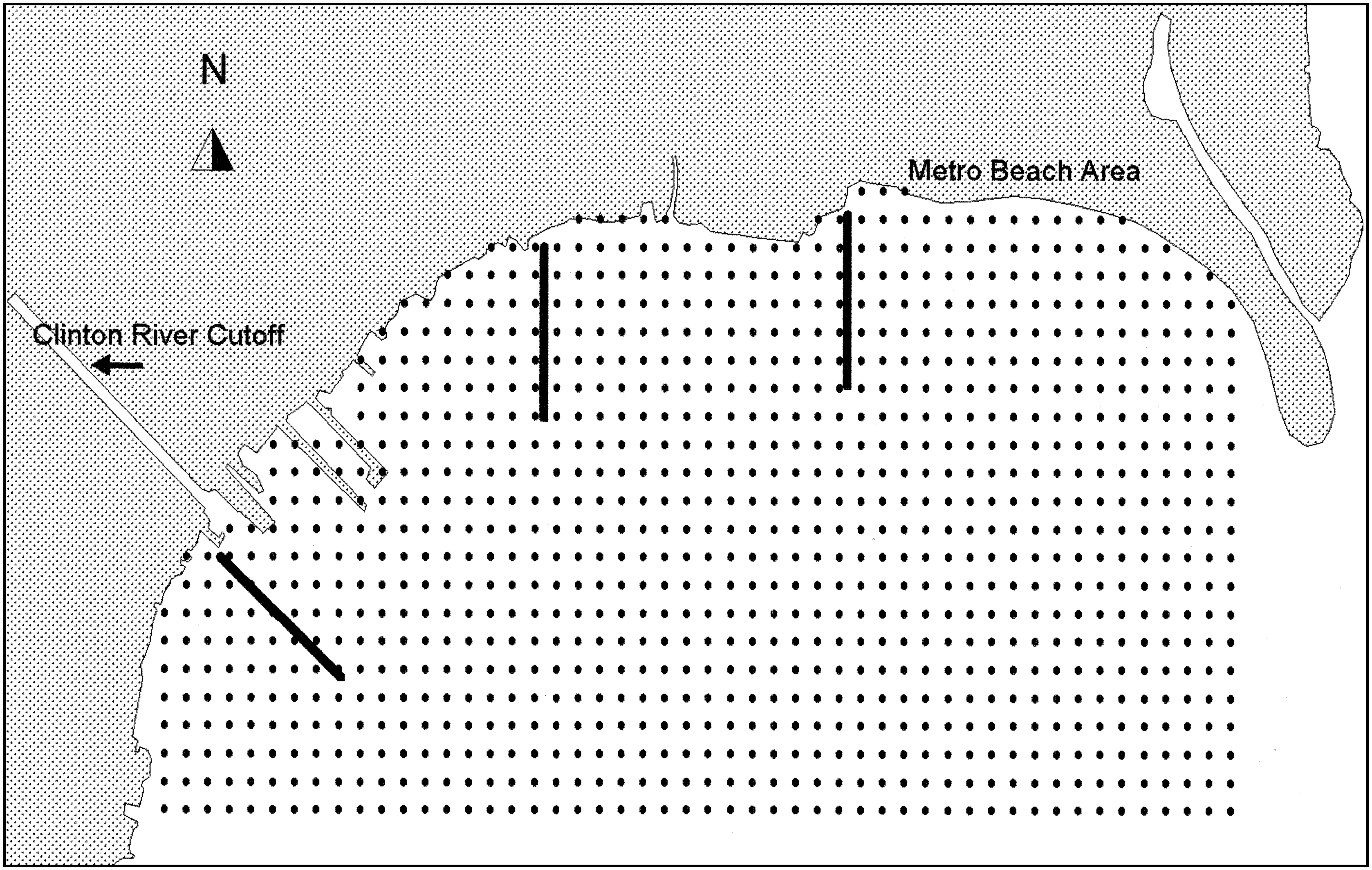

Figure 1. Dye injection transect locations in the Clinton River cutoff-Metro Beach area

Figure 2. Sampling station locations for dye cloud characterization at 1700 hours, 25 August 1998

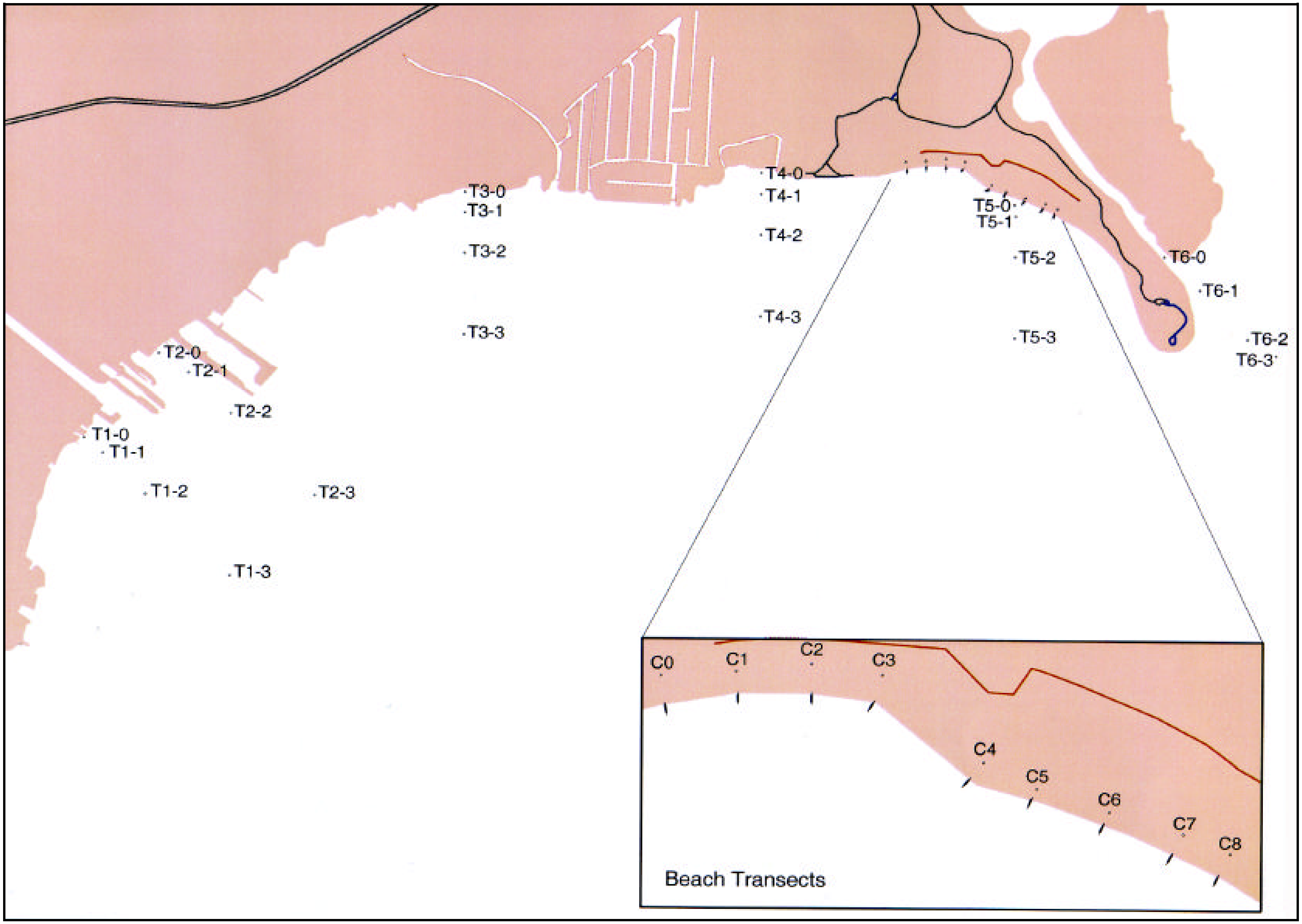

Figure 3. 1998 bacterial sampling locations

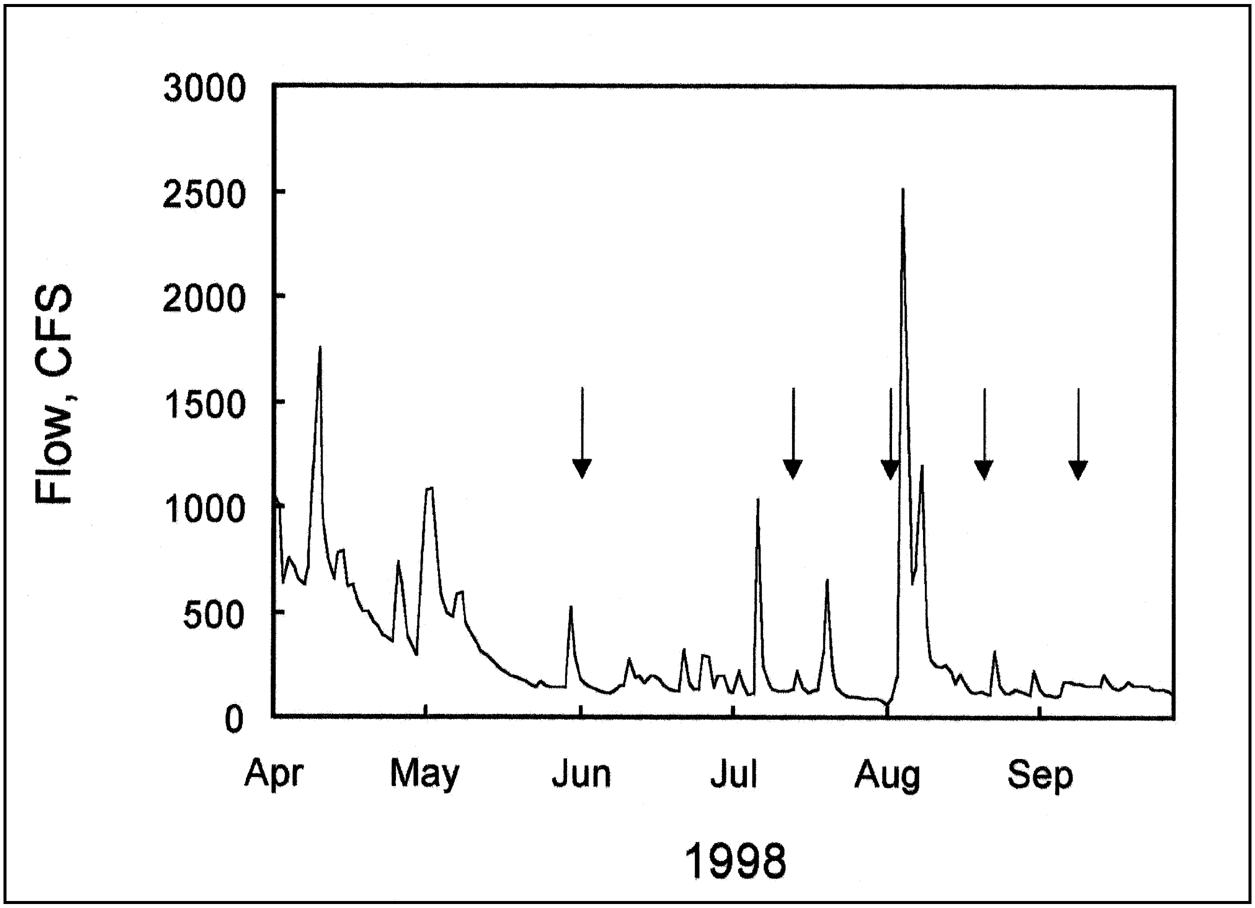

Figure 4. Mean daily flow for the Clinton River near Fraser, MI, for the summer period, 1998. Arrows denote study periods for examination of water movement near the Clinton River cutoff-Metro Beach area of Lake St. Clair

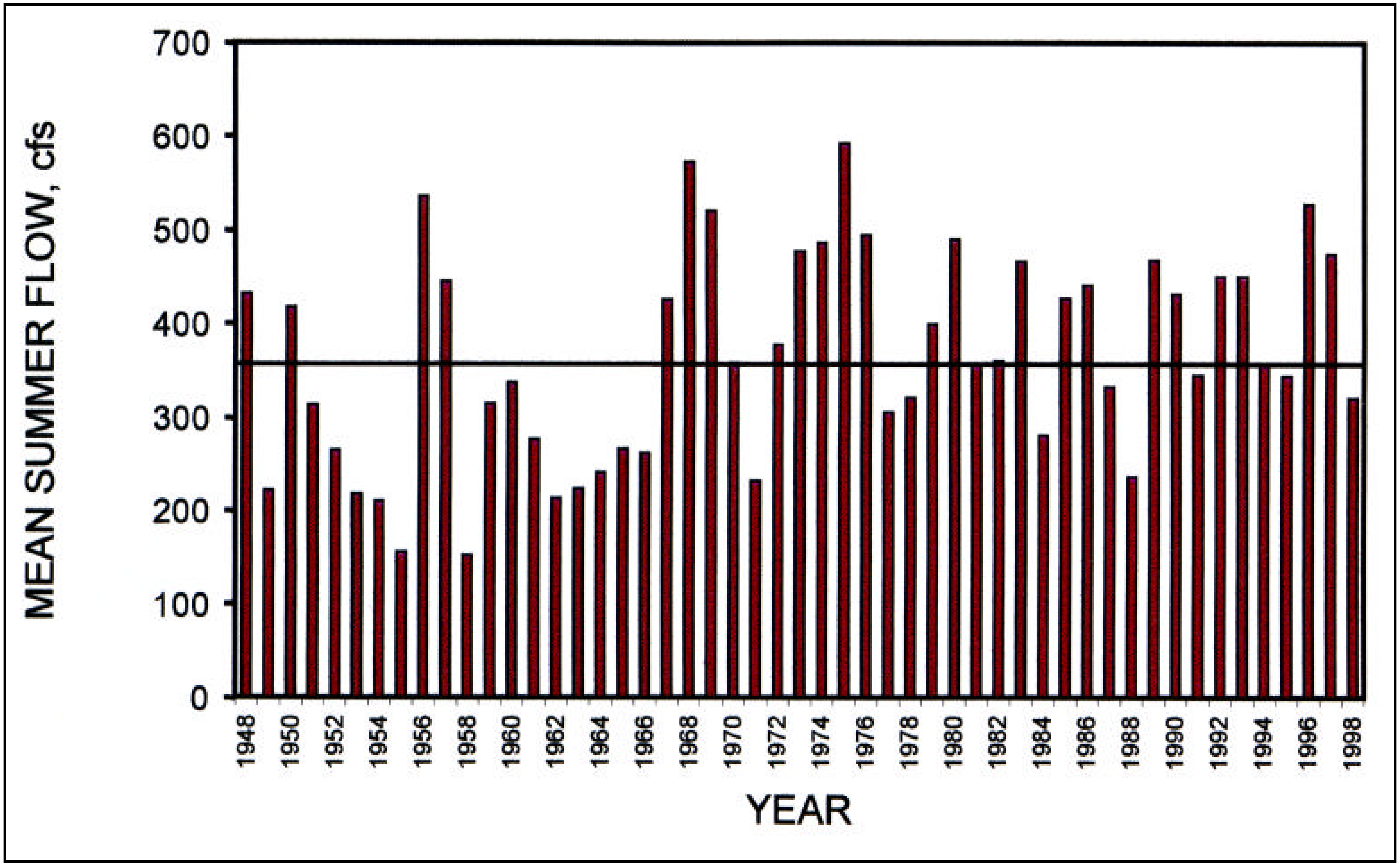

Figure 5. Mean summer (April-September) flow for the Clinton River near Fraser, MI, between 1948 and 1998. Horizontal line represents the average flow over the summer for the 50-year period

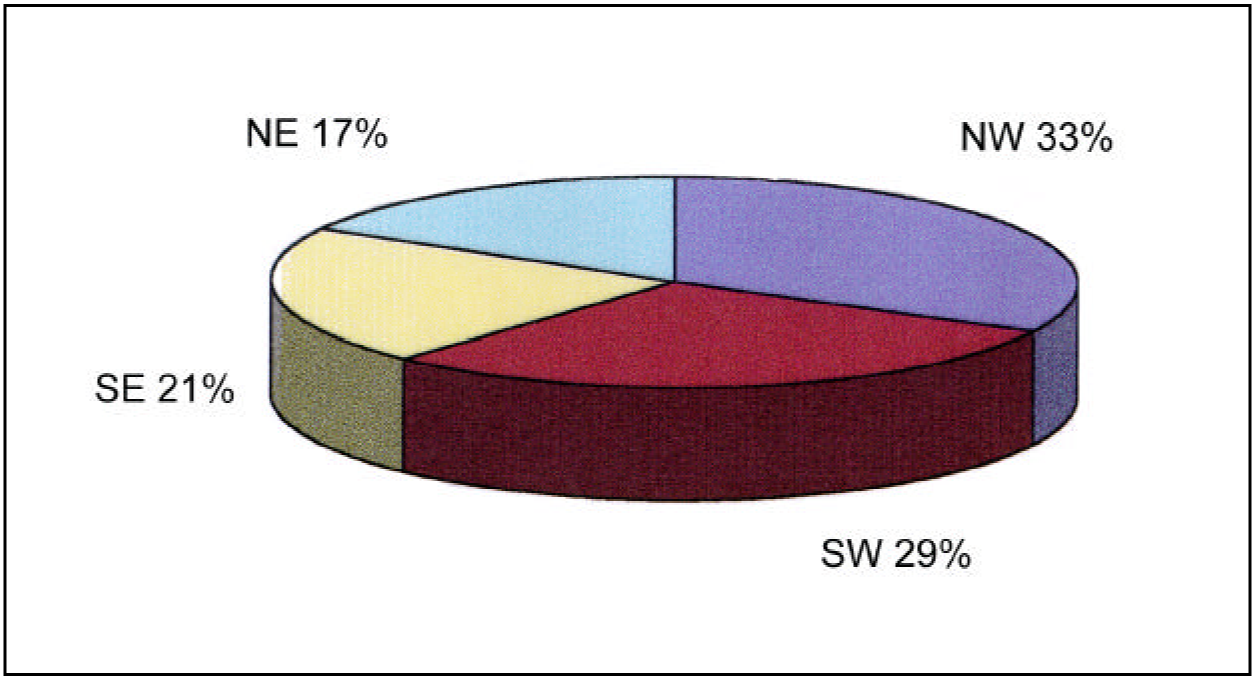

Figure 6. Wind direction relative percent during the summer of 1998

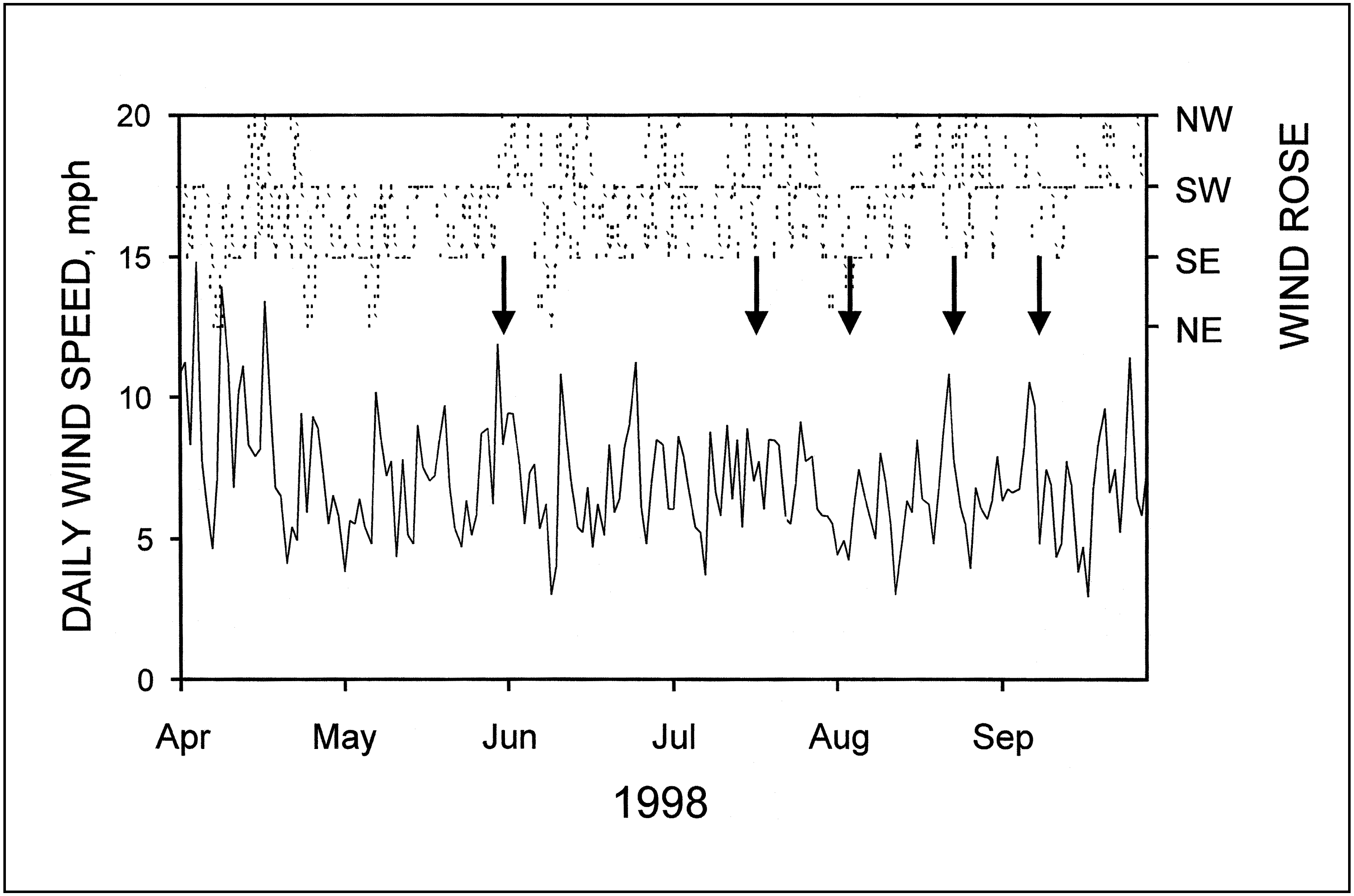

Figure 7. Variations in mean daily wind speed (solid line) and mean daily wind rose (dashed line) during the summer of 1998. Arrows denote study periods for examination of water movement near Clinton River cutoff-Metro Beach area of Lake St. Clair

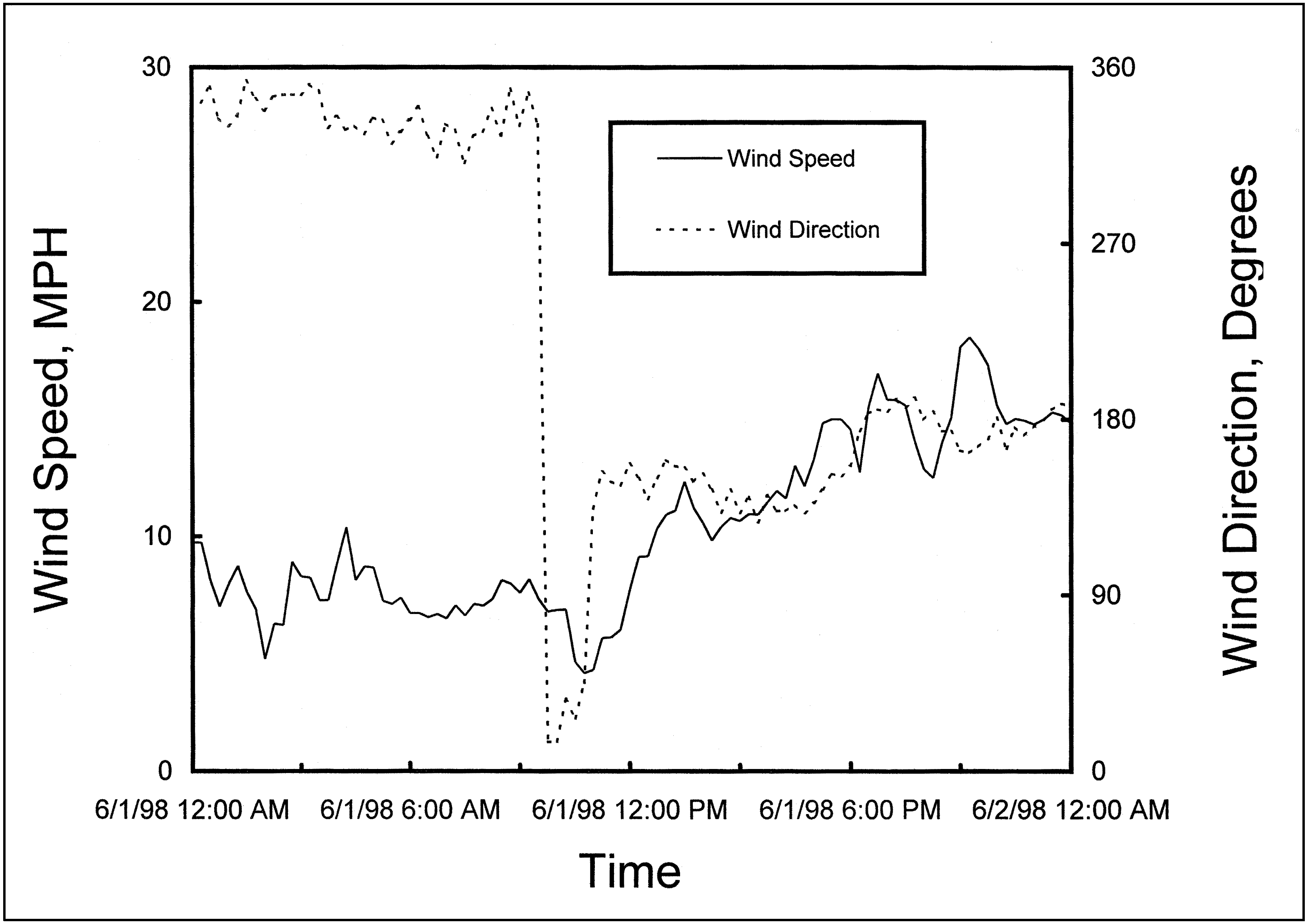

Figure 8. Variations in wind speed and wind direction at the Metro Beach area between 1 and 2 June 1998

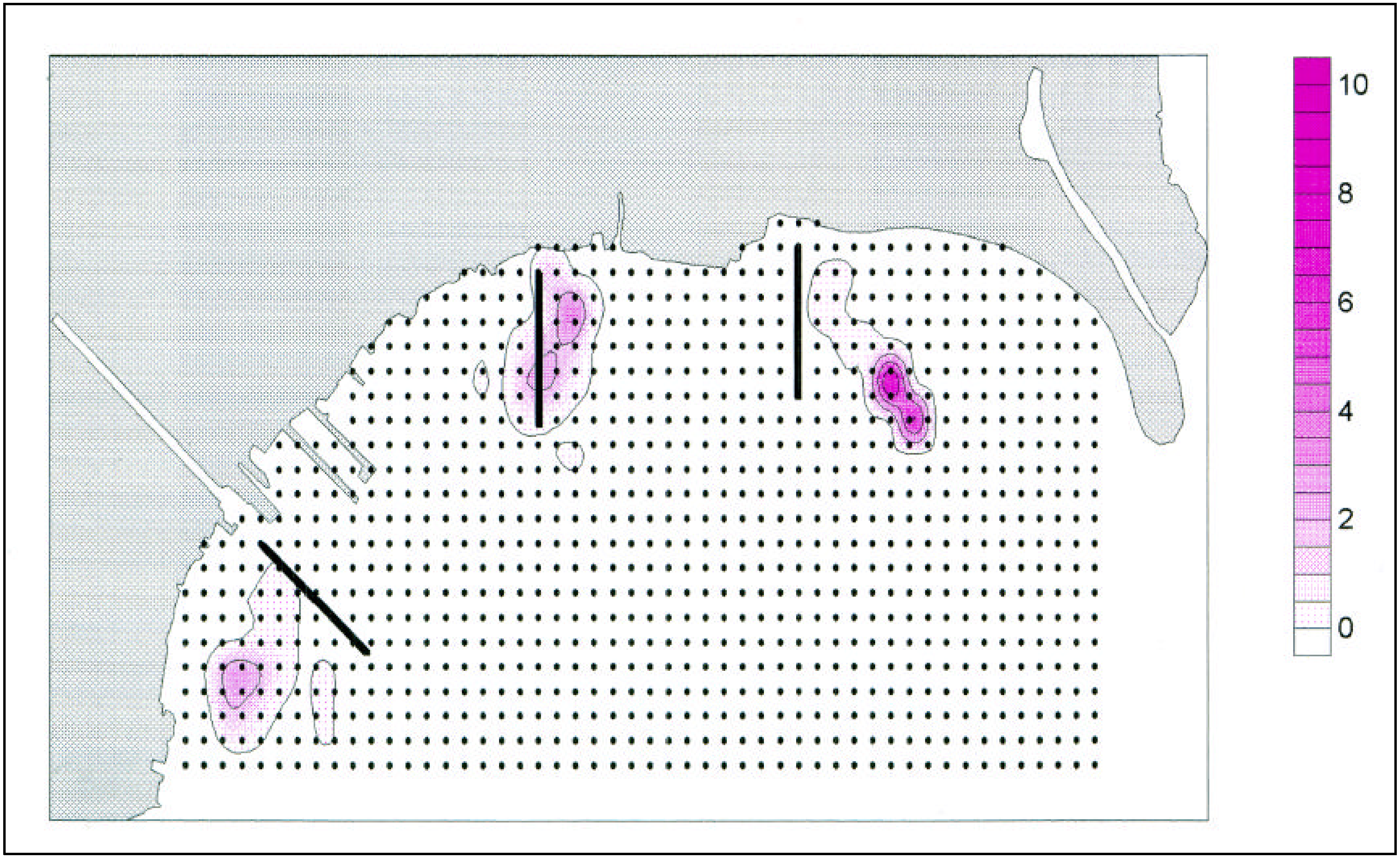

Figure 9. Position of the dye clouds at 1300 hours on 1 June 1998. Dye was injected along transects (represented by solid lines) between 0700 and 0800 hours on 1 June. Grid points (solid dots) are positioned at 100-m intervals for reference

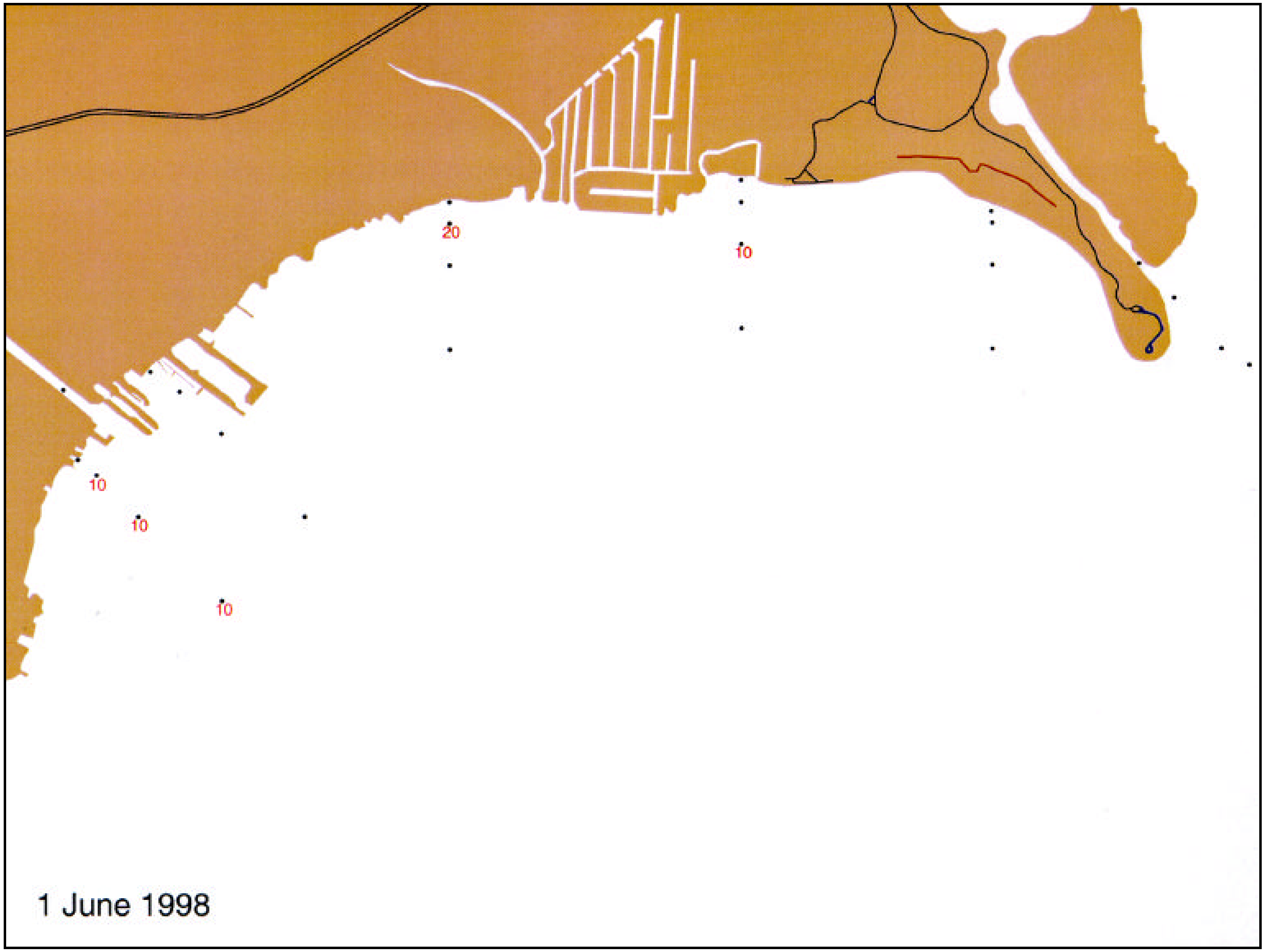

Figure 10. Concentrations of fecal indicator bacteria measured on 1 June 1998. Numbers indicate *E. coli* counts at the adjacent sampling point. Unlabeled sampling points had *E. coli* concentrations below the detection limits

Figure 11. Concentrations of fecal indicator bacteria measured on 30 June 1998. Numbers indicate *E. coli* counts at the adjacent sampling point. Unlabeled sampling points had *E. coli* concentrations below the detection limit

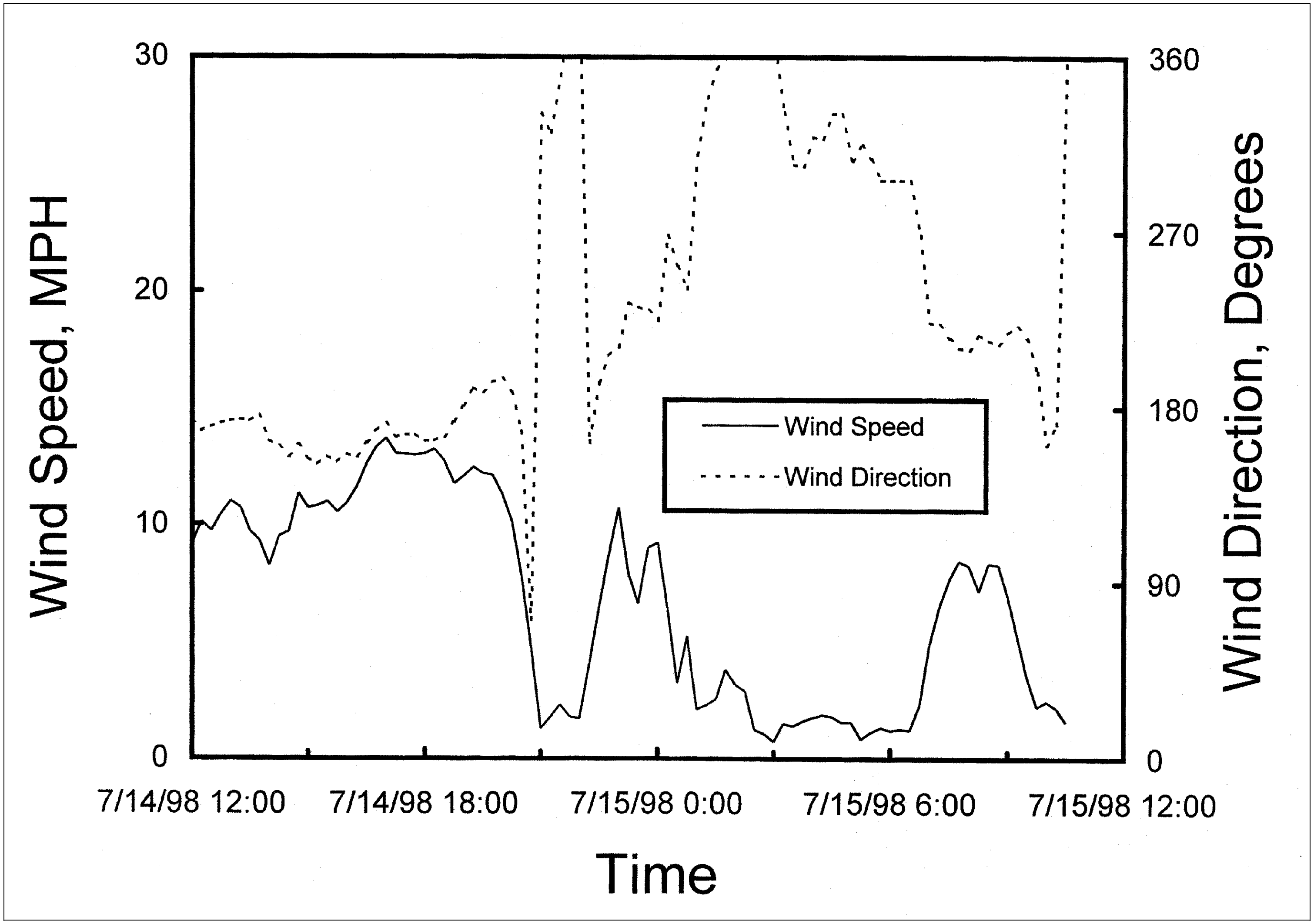

Figure 12. Variations in wind speed and wind direction at the Metro Beach area beach between 14 and 15 July 1998

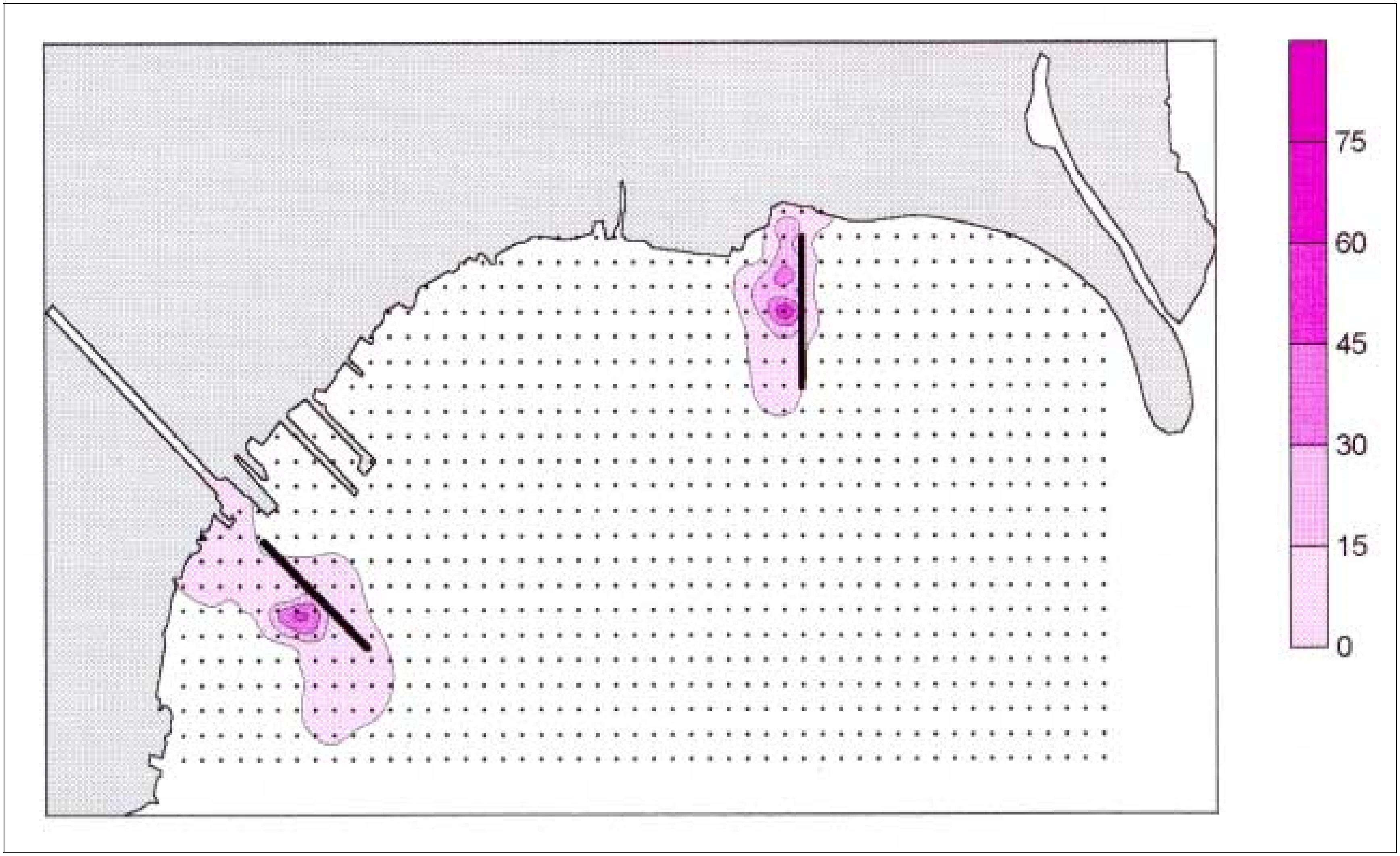

Figure 13. Position of the dye clouds at 1300 hours on 14 July 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 14 July. Grid points (solid dots) are positioned at 100-m intervals for reference

Figure 14. Position of the dye clouds at 1500 hours on 14 July 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 14 July. Grid points (solid dots) are positioned at 100-m intervals for reference

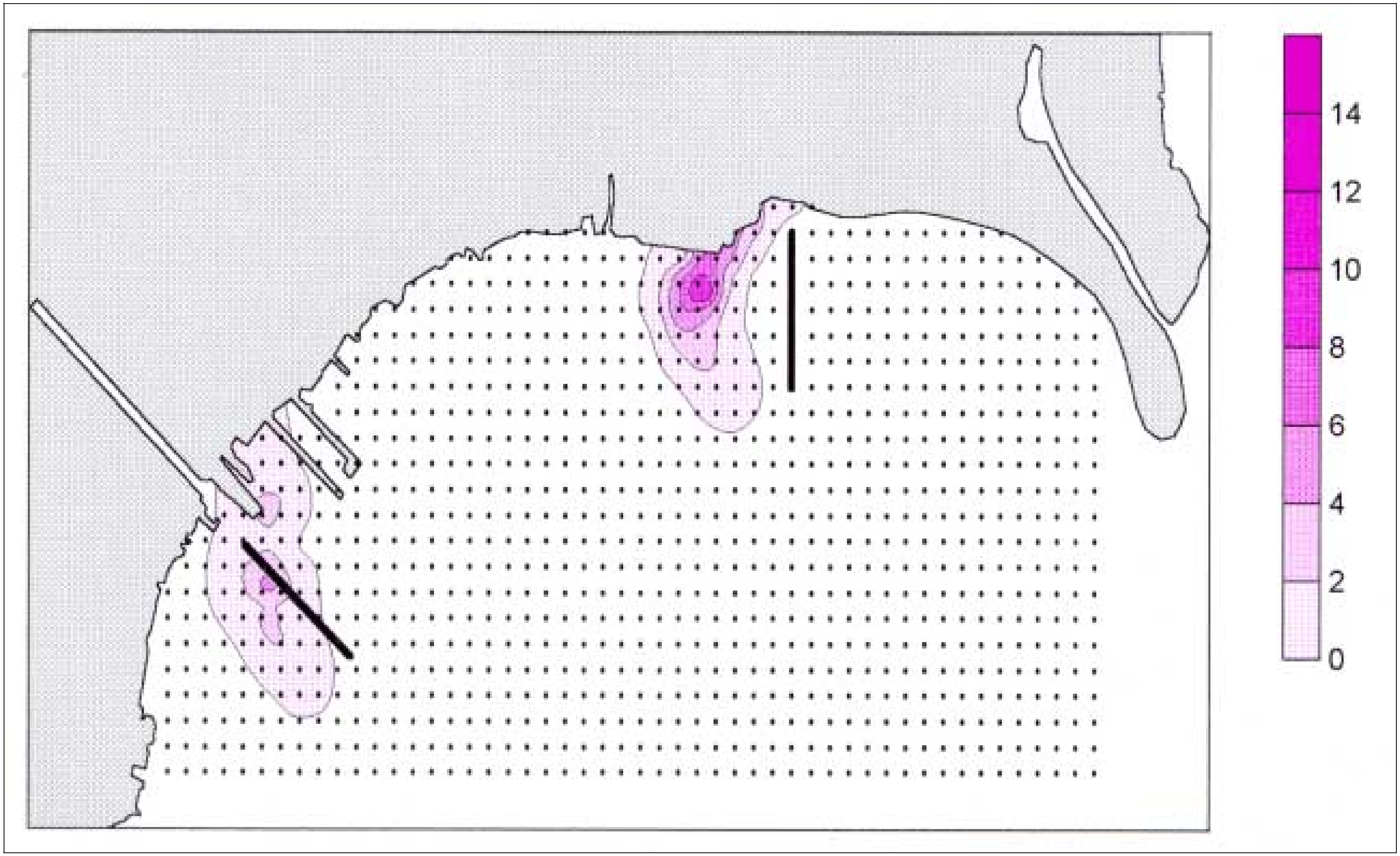

Figure 15. Position of the dye clouds at 1700 hours on 14 July 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 14 July. Grid points (solid dots) are positioned at 100-m intervals for reference

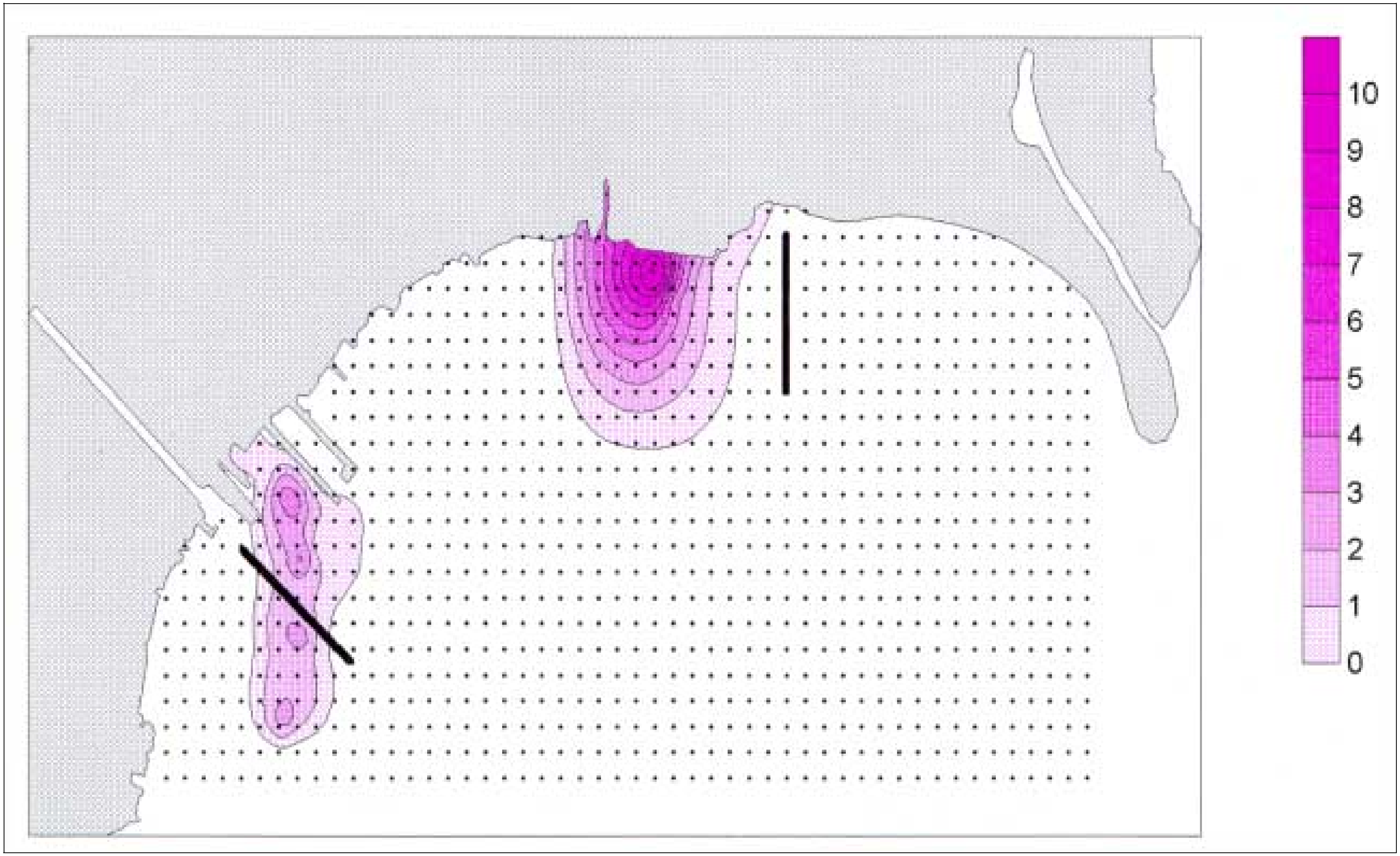

Figure 16. Position of the dye clouds at 1900 hours on 14 July 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 14 July. Grid points (solid dots) are positioned at 100-m intervals for reference

Figure 17. Position of the dye clouds at 1000 hours on 15 July 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 14 July. Grid points (solid dots) are positioned at 100-m intervals for reference

Figure 18. Concentrations of fecal indicator bacteria measured on 14 July 1998. Numbers indicate *E. coli* counts at the adjacent sampling point. Unlabeled sampling points had *E. coli* concentrations below the detection limit

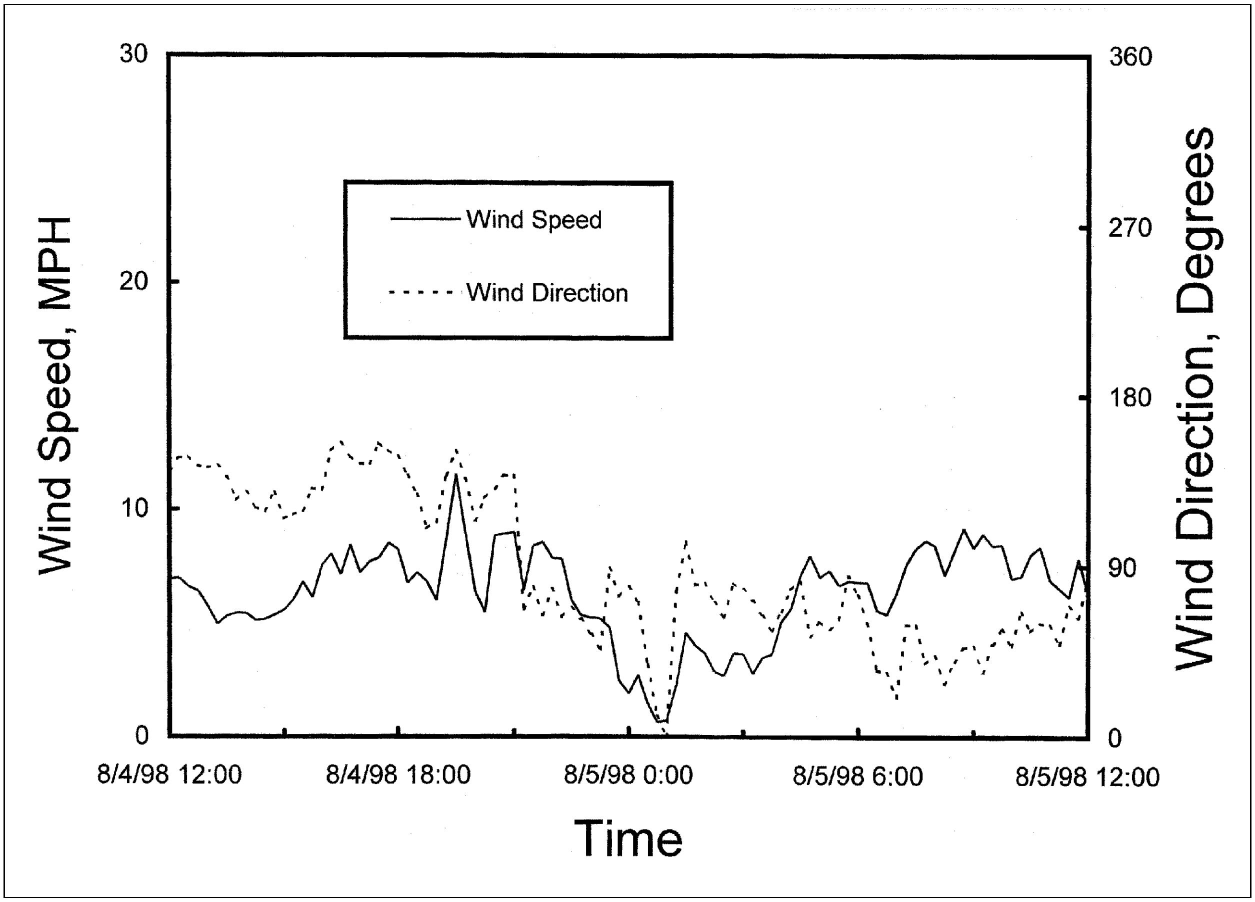

Figure 19. Variations in wind speed and wind direction at the Metro Beach area beach between 4 and 5 August 1998

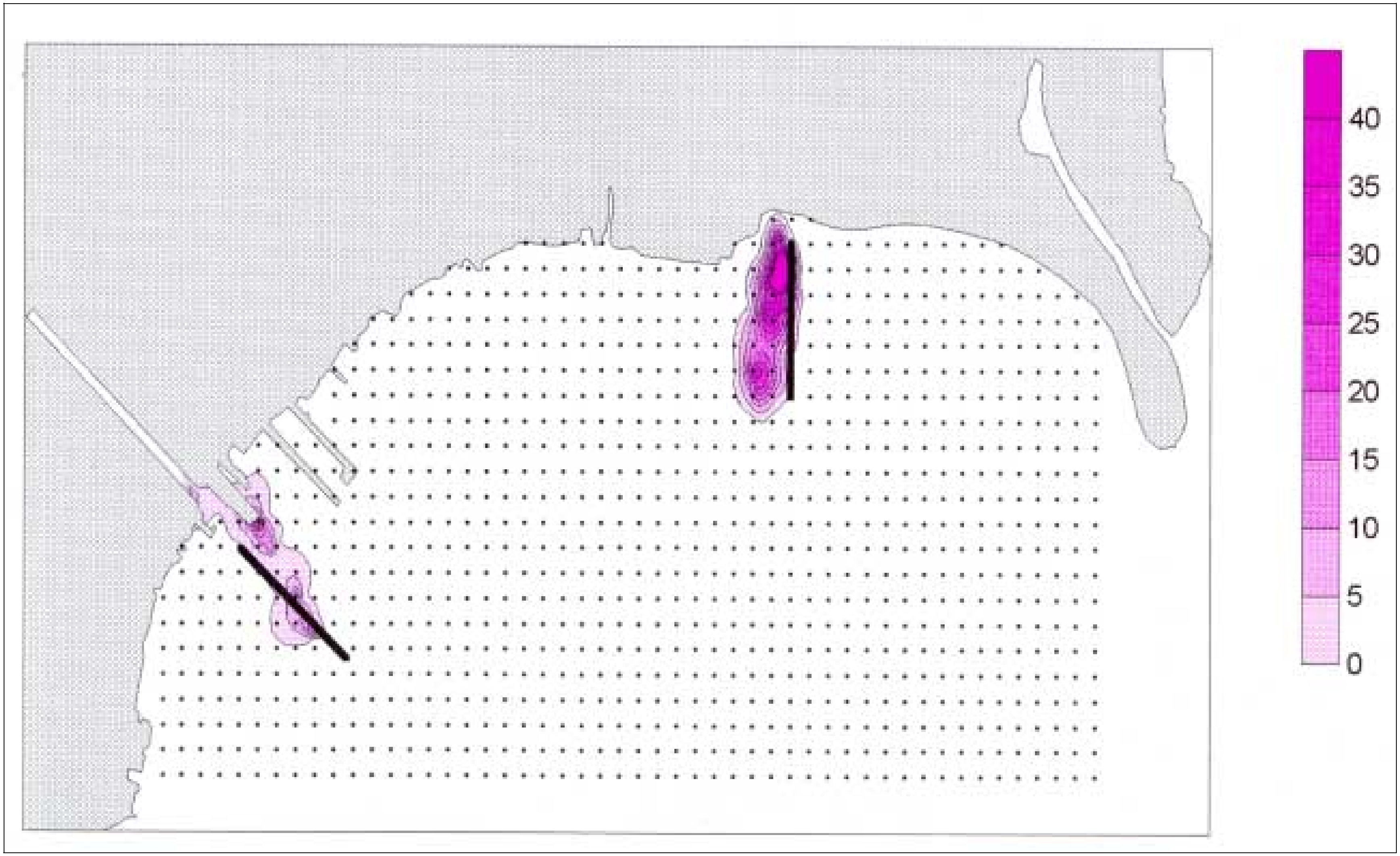

Figure 20. Position of the dye clouds at 1300 hours on 4 August 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 4 August. Grid points (solid dots) are positioned at 100-m intervals for reference

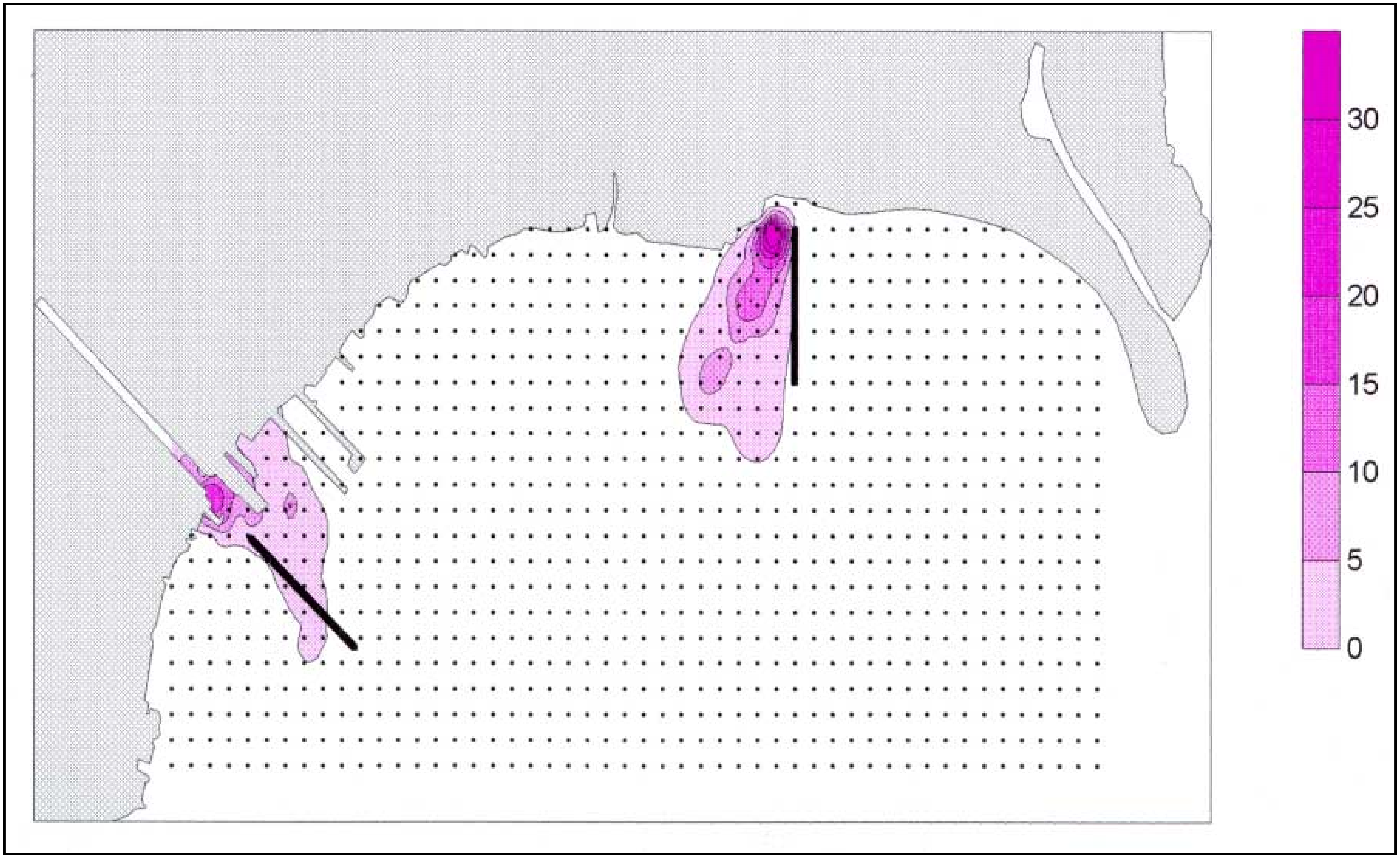

Figure 21. Position of the dye clouds at 1500 hours on 4 August 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 4 August. Grid points (solid dots) are positioned at 100-m intervals for reference

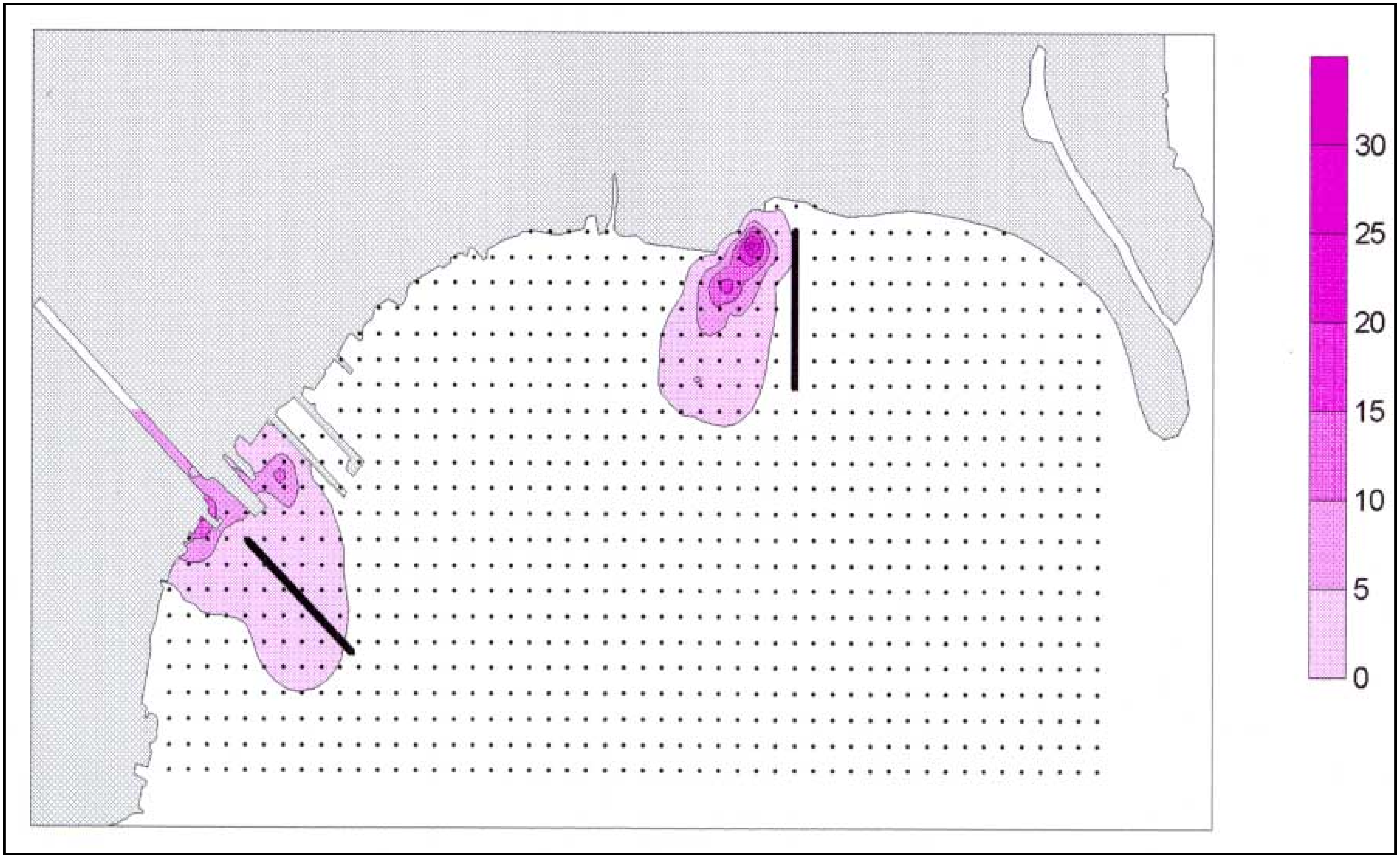

Figure 22. Position of the dye clouds at 1700 hours on 4 August 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 4 August. Grid points (solid dots) are positioned at 100-m intervals for reference

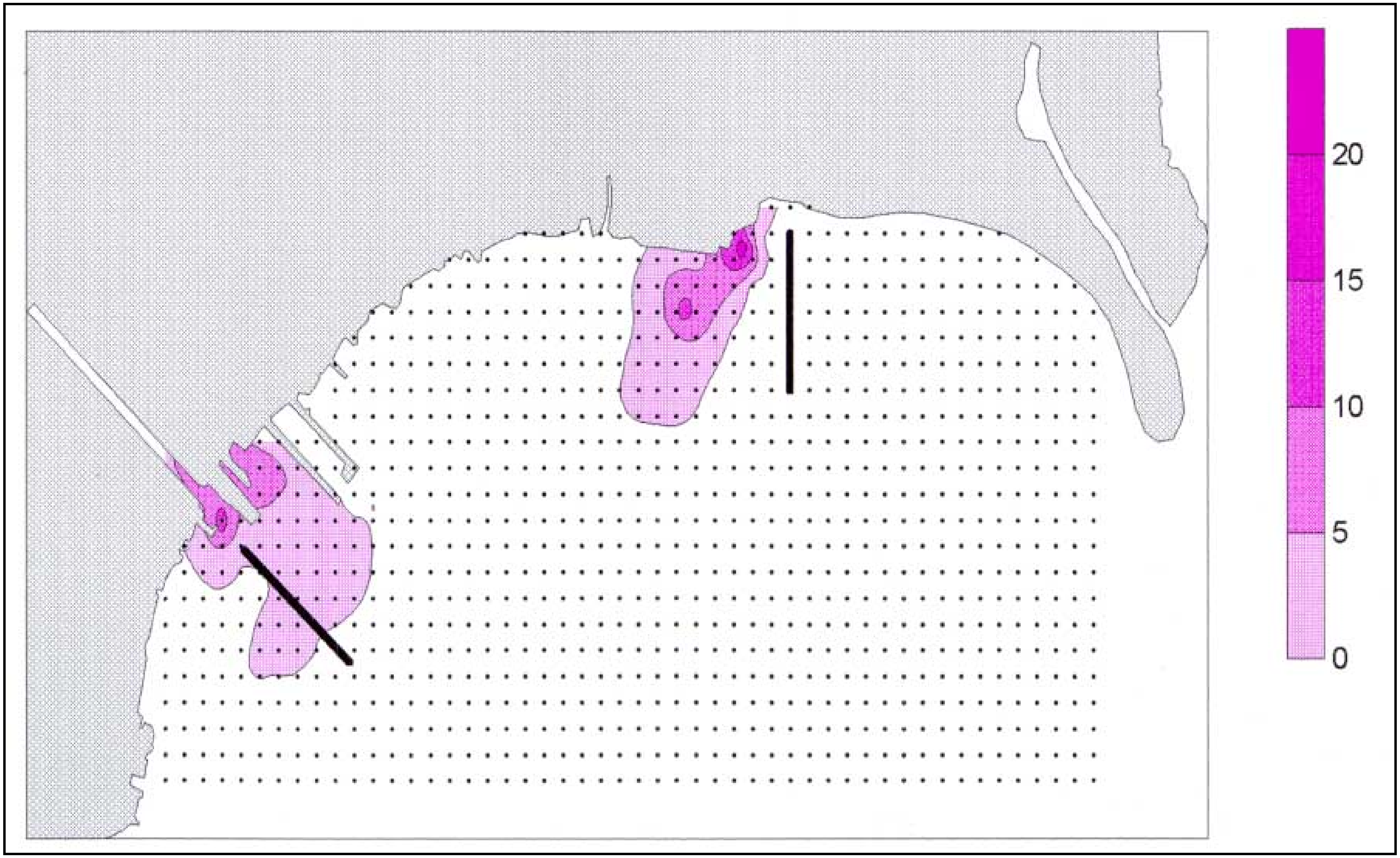

Figure 23. Position of the dye clouds at 1900 hours on 4 August 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 4 August. Grid points (solid dots) are positioned at 100-m intervals for reference

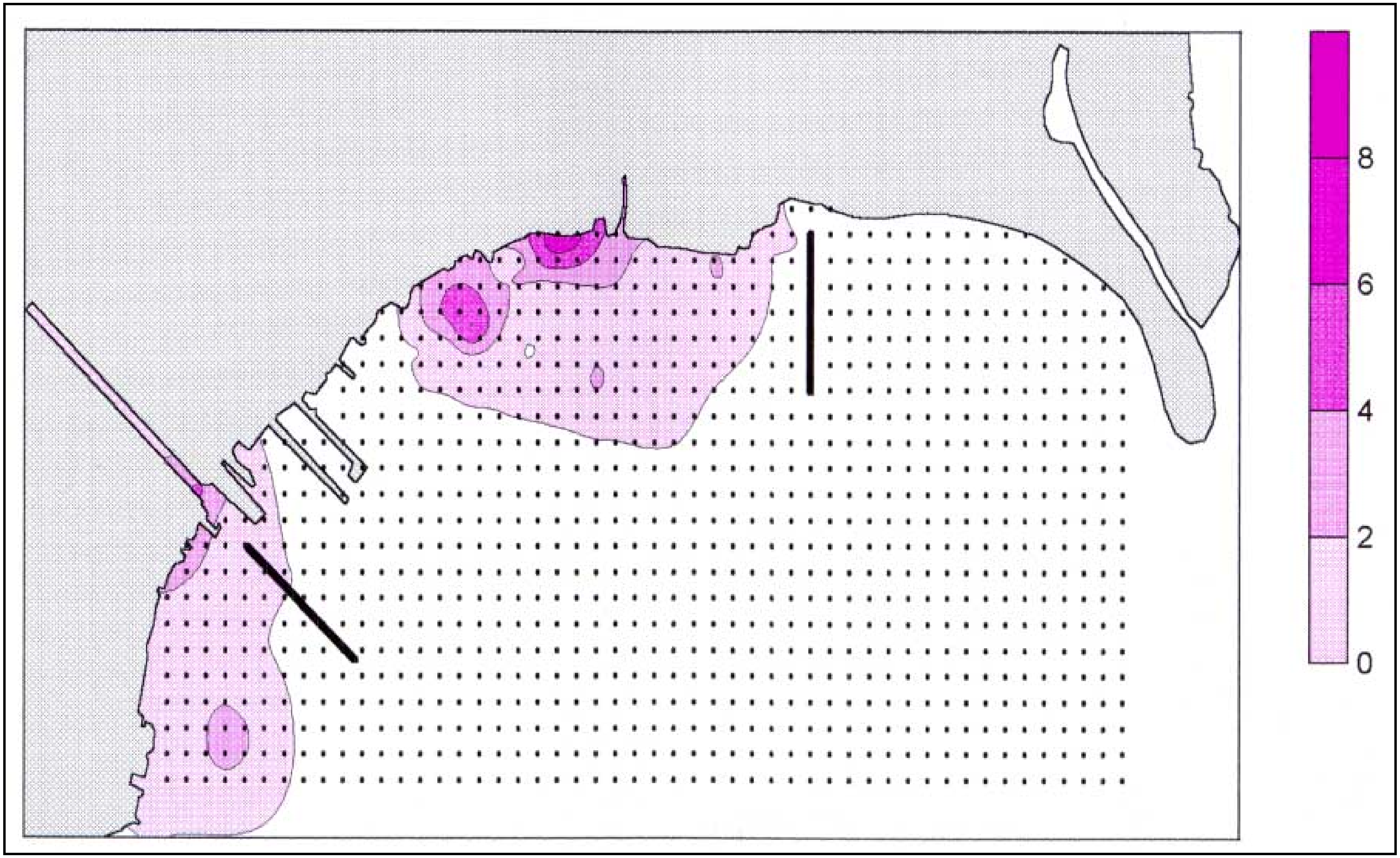

Figure 24. Position of the dye clouds at 1030 hours on 5 August 1998. Dye was injected along transects (represented by solid lines) between 1130 and 1300 hours on 4 August. Grid points (solid dots) are positioned at 100-m intervals for reference

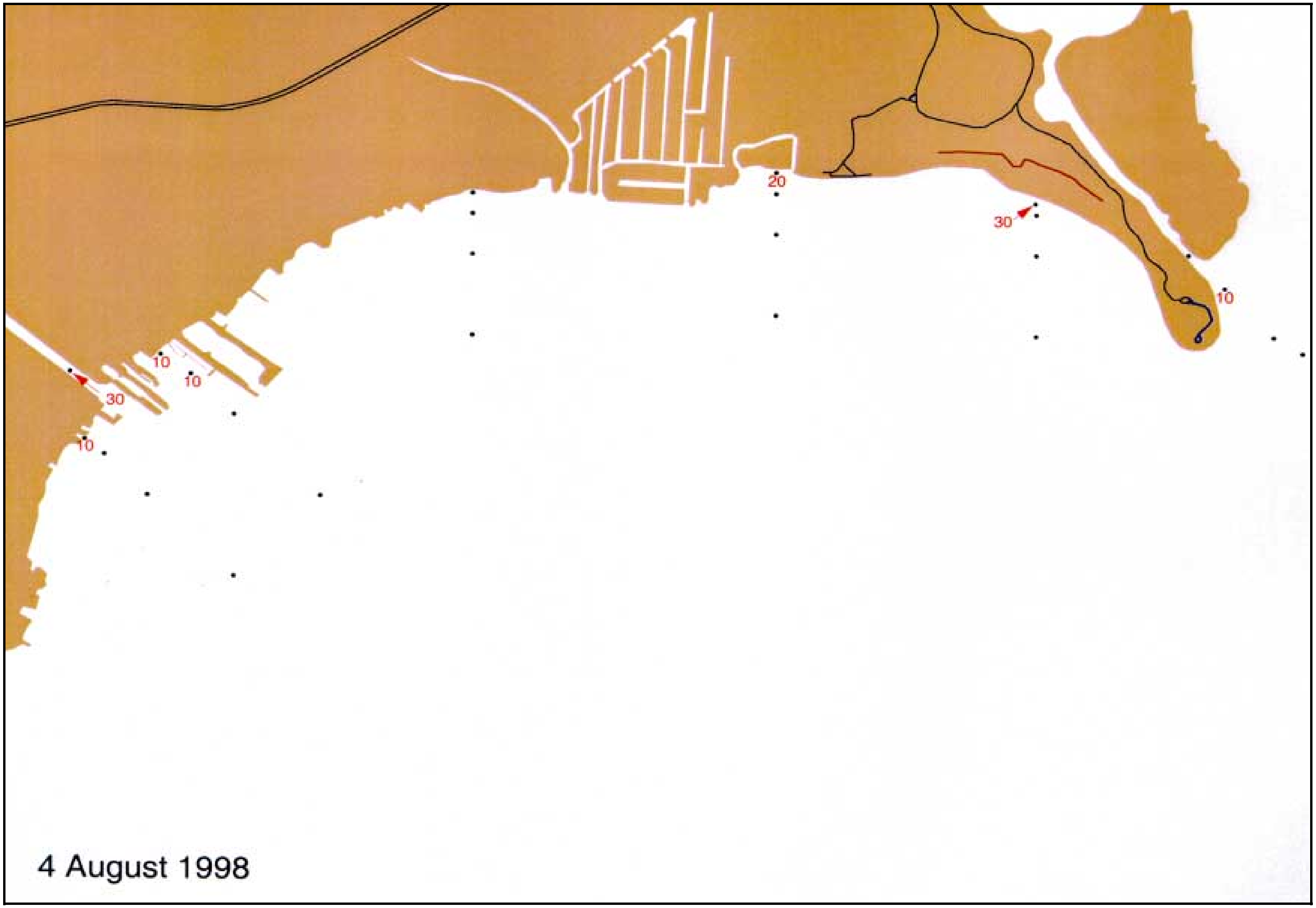

Figure 25. Concentrations of fecal indicator bacteria measured on 4 August 1998. Numbers indicate *E. coli* counts at the adjacent sampling point. Unlabeled sampling points had *E. coli* concentrations below the detection limit

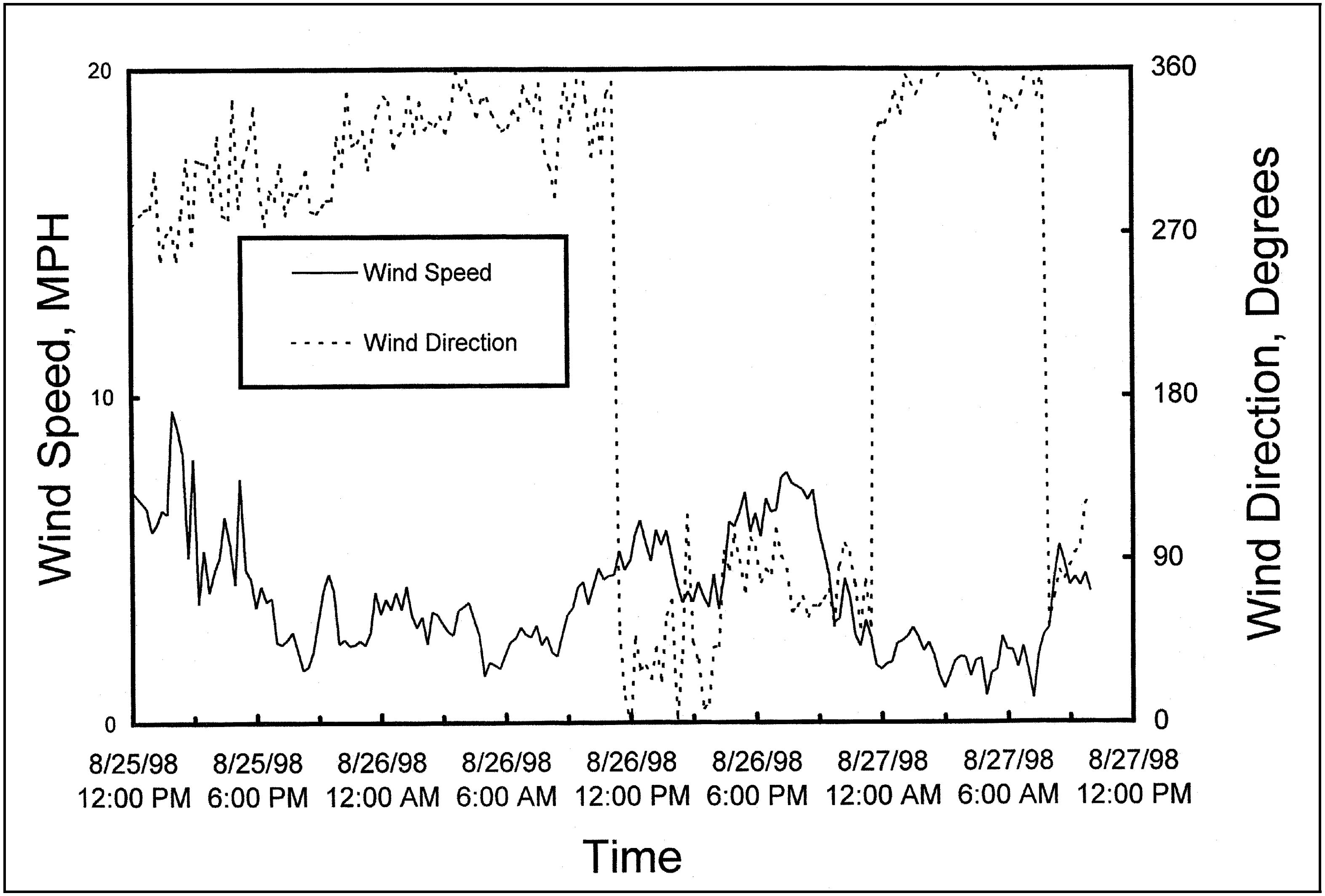

Figure 26. Variations in wind speed and wind direction at the Metro Beach area beach between 25 and 27 August 1998

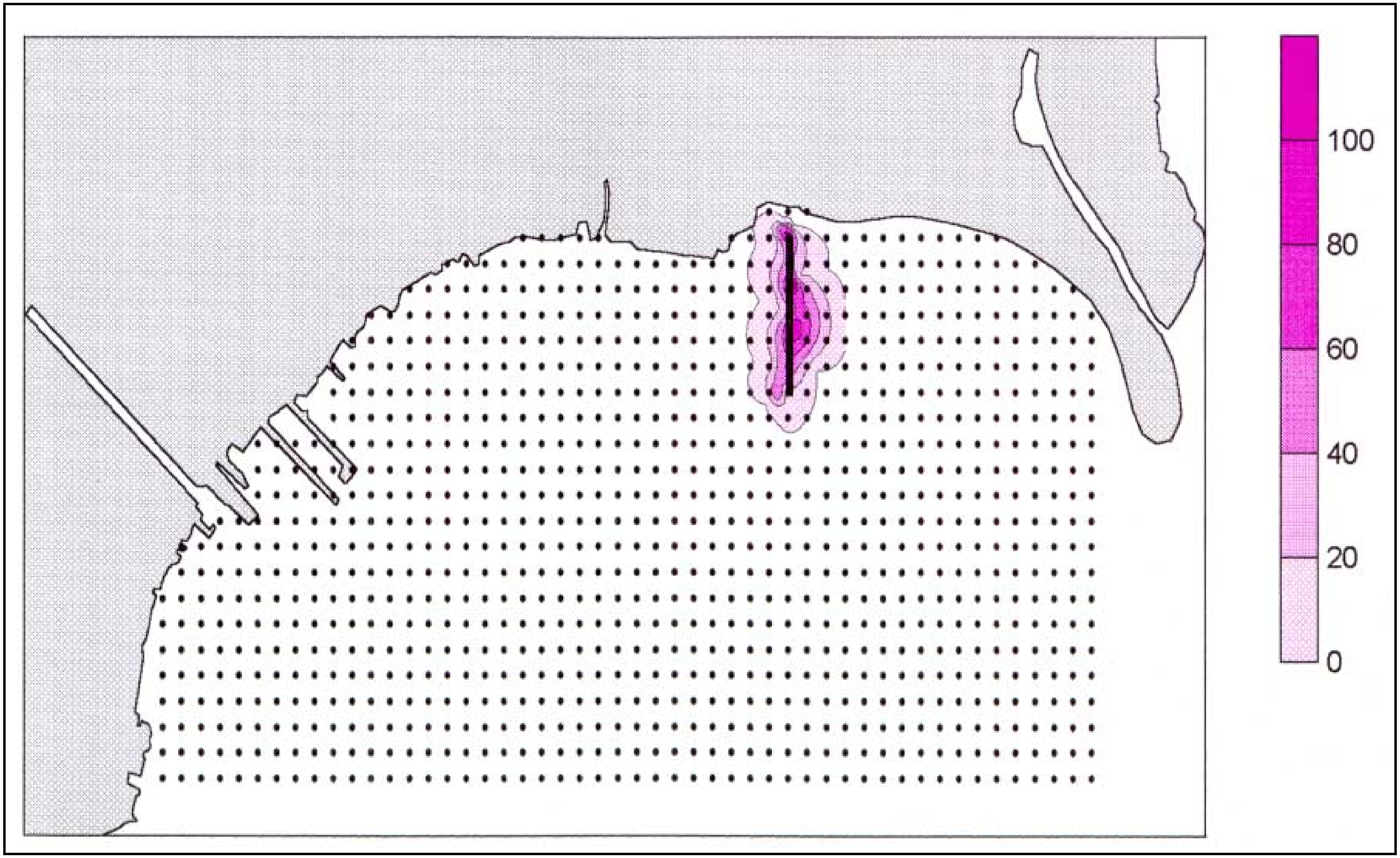

Figure 27. Position of the dye cloud at 1400 hours on 25 August 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1300 hours on 25 August. Grid points (solid dots) are positioned at 100-m intervals for reference

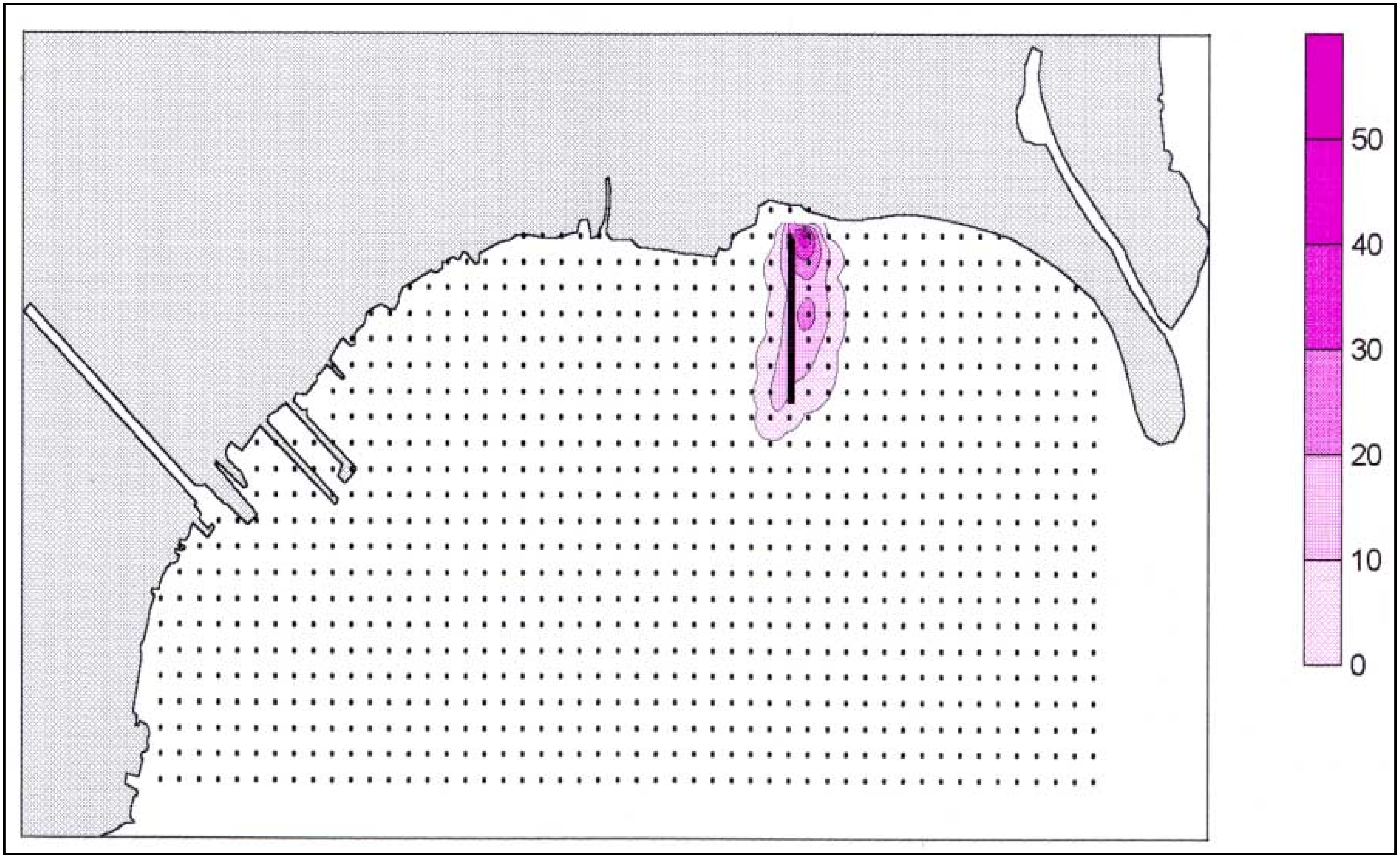

Figure 28. Position of the dye cloud at 1530 hours on 25 August 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1300 hours on 25 August. Grid points (solid dots) are positioned at 100-m intervals for reference

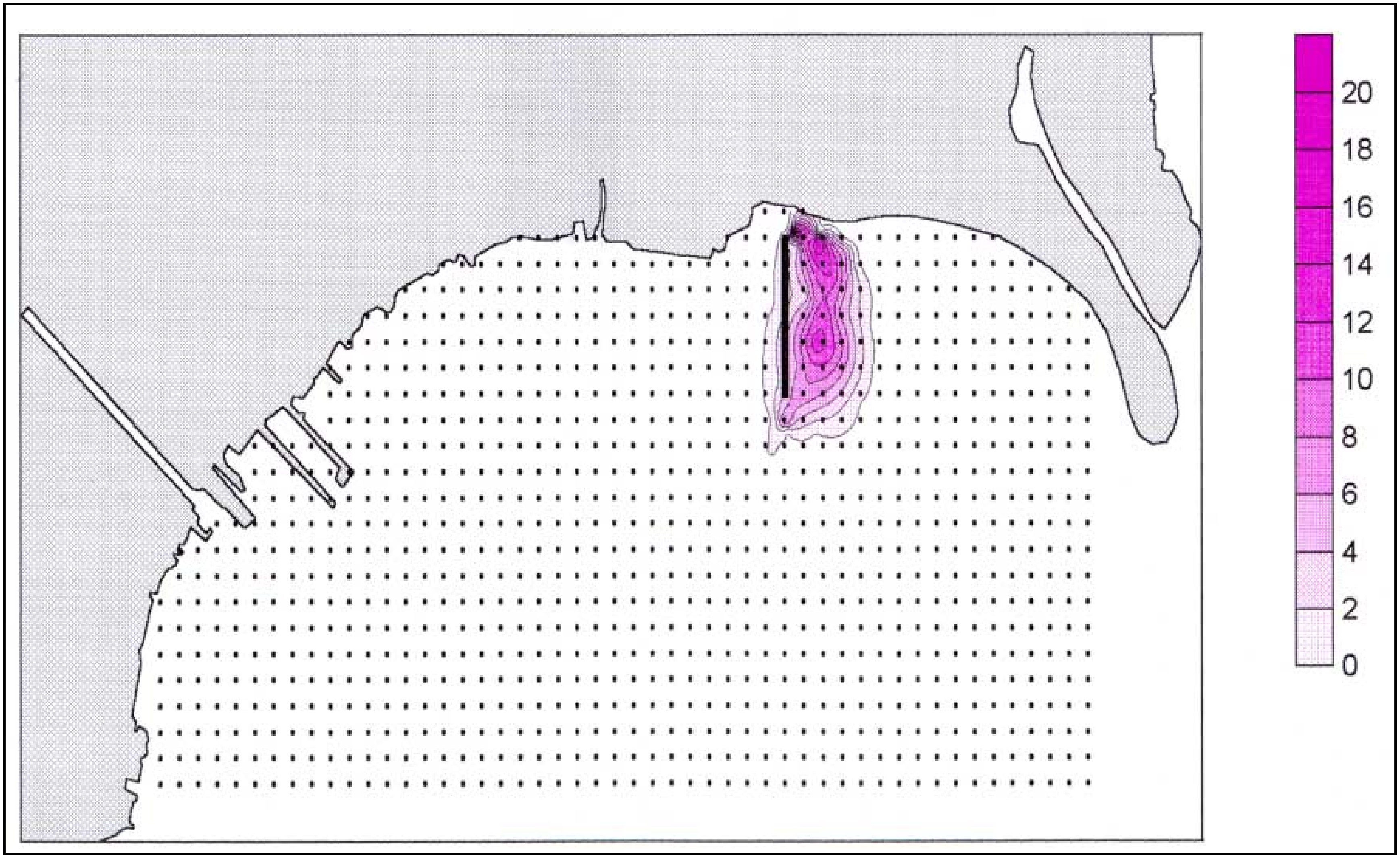

Figure 29. Position of the dye cloud at 1700 hours on 25 August 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1300 hours on 25 August. Grid points (solid dots) are positioned at 100-m intervals for reference

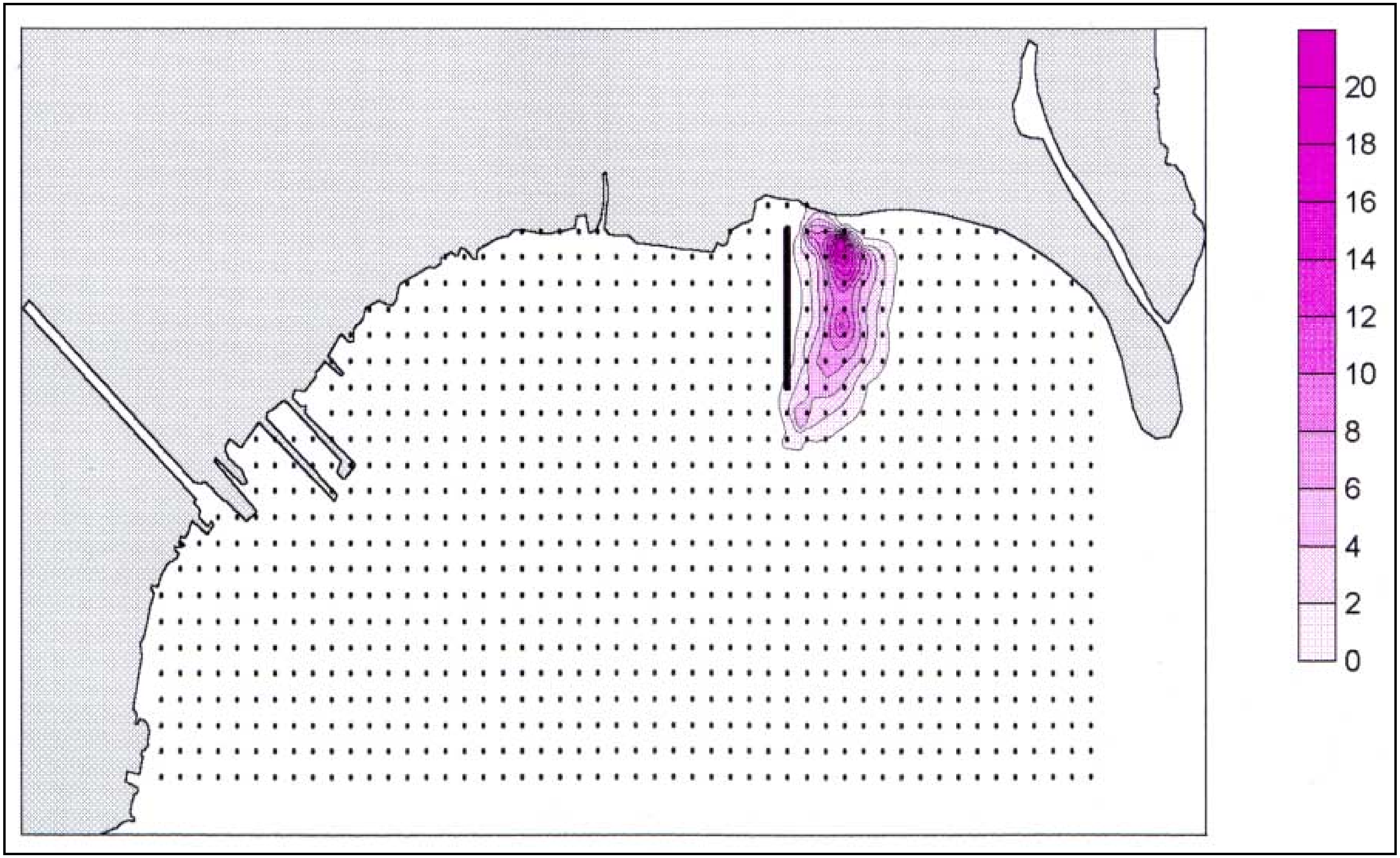

Figure 30. Position of the dye cloud at 1830 hours on 25 August 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1300 hours on 25 August. Grid points (solid dots) are positioned at 100-m intervals for reference

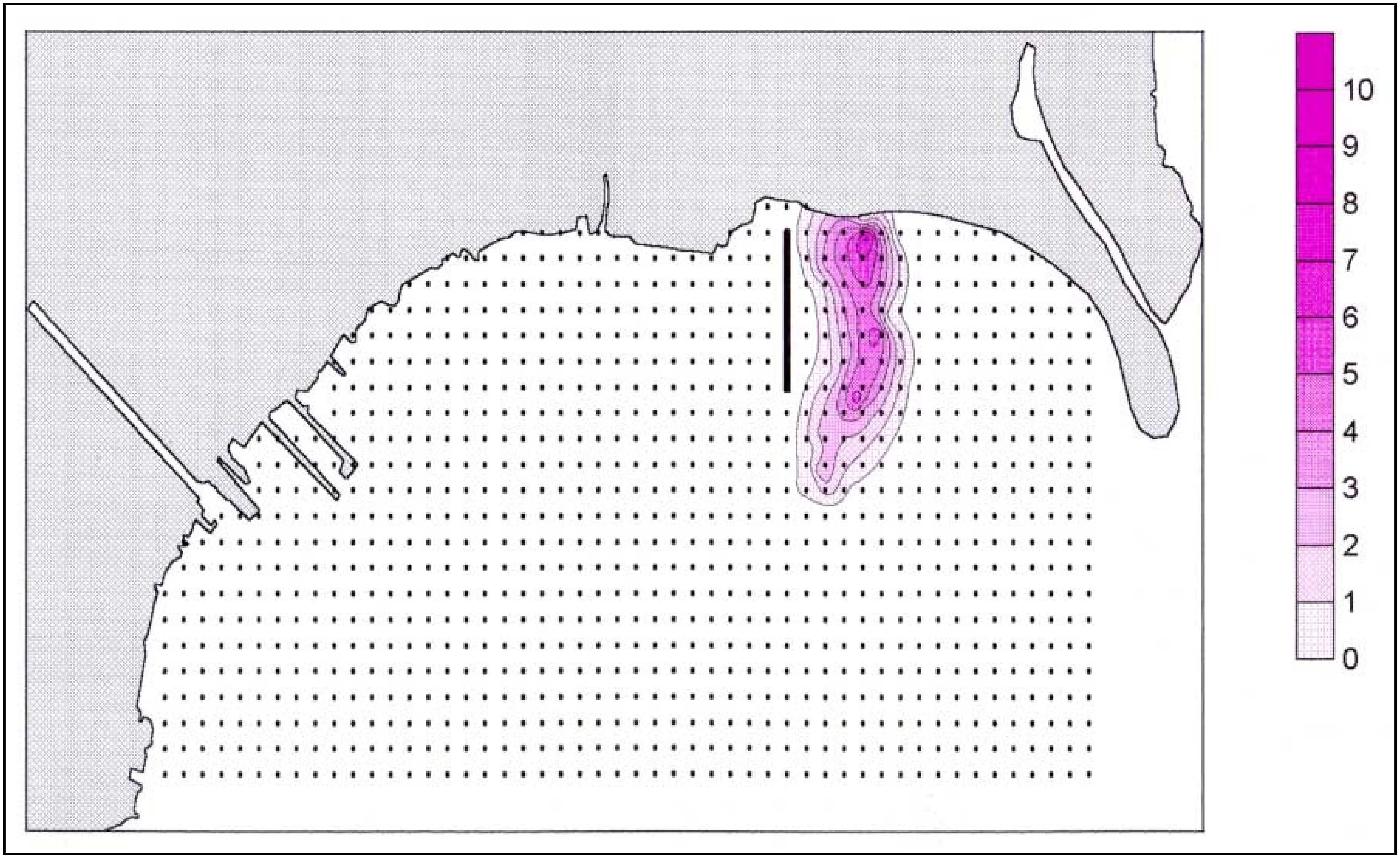

Figure 31. Position of the dye cloud at 1100 hours on 26 August 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1300 hours on 25 August. Grid points (solid dots) are positioned at 100-m intervals for reference

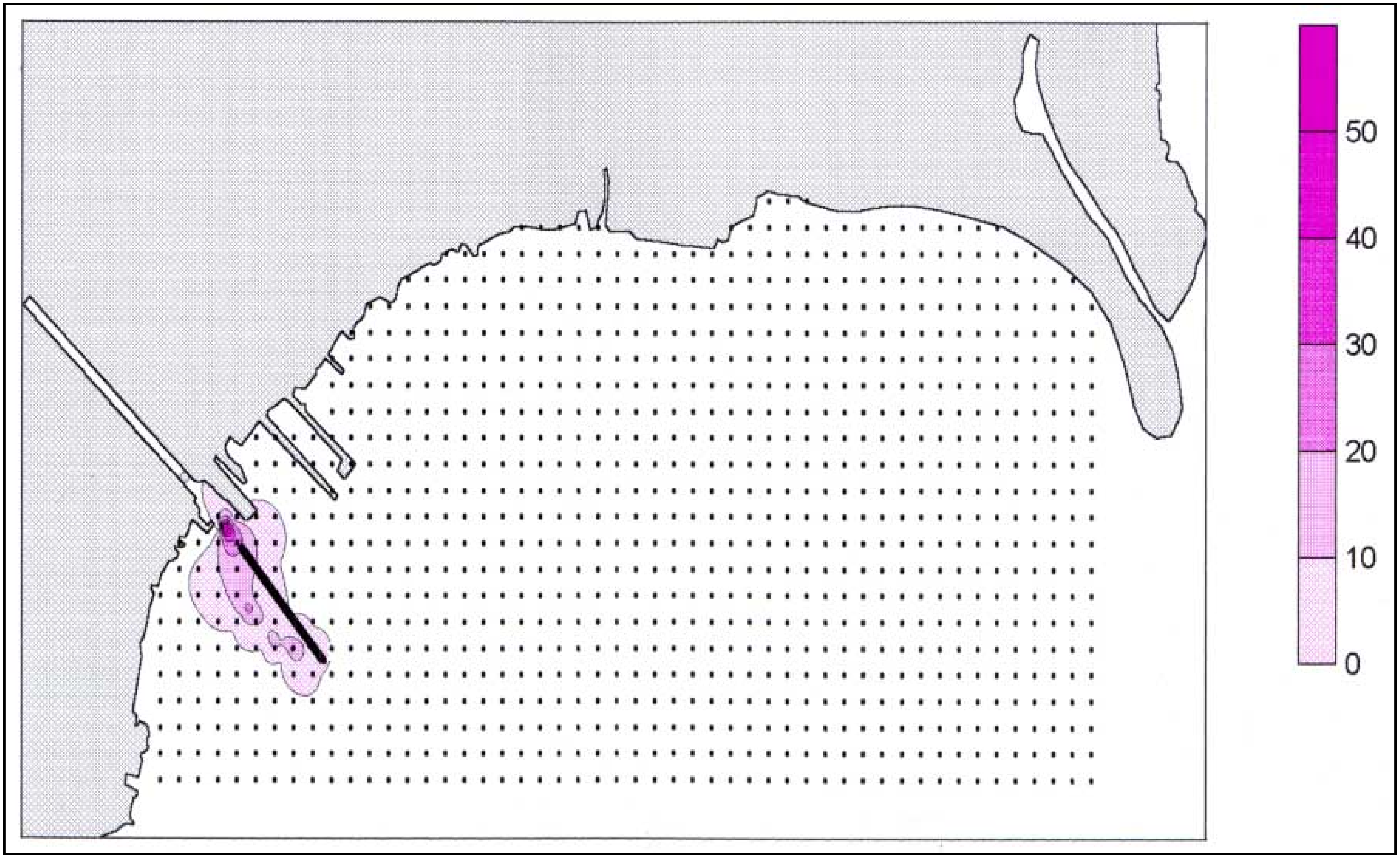

Figure 32. Position of the dye cloud at 1300 hours on 26 August 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1200 hours on 26 August. Grid points (solid dots) are positioned at 100-m intervals for reference

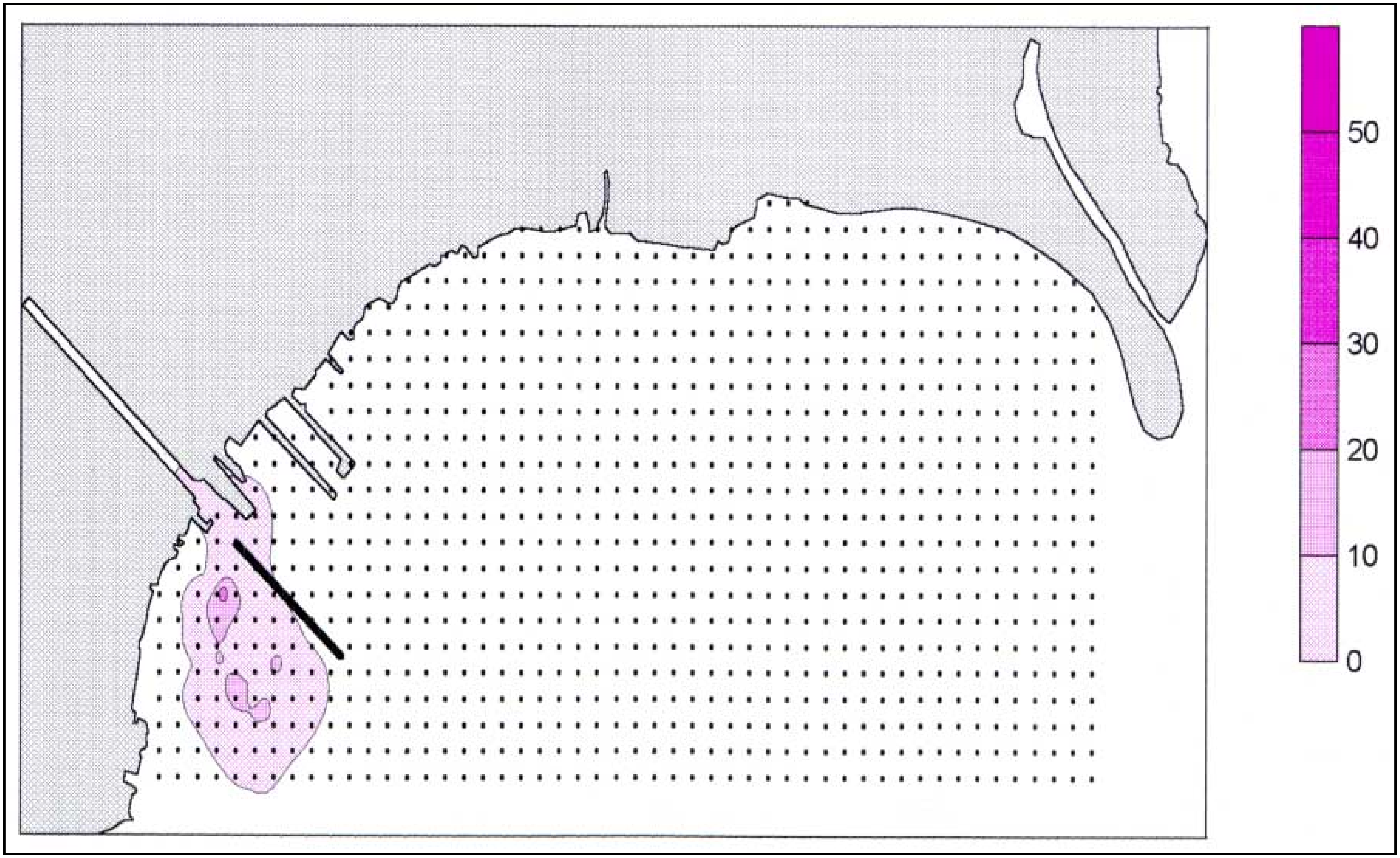

Figure 33. Position of the dye cloud at 1400 hours on 26 August 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1200 hours on 26 August. Grid points (solid dots) are positioned at 100-m intervals for reference

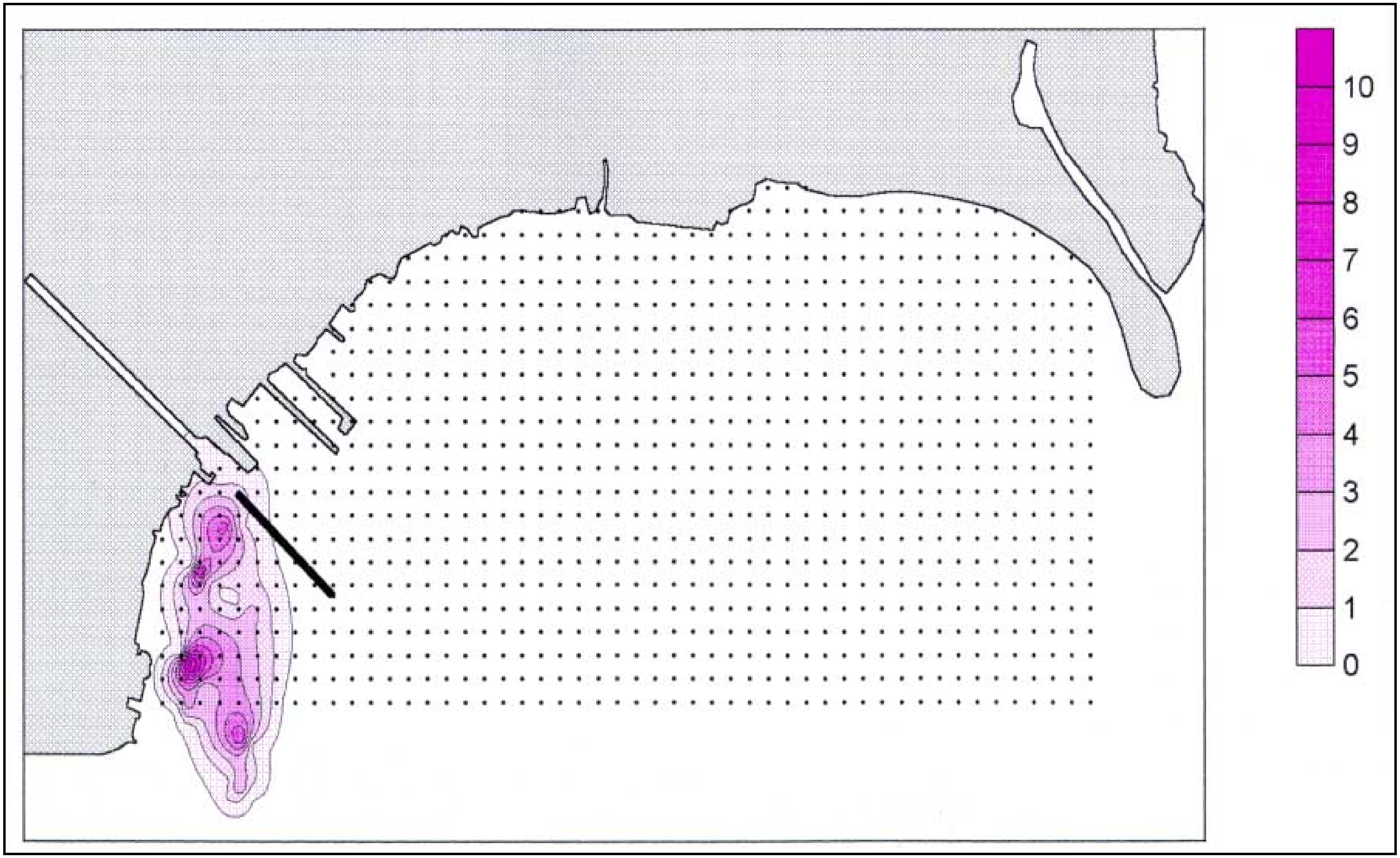

Figure 34. Position of the dye cloud at 1600 hours on 26 August 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1200 hours on 26 August. Grid points (solid dots) are positioned at 100-m intervals for reference

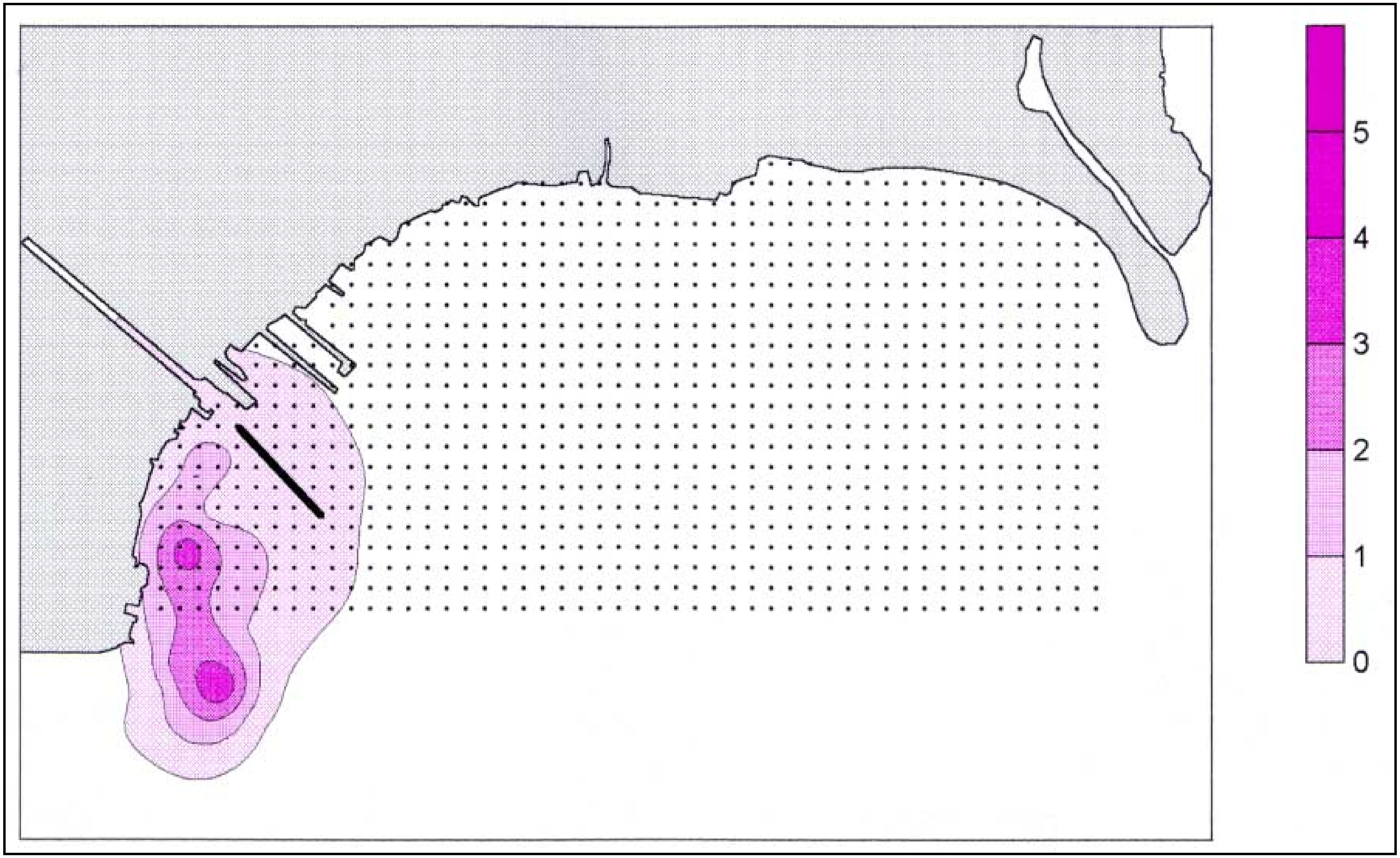

Figure 35. Position of the dye cloud at 1730 hours on 26 August 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1200 hours on 26 August. Grid points (solid dots) are positioned at 100-m intervals for reference

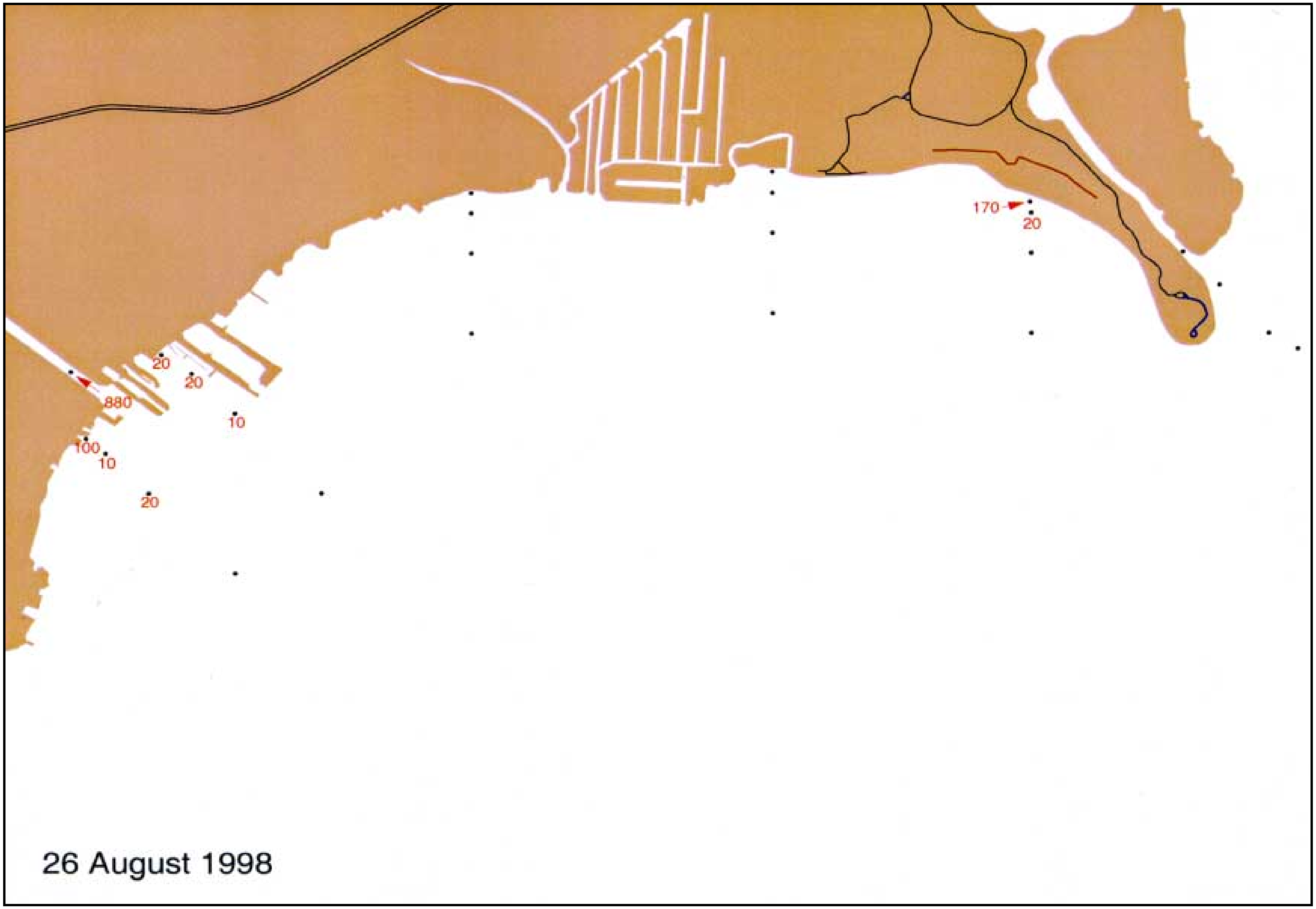

Figure 36. Concentrations of fecal indicator bacteria measured on 26 August 1998. Numbers indicate *E. coli* counts at the adjacent point. Unlabeled points had *E. coli* concentrations below the detection limit

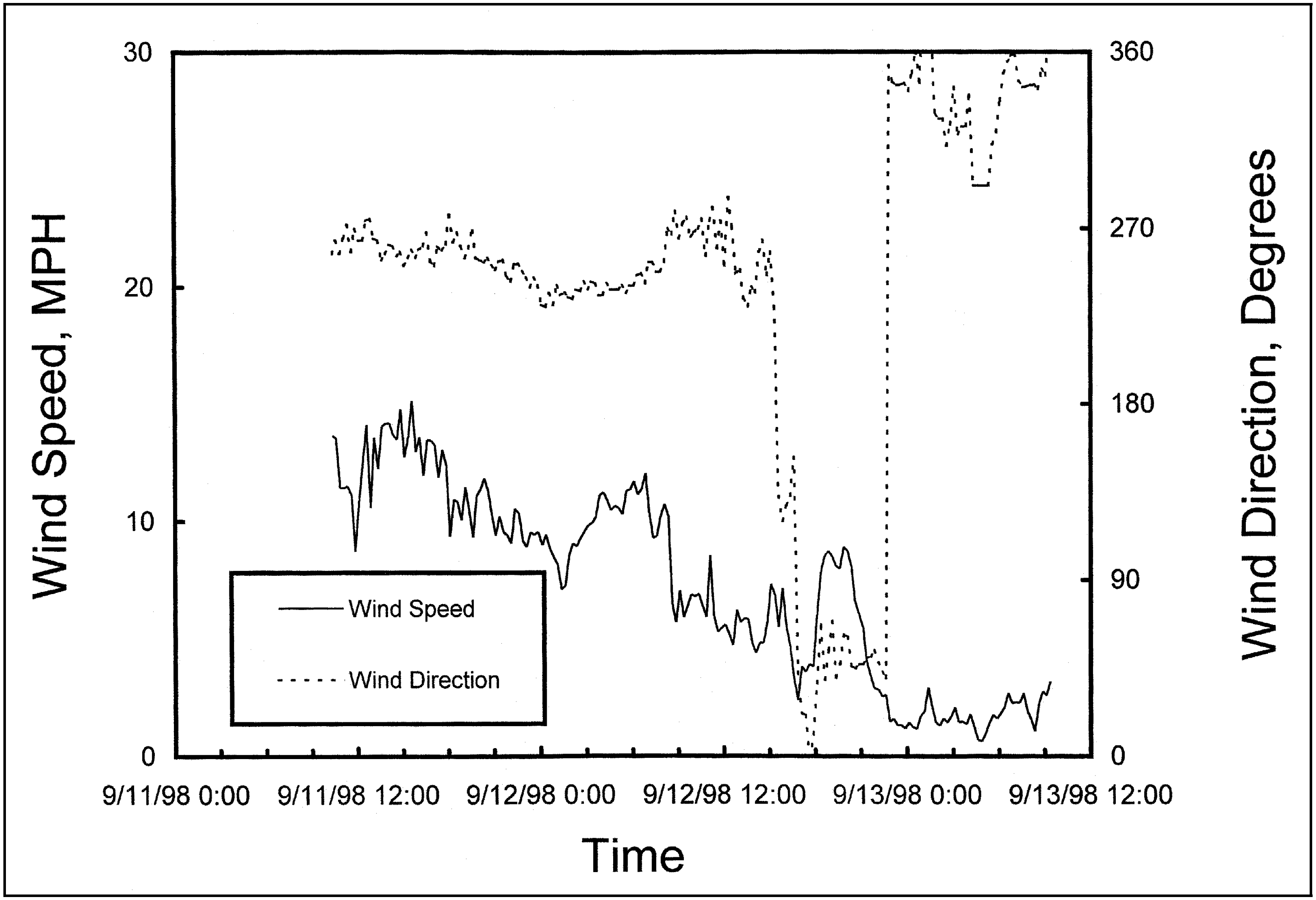

Figure 37. Variations in wind speed and wind direction at the Metro Beach area beach between 11 and 13 September 1998

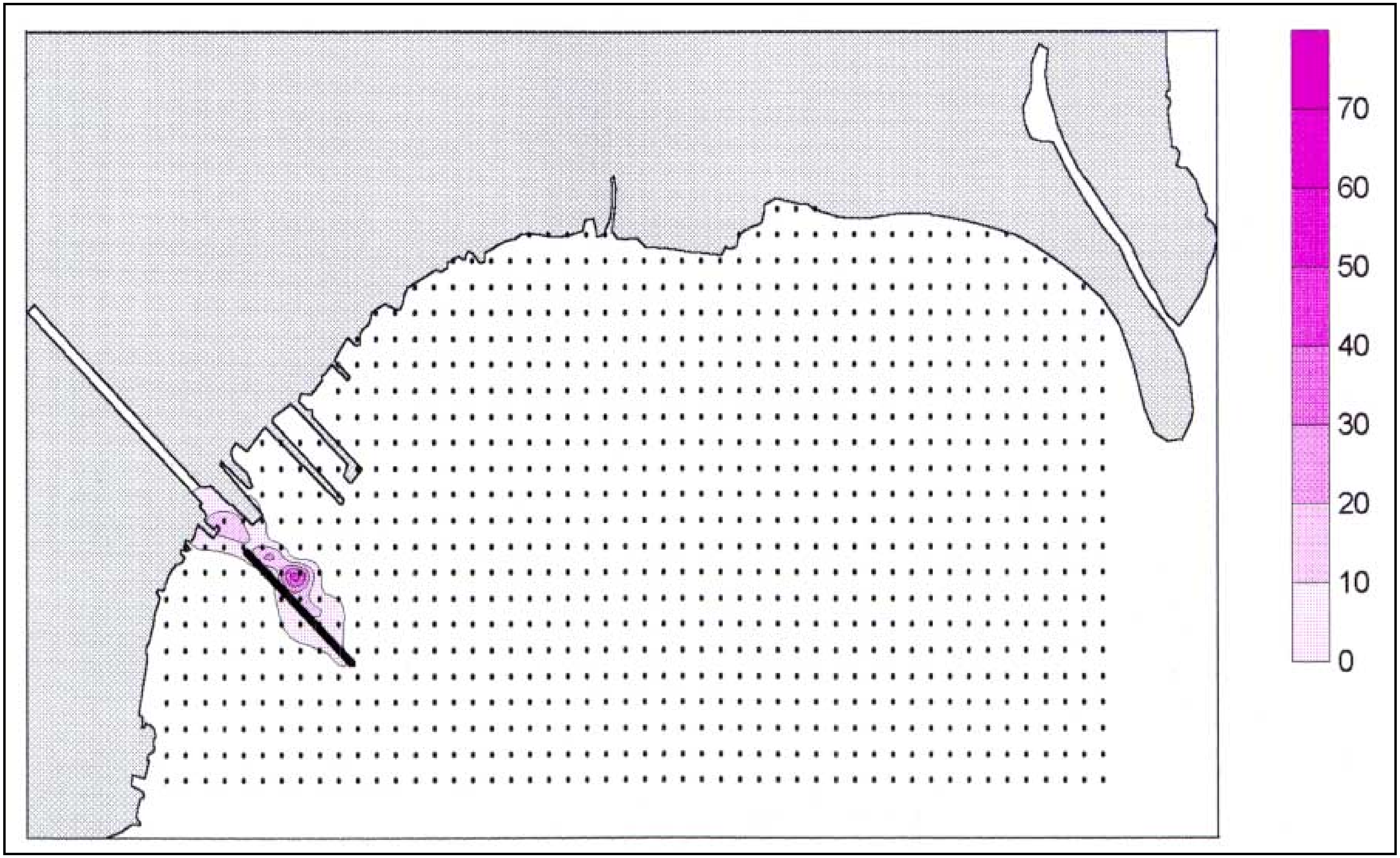

Figure 38. Position of the dye cloud at 1200 hours on 11 September 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1130 hours on 11 September. Grid points (solid dots) are positioned at 100-m intervals for reference

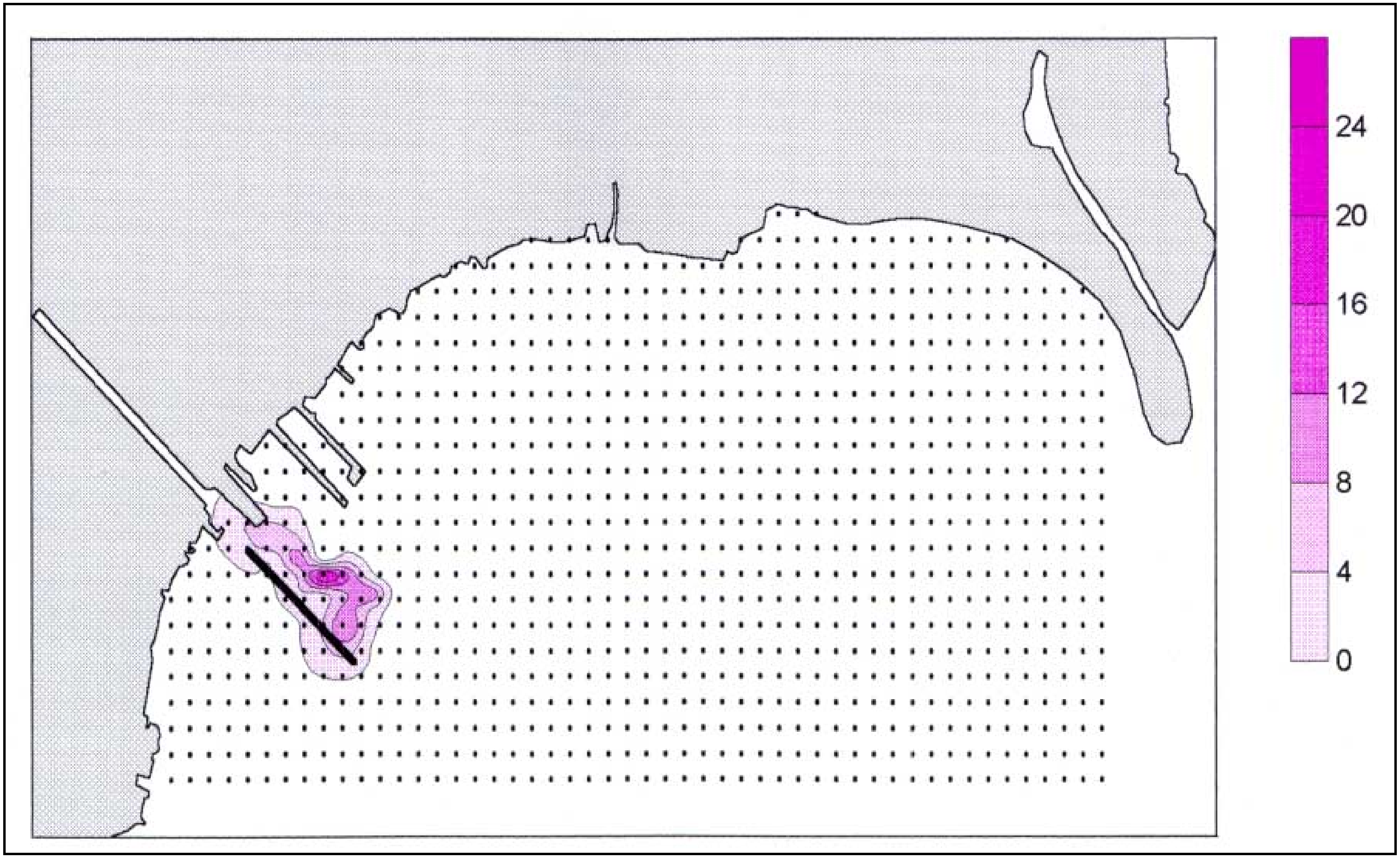

Figure 39. Position of the dye cloud at 1330 hours on 11 September 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1130 hours on 11 September. Grid points (solid dots) are positioned at 100-m intervals for reference

Figure 40. Position of the dye cloud at 1500 hours on 11 September 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1130 hours on 11 September. Grid points (solid dots) are positioned at 100-m intervals for reference

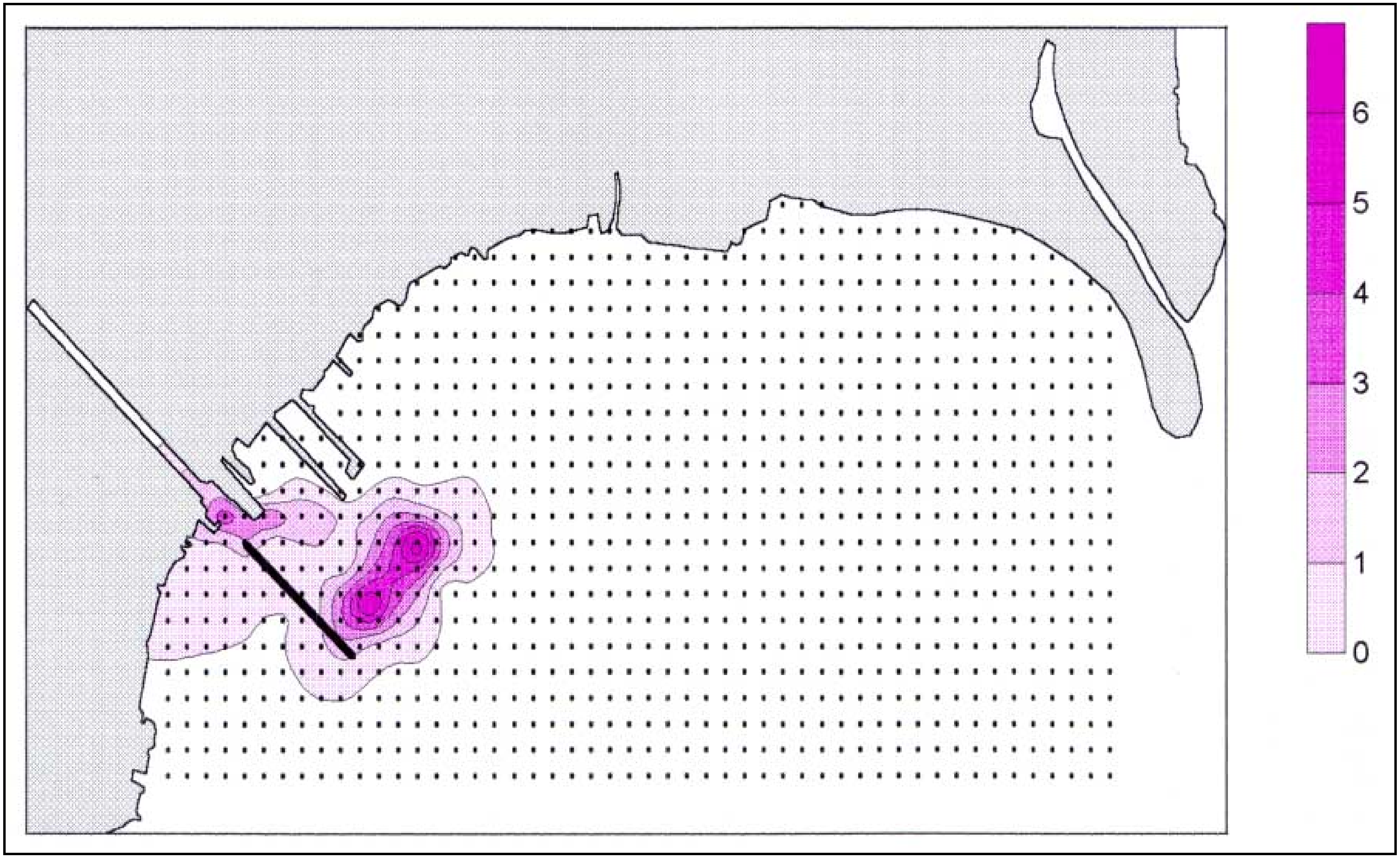

Figure 41. Position of the dye cloud at 1630 hours on 11 September 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1130 hours on 11 September. Grid points (solid dots) are positioned at 100-m intervals for reference

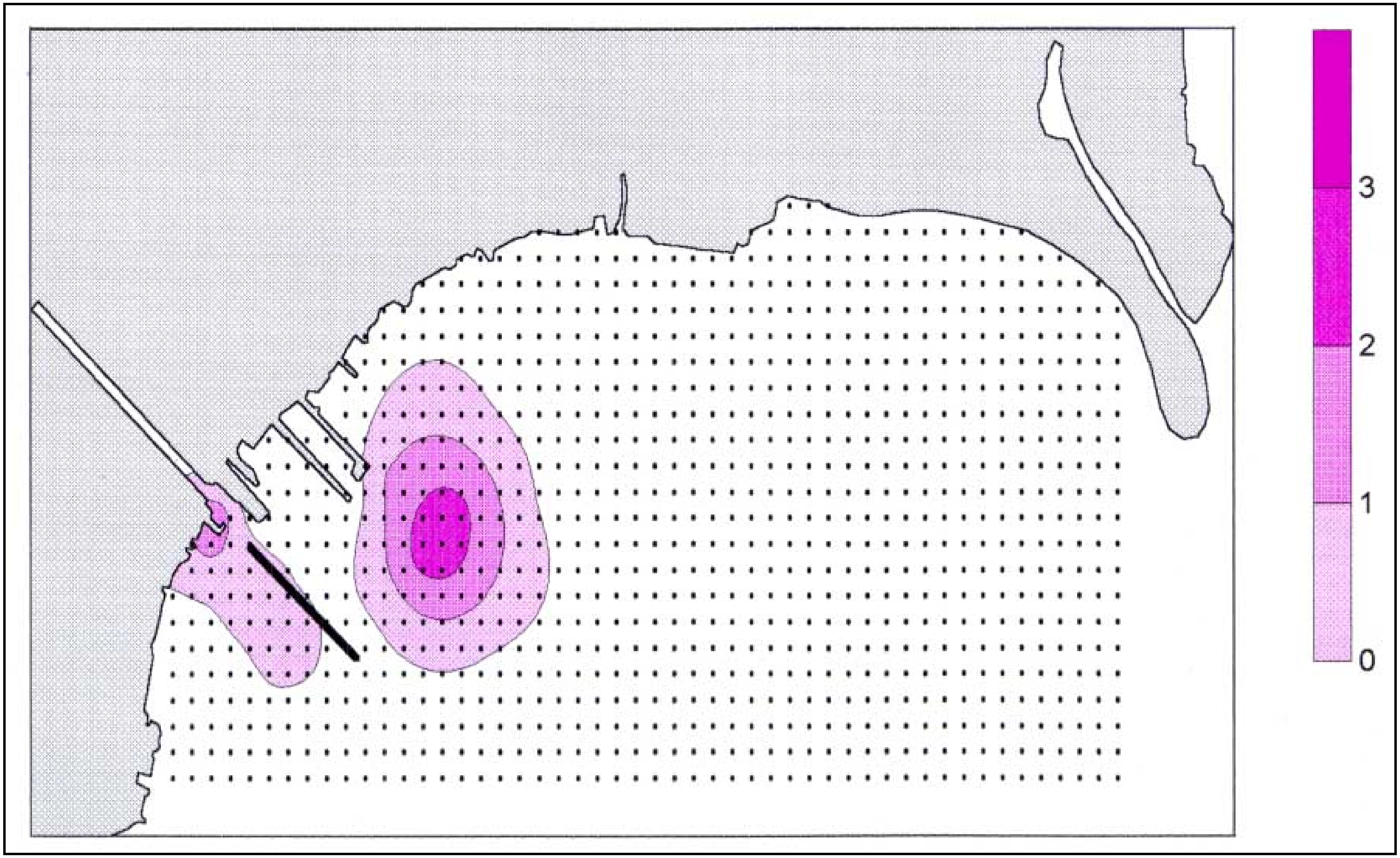

Figure 42. Position of the dye cloud at 0930 hours on 12 September 1998. Dye was injected along the Clinton River cutoff transect (represented by the solid line) at ~ 1130 hours on 11 September. Grid points (solid dots) are positioned at 100-m intervals for reference

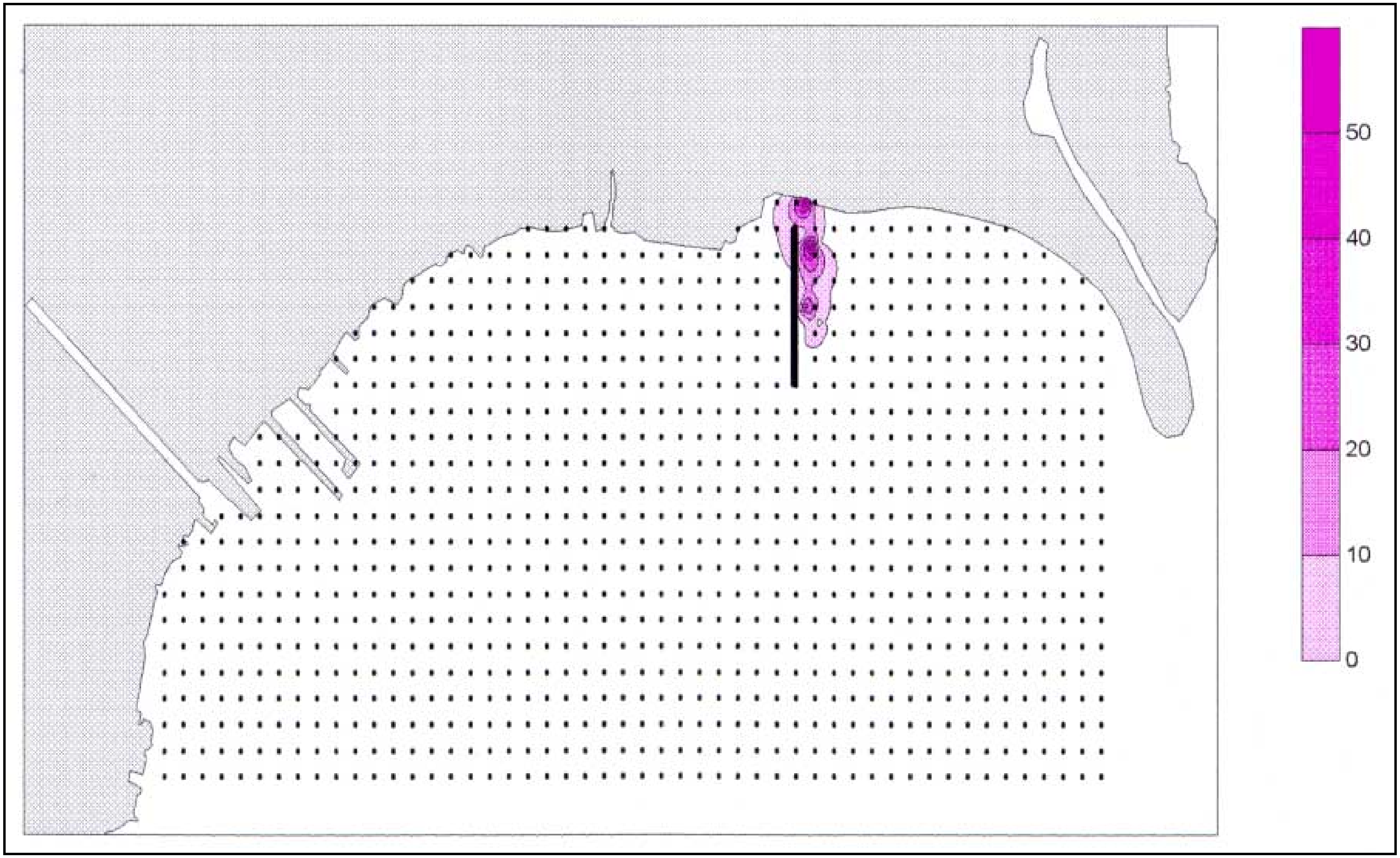

Figure 43. Position of the dye cloud at 1030 hours on 12 September 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1000 hours on 12 September. Grid points (solid dots) are positioned at 100-m intervals for reference

Figure 44. Position of the dye cloud at 1200 hours on 12 September 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1000 hours on 12 September. Grid points (solid dots) are positioned at 100-m intervals for reference

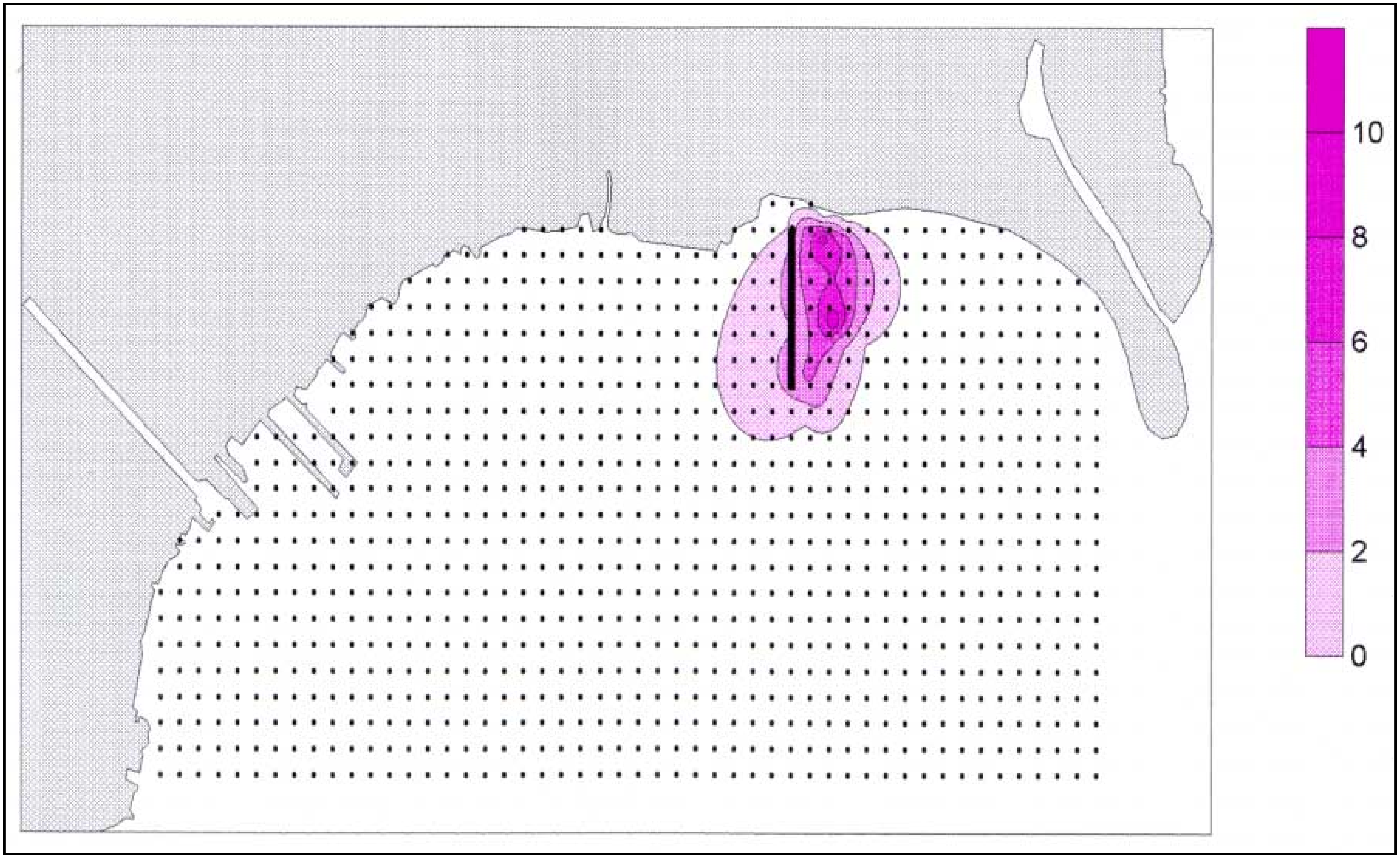

Figure 45. Position of the dye cloud at 1330 hours on 12 September 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1000 hours on 12 September. Grid points (solid dots) are positioned at 100-m intervals for reference

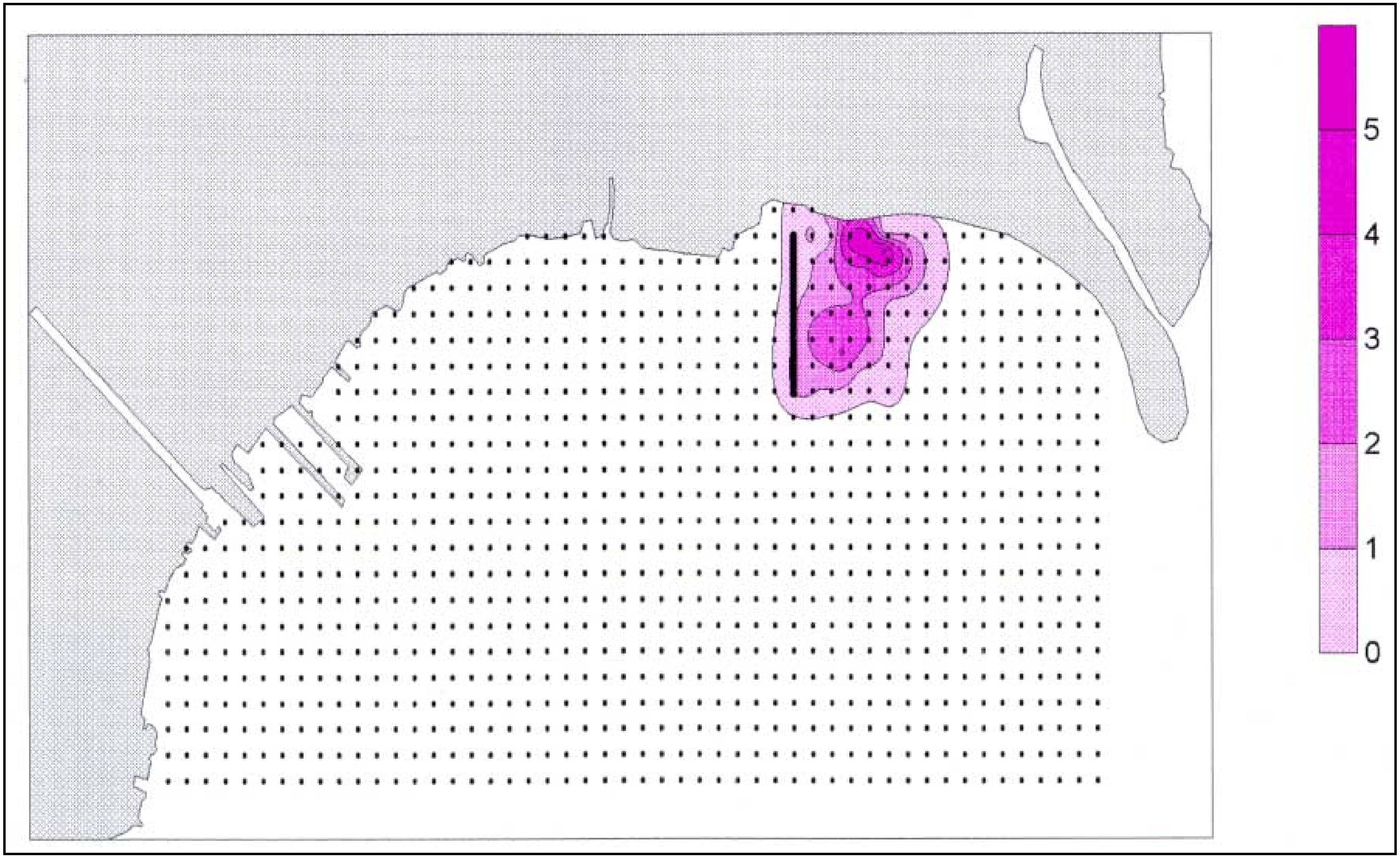

Figure 46. Position of the dye cloud at 1630 hours on 12 September 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1000 hours on 12 September. Grid points (solid dots) are positioned at 100-m intervals for reference

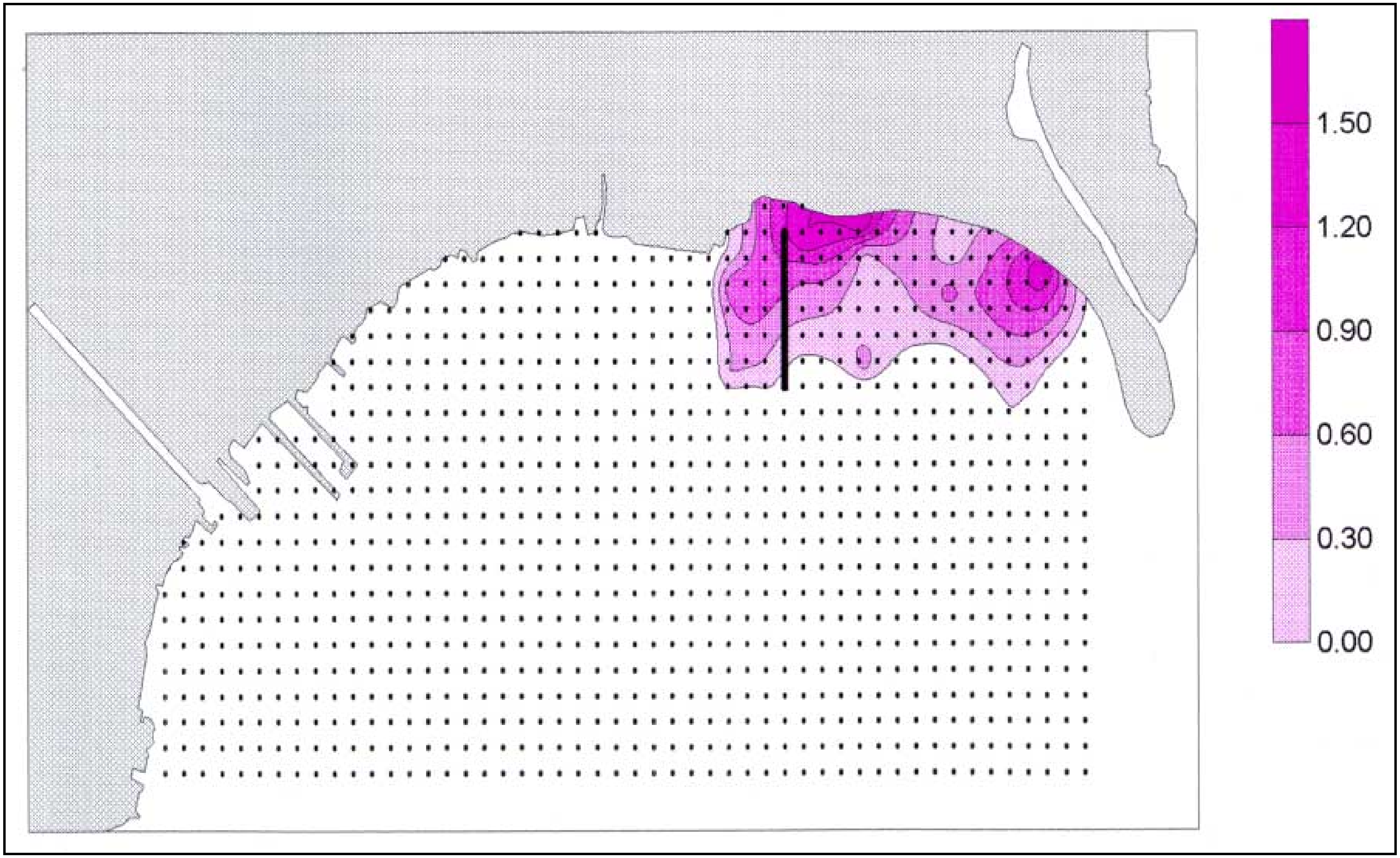

Figure 47. Position of the dye cloud at 0900 hours on 13 September 1998. Dye was injected along the Metro Beach area transect (represented by the solid line) at ~ 1000 hours on 12 September. Grid points (solid dots) are positioned at 100-m intervals for reference

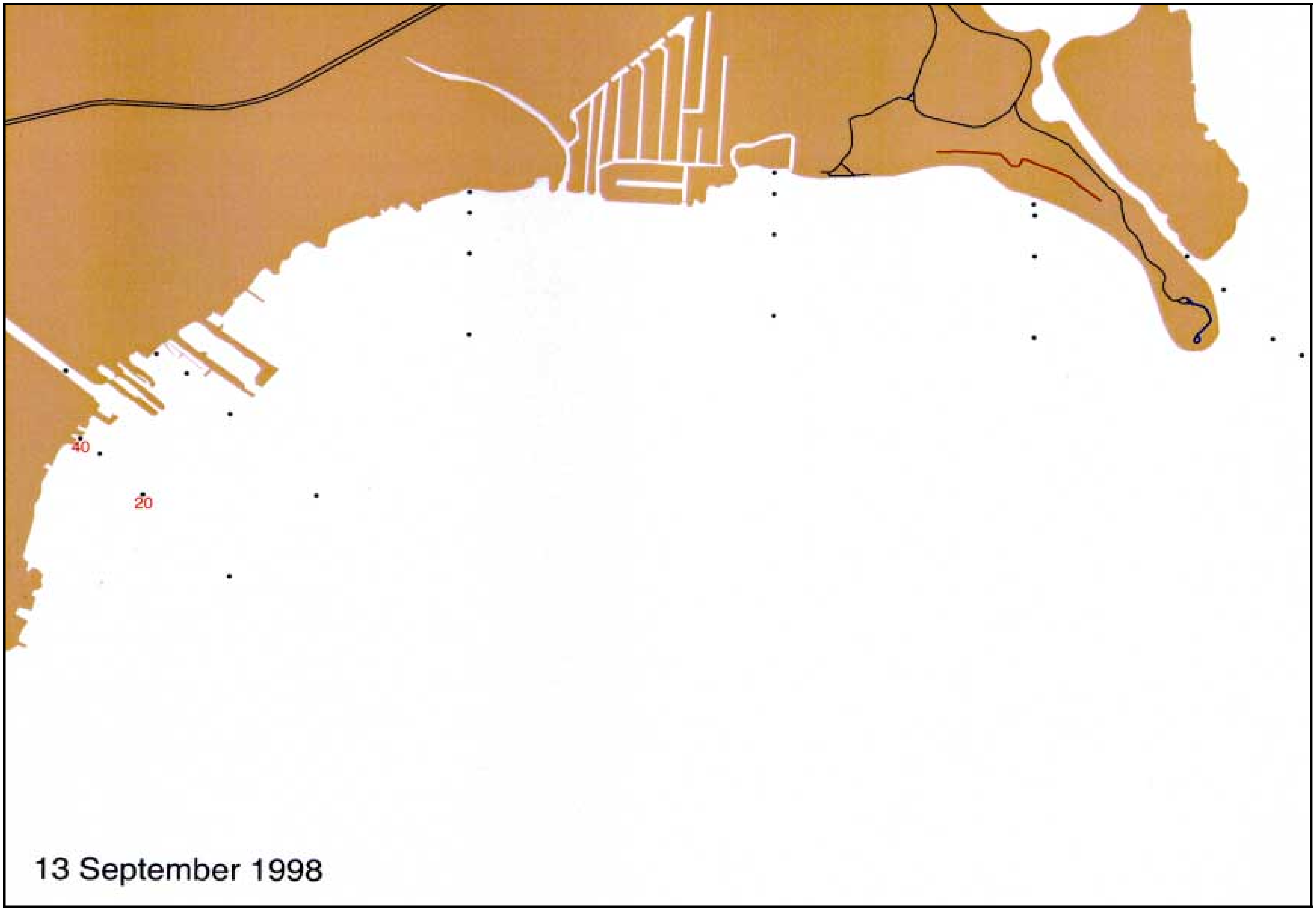

Figure 48. Concentrations of fecal indicator bacteria measured on 13 September 1998. Numbers indicate *E. coli* counts at the adjacent sampling point. Unlabeled sampling points had *E. coli* concentrations below the detection limit

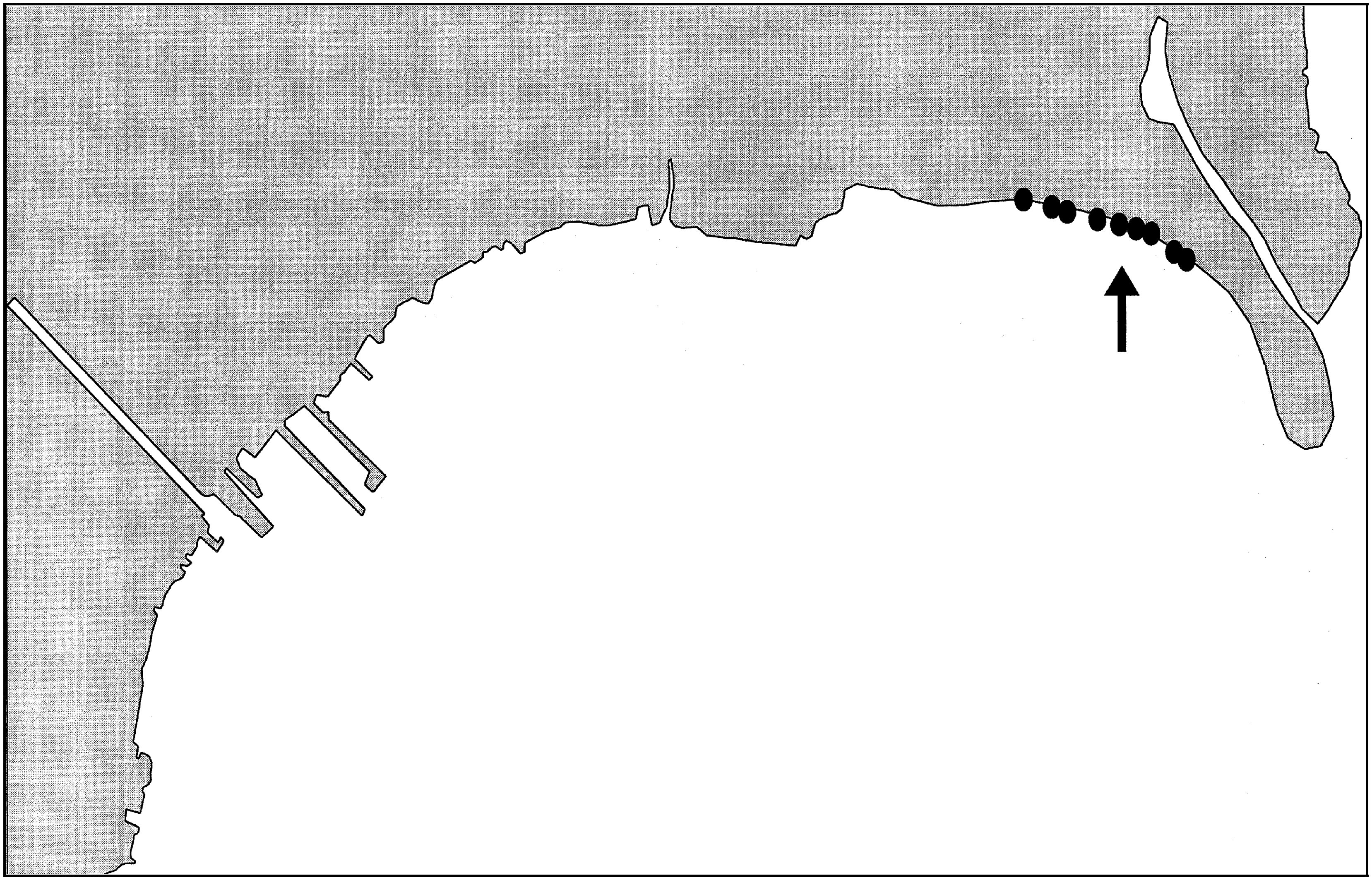

Figure 49. Sampling station locations along the Metro Beach area during the dye dissipation study on 5 August 1998. Arrow identifies the sampling station used to determine residence time of the nearshore beach area

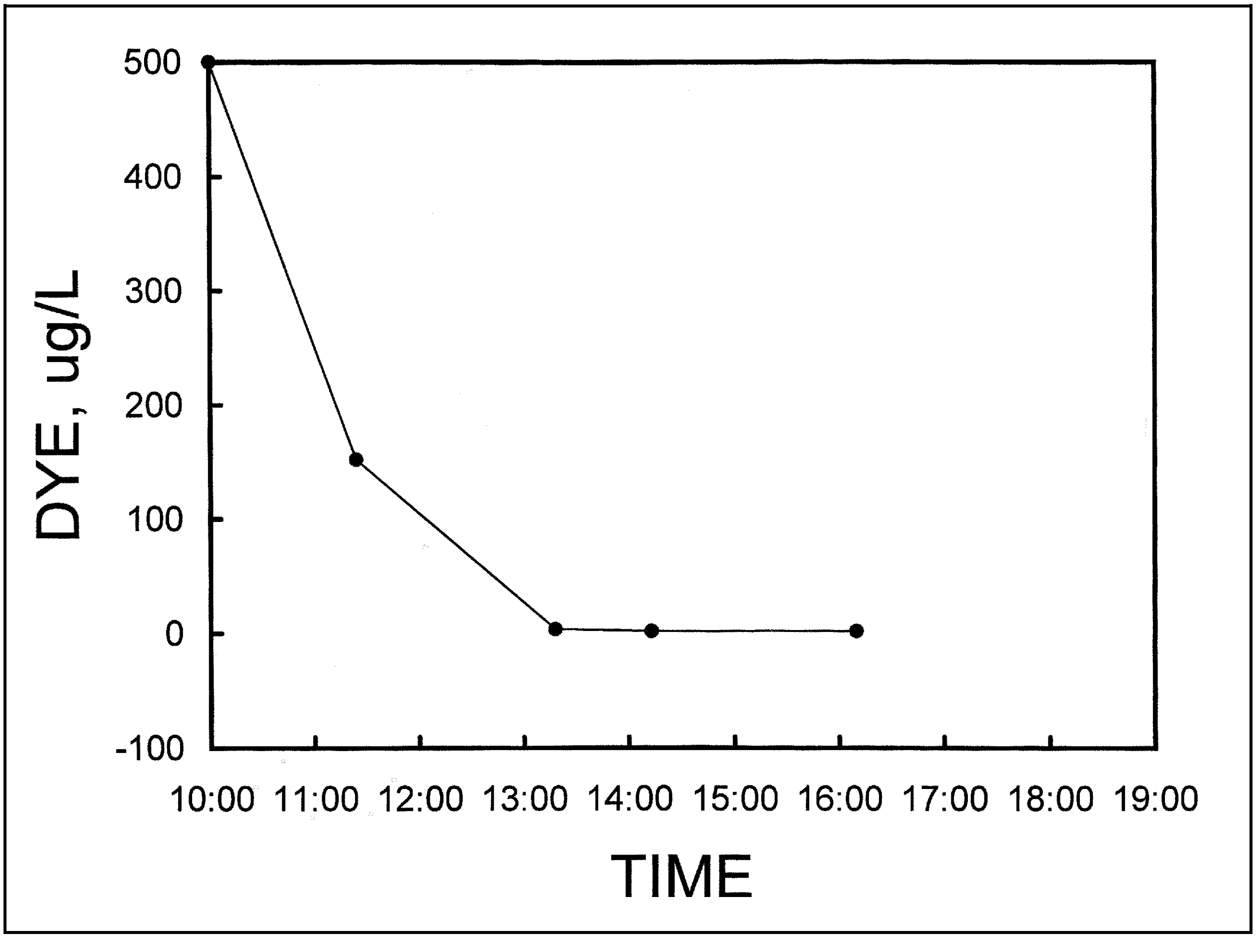

Figure 50. Changes in dye concentration as a function of time at the centrally located station (see Figure 49) of the Metro Beach area dye dissipation study on 5 August 1998

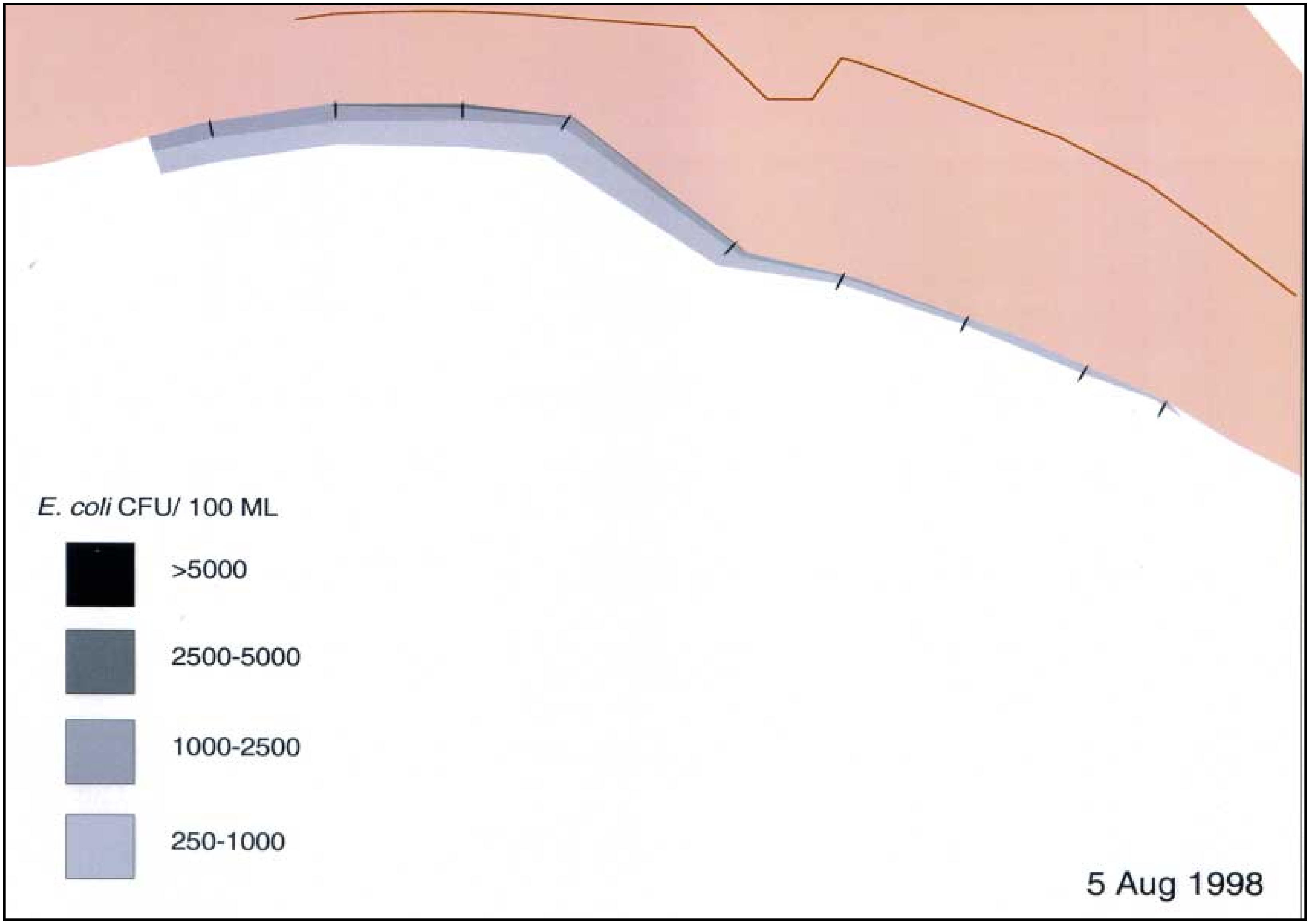

Figure 51. Concentrations of fecal indicator bacteria in the beach area on 5 August 1998. Lines perpendicular to shore indicate the locations of bacterial sampling transects

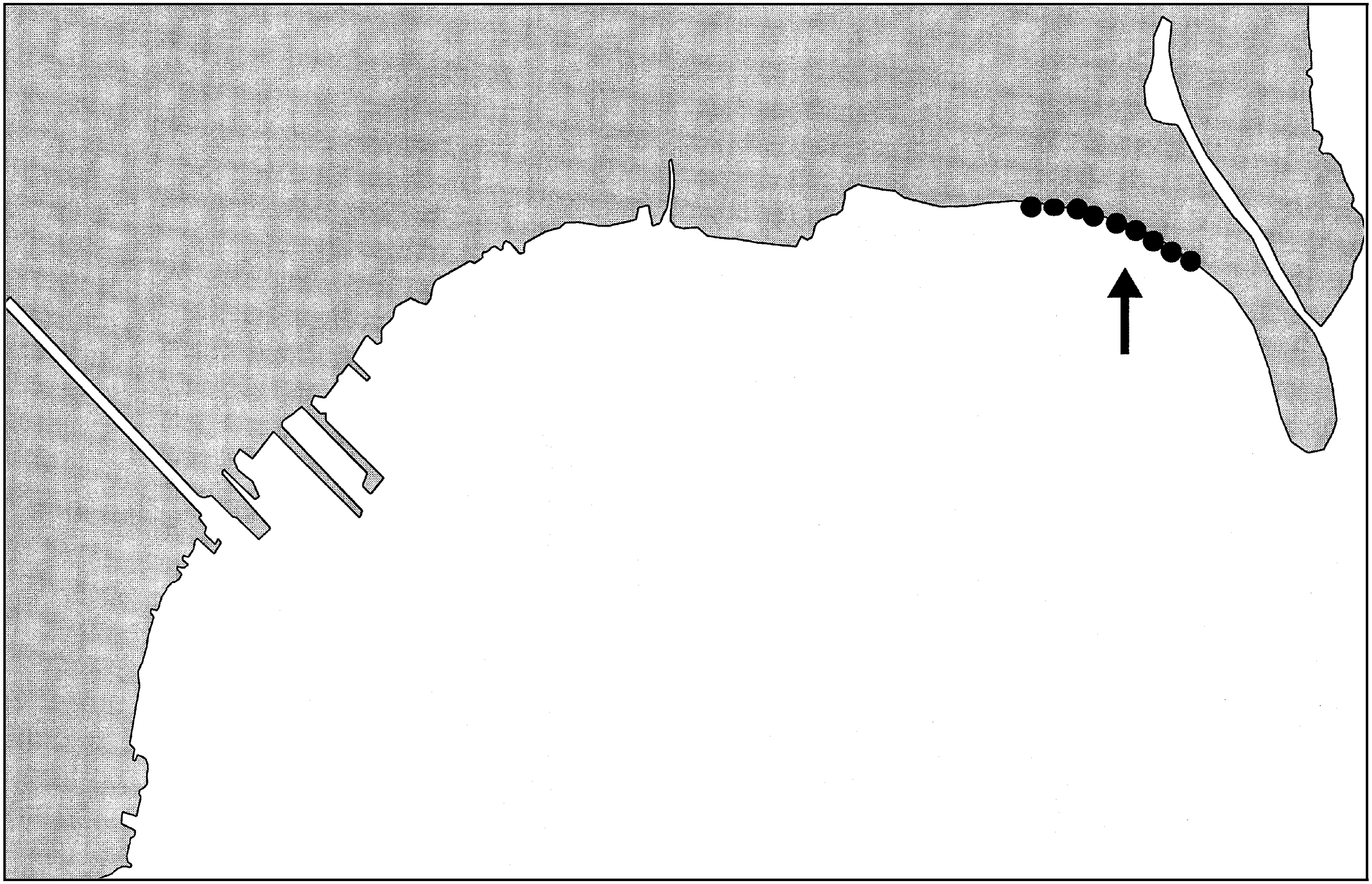

Figure 52. Sampling station locations along the Metro Beach area during the dye dissipation study on 25 August 1998. Arrow identifies the sampling station used to determine residence time of the nearshore beach area

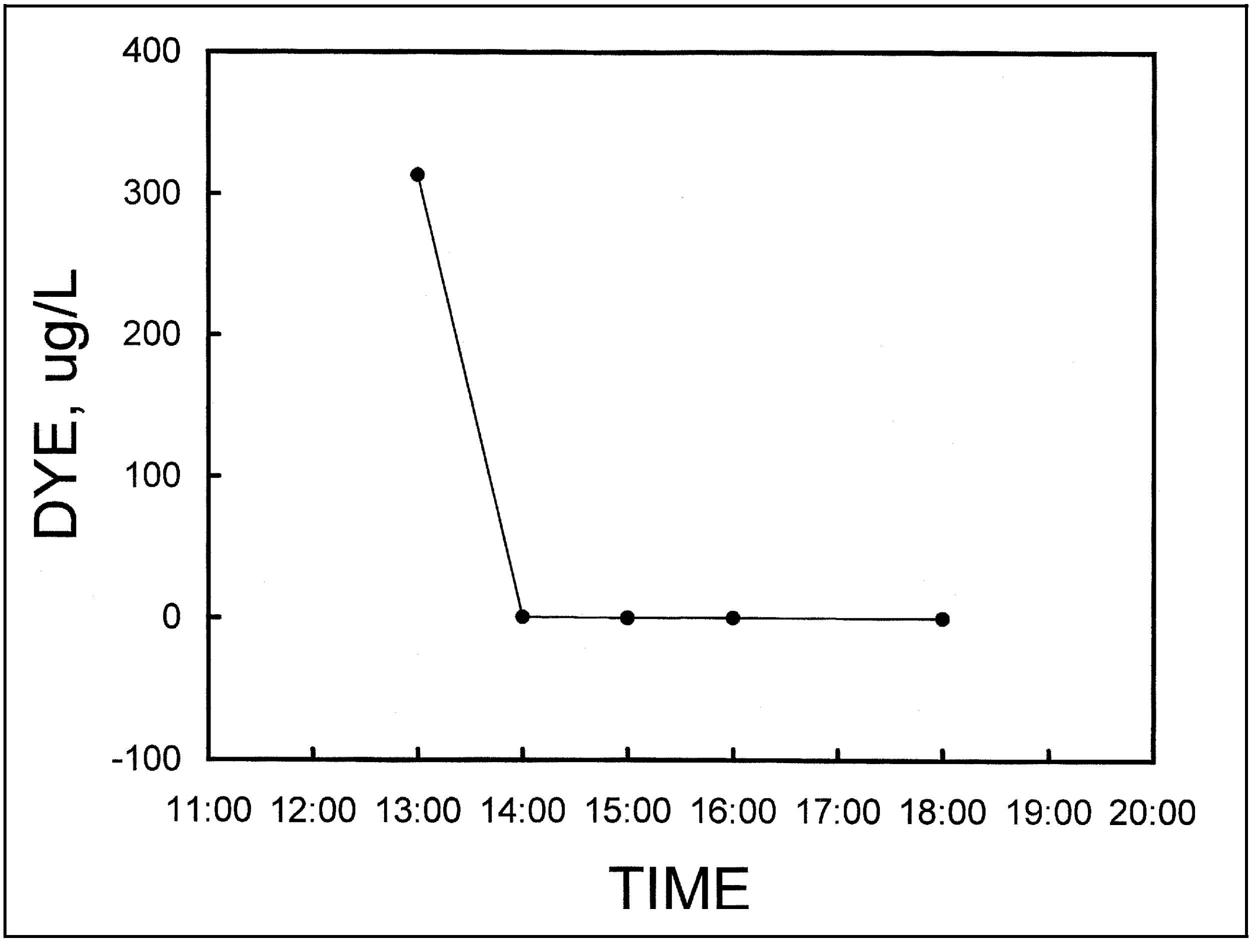

Figure 53. Changes in dye concentration as a function of time at the centrally located station (see Figure 52) of the Metro Beach area dye dissipation study on 25 August 1998

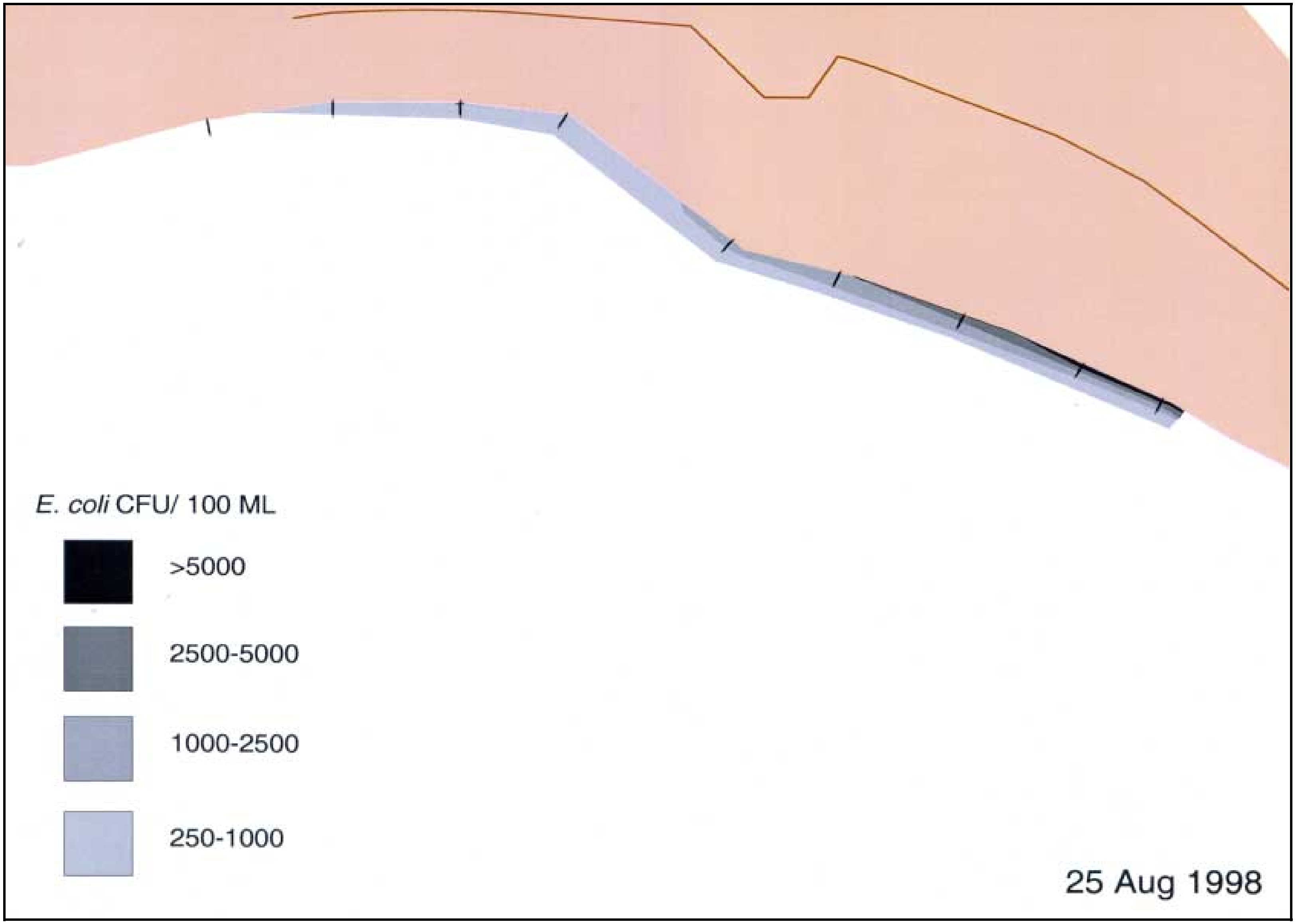

Figure 54. Concentrations of fecal indicator bacteria in the beach area on 25 August 1998. Lines perpendicular to shore indicate the locations of bacterial sampling transects

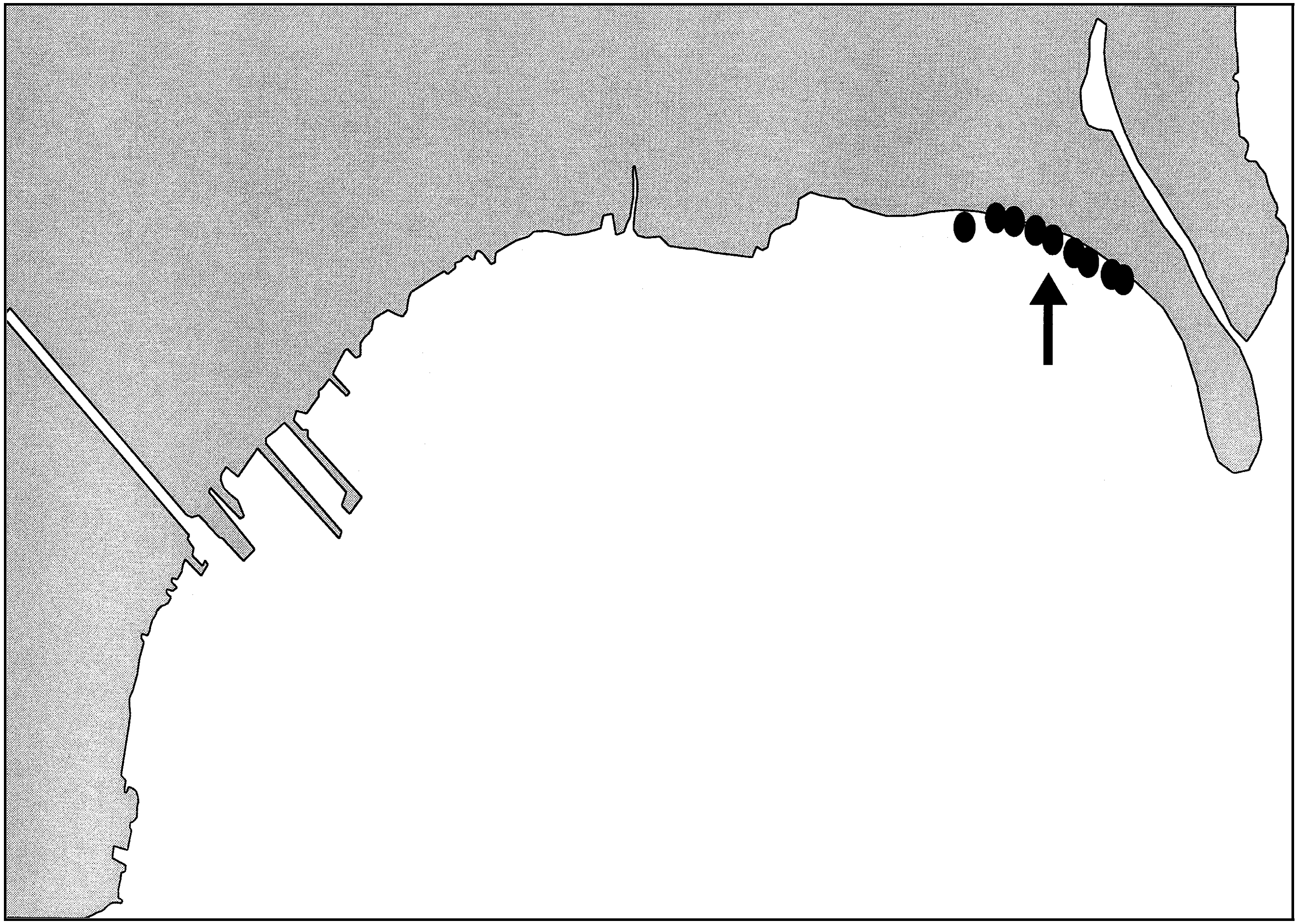

Figure 55. Sampling station locations along the Metro Beach area during the dye dissipation study on 11 September 1998. Arrow identifies the sampling station used to determine residence time of the nearshore beach area

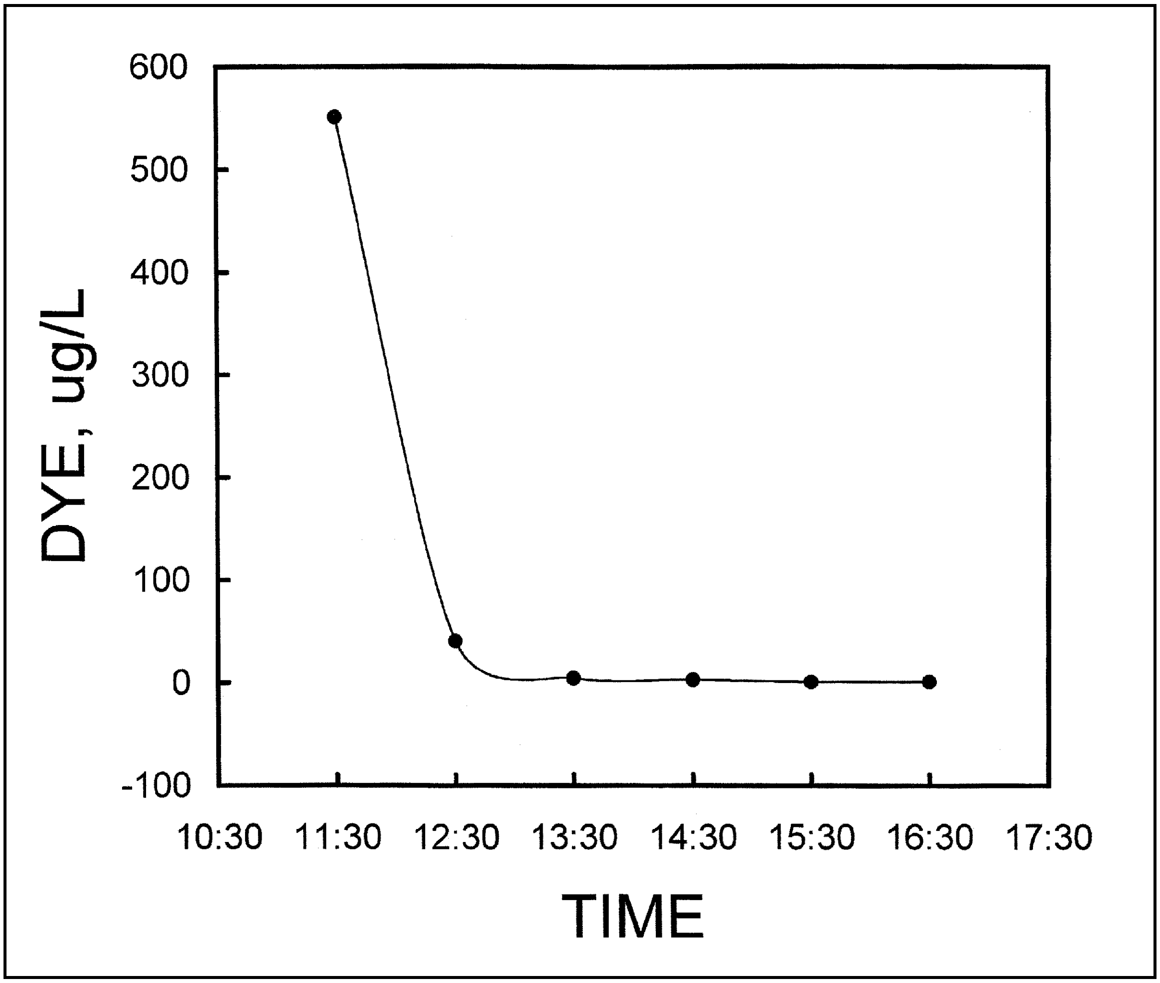

Figure 56. Changes in dye concentration as a function of time at the centrally located station (see Figure 55) of the Metro Beach area dye dissipation study on 11 September 1998

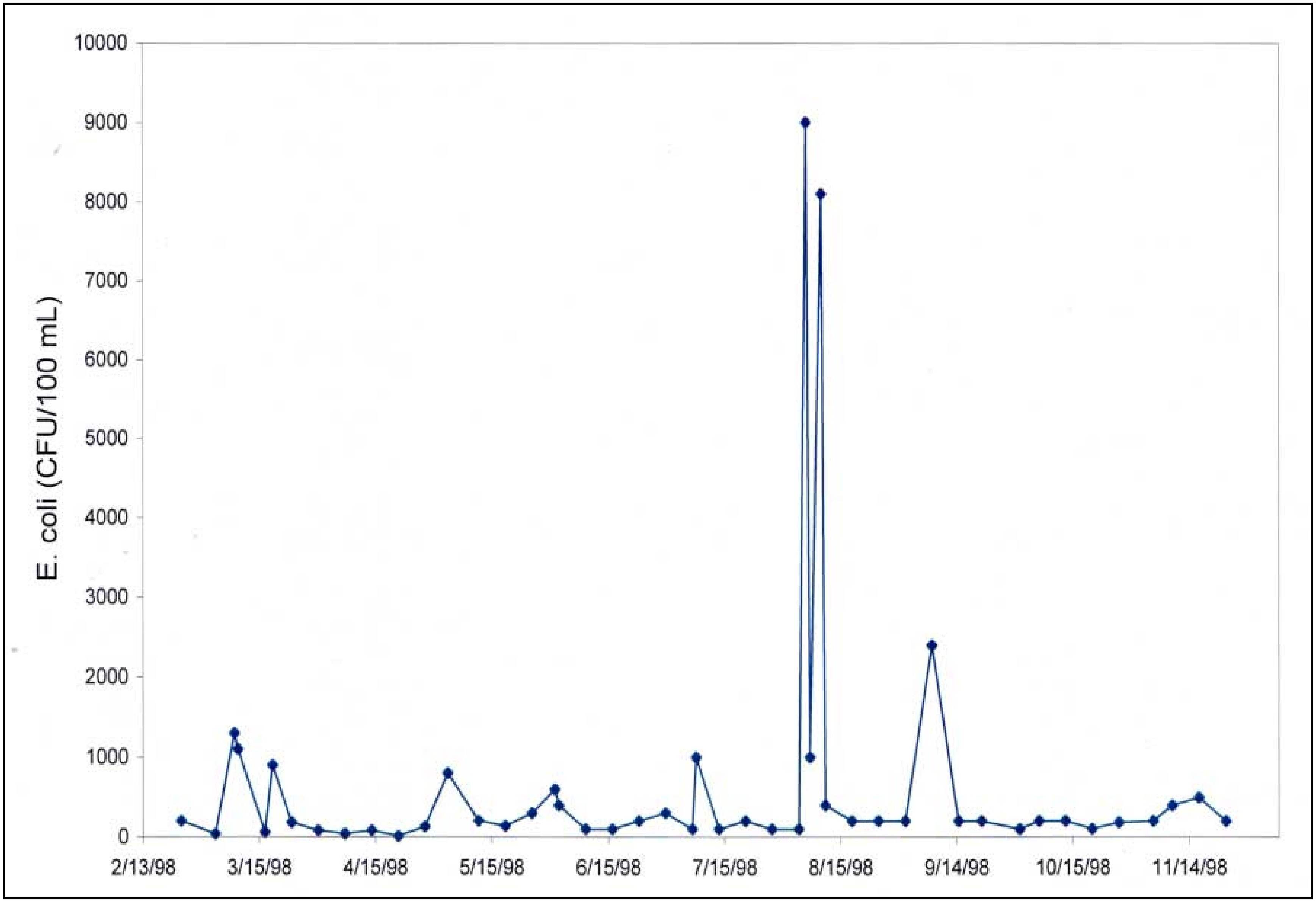

Figure 57. Concentrations of *E. coli* measured in the Clinton River cutoff by the Macomb County Health Department during 1998

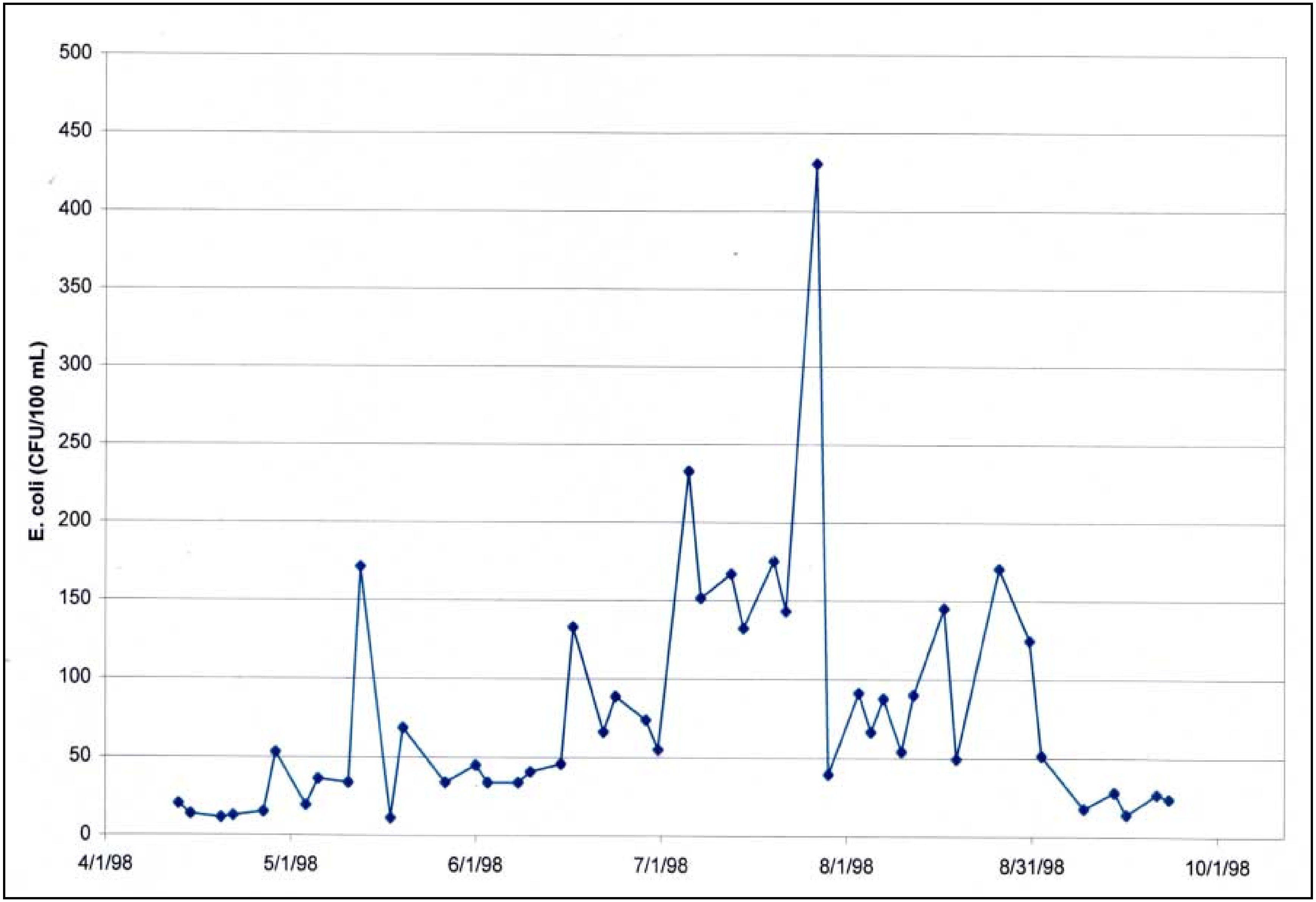

Figure 58. Concentrations of *E. coli* measured in the Metro Beach swimming area by the Macomb County Health Department during 1998

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13. ABSTRACT ***(Maximum 200 words)***

The purpose of this investigation was to determine sources of fecal coliform bacteria contaminating the Metro Beach area of Lake St. Clair and the likelihood that water currents moved contaminated water from the Clinton River cutoff into the Metro Beach area rapidly enough and with sufficiently limited dilution that bacteria from this source would exceed Michigan state standards for body contact recreation. Rhodamine WT, a red fluorescent dye, was used as a tracer for monitoring water movement near the Metro Beach area of Lake St. Clair during the weeks of 1 June, 13 July, 3 August, 24 August, and 7 September, 1998. The dye was injected into the upper 1 m of the water column near these locations along transects that were established perpendicular to the shoreline and approximately 600 m in length. Dye cloud movement from each transect was tracked at ~2-hour intervals over a 12- to 24-hour period. In conjunction with water movement studies, bacterial sampling transects, established perpendicular to the shore, were located between the Clinton River cutoff and the Metro Beach area. Along each transect, samples were collected at distances of approximately 100, 300, and 700-1000 m from shore. Bacterial samples were also taken from the mouth of the Clinton River Spillway. Dye dissipation studies and bacterial sampling were also conducted along the Metro Beach during the weeks of 3 and 24 August and 7 September, as mounting evidence indicated that bacterial contamination might be a localized nearshore phenomenon.

(Continued)

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Water currents in the part of Lake St. Clair between Metro Beach and the Clinton River cutoff were predominantly driven by wind direction and speed. In particular, winds blowing out of the west and southwest resulted in water circulation that followed an easterly trajectory toward the beach area. During the summer of 1998,winds blew out of the westerly wind rose (i.e., NW and SW wind rose) 62 percent of the time. Thus water movement from the mouth of the cutoff toward Metro Beach would have been expected to dominate circulation patterns from April until September. One possible source of fecal coliform contamination in the Metro Beach area was contaminated Clinton River water from the cutoff, transported to the beach by these water currents generated due to winds blowing out of the westerly wind rose. In order for this mechanism to operate, three conditions must be met: (1) the Clinton River cutoff must carry water with a high concentration of bacteria, (2) the flow of contaminated water from the Clinton River cutoff must be sufficient to produce a mass of contaminated water in the lake, and (3) water circulation must move the contaminated water mass from the cutoff to the beach rapidly enough so that the bacteria remain viable. However, these conditions were rarely met during the summer of 1998. Despite low flows from the Clinton River cutoff in 1998 and low bacterial concentrations in the area between the cutoff and Metro Beach, *E. coli* concentrations were often elevated in the immediate vicinity of the beach.

Bacterial concentrations along the beach transects were consistently highest close to shore, suggesting that bacteria were entering the lake directly from the beach. Bacterial concentration patterns observed near the beach during dye studies indicated relatively low bacterial concentrations in the water on the upstream end of the beach, which increased toward the downstream end of the beach. This pattern suggests that relatively clean water from the lake was becoming contaminated as it passed by the beach.

Relatively high levels of bacterial contamination in the beach area were attained despite the brief residence time of water in the area, indicating that the beach must be a substantial source of bacteria. The source of bacteria contaminating the beach was not positively identified, but large numbers of gulls and geese congregate on the beach at night, and their droppings are the most likely source. The results of this study provide very strong evidence that bacterial contamination of the beach at Metro Beach is an important source of bacterial contamination in the swimming area.