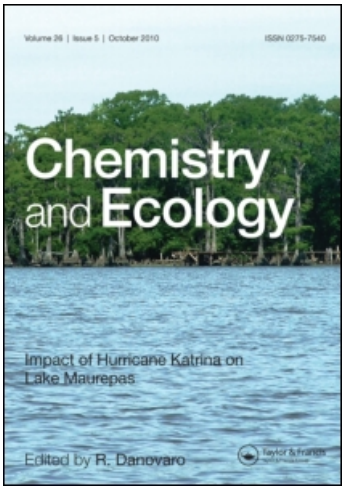


Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Transport of Sewage Sludge From the 106-Mile Site - Results From an October Survey

Carlton D. Hunt[a]; Scott E. Mcdowell[a]; Damian Shea[a]; Robert Hillman[a]; Wayne Trulli[a]; Tom Berger[b]; David Redford[c]; Doug Pabst[d]
[a] Battelle Ocean Sciences, Duxbury, MA [b] Science Applications International Corporation, Raleigh, NC [c] Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Oceans and Coastal Protection Division, Washington, DC [d] Environmental Protection Agency, New York, NY

To cite this Article Hunt, Carlton D. , Mcdowell, Scott E. , Shea, Damian , Hillman, Robert , Trulli, Wayne , Berger, Tom , Redford, David and Pabst, Doug(1992) 'Transport of Sewage Sludge From the 106-Mile Site - Results From an October Survey', Chemistry and Ecology, 7: 1, 195 — 231
To link to this Article: DOI: 10.1080/02757549208055441
URL: http://dx.doi.org/10.1080/02757549208055441

Chemistry and Ecology, 1992, Vol. 7, pp 195–231 Reprints available directly from the publisher Photocopying permitted by license only

TRANSPORT OF SEWAGE SLUDGE FROM THE 106-MILE SITE – RESULTS FROM AN OCTOBER SURVEY

CARLTON D. HUNT,* SCOTT E. McDOWELL,* DAMIAN SHEA,* ROBERT HILLMAN,* WAYNE TRULLI,* TOM BERGER,** DAVID REDFORD*** and DOUG PABST†

Battelle Ocean Sciences, 397 Washington St., Duxbury, MA 02332, Science Applications International Corporation, 615 Oberlin Road, Raleigh, NC 27605**, Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Oceans and Coastal Protection Division, 401 M St., Washington, DC 20460***, Environmental Protection Agency, Region II, 26 Federal Plaza, New York, NY 10278†*

(Received 2 March 1991)

Approximately 8 million tons of sewage sludge were disposed of annually at the 106-Mile Deepwater Municipal Sludge Dump Site (106-Mile Site) between 1987 and 1990. Beginning in 1988 and continuing to the present, the focus of monitoring at the 106-Mile Site moved towards improved understanding of the fate of the sludge. A survey conducted in October 1989 was designed to (1) detect the presence of any sludge particles that settle rapidly following disposal, (2) determine if sludge could be detected in the surface waters at locations away from the immediate disposal site, and (3) determine if water quality was degraded, by assessing whether the Environmental Protection Agency's marine water quality criteria were being exceeded.

The survey showed that the sludge does have a rapidly settling component composed of organic floc, mineral grains, and other heavy, gritlike particles, all of which are relatively large. These particles may settle at rates of between 8 and 180 m h^{-1} and may reach the sea floor within 1 to 13 days following disposal. Even though a rapidly settling component is present in the sludge, a significant fraction of the sludge was detectable in the form of intact sludge plumes in the upper 35 m of the water column at least 15 km from the Site. In addition, unique tracers of sludge such as xylem tracheids and *Clostridium perfringens* plus elevated total suspended solids and trace metals concentrations, were found at locations up to 40 km from the Site. The presence of these tracers correspond with *in situ* transmissometry data suggesting that a fraction of the sludge was remaining in the near-surface waters above the seasonal pycnocline. Concentrations of metals were below EPA chronic marine water quality criteria, which indicates that the water quality downstream of the Site was not impaired. The detection of sludge downstream of the 106-Mile Site is consistent with the southwestward movement of the surface water mass during the survey, as recorded by satellite-tracked surface drifters and current vectors derived from a current meter moored at 100-m depth immediately west of the Site. Near-surface transport was generally towards the southwest at a speed of approximately 22 cm s^{-1}.

KEY WORDS: Sewage sludge, transport

INTRODUCTION

Nine muncipal sewage authorities from New York and New Jersey have been disposing of sewage sludge at the 106-Mile Deepwater Municipal Sludge Dump Site (106-Mile Site) since the winter of 1986. The 106-Mile Site is located beyond the edge of the continental shelf, approximately 120 nmi southeast of Ambrose Light, at the entrance of the New York/New Jersey Harbor (Figure 1). Water depths there range

from 2250 to 2750 m. The [US] Environmental Protection Agency (EPA) designated the 106-Mile Site for the disposal of sewage sludge in 1984 and implemented a monitoring program (EPA 1991 a, b) in the summer of 1986.

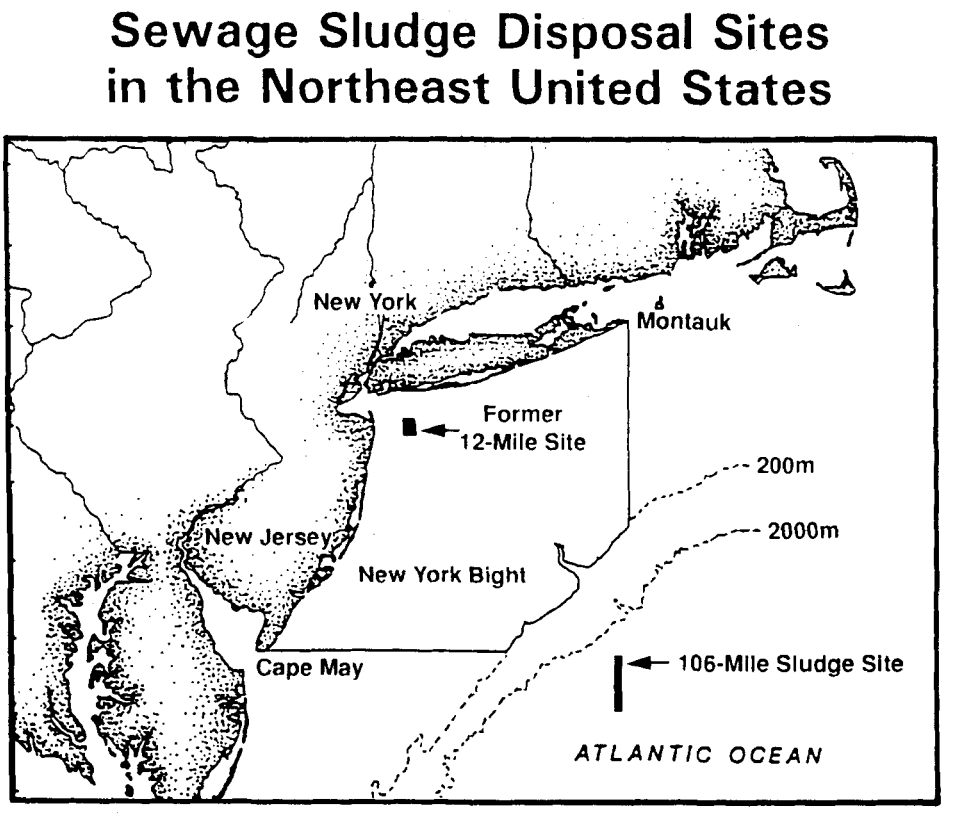


Figure 1 Location of the 106-Mile Site Deepwater Municipal Sludge Site

The objectives of the EPA monitoring program are to assess (1) compliance by the permittees with the conditions of ocean-dumping permits and (2) the environmental impacts and fate of sewage-sludge disposal at the 106-Mile Site. The programme was implemented according to a four-tiered approach whereby data generated in one tier may be used in making management decisions about continued use of the 106-Mile Site, the awarding of dumping permits, and the design and implementation of future surveys. Within each tier is a group of hypotheses that were to be tested through the activities of the monitoring progam.

From 1986 through 1988 the focus of the EPA monitoring program was on issues related to compliance, evaluation of the near-field fate of the sludge, and short-term effects. Results from studies conducted during this period are summarized in Redford *et al.* (1992). Tracking of sludge plumes for up to 12 h following disposal showed that much of the sludge remained above 25-m depth immediately following disposal and that sludge settling was a relatively slow process. Over short time-scales, sludge plumes were found to be transported in all directions from the disposal 106-Mile Site by surface currents. However, surface-current data and the trajectories of satellite-

tracked surface drifters showed that the long-term transport was on average towards the southwest. As a result of the slow settling rates and long-term net directions of the oceanic currents, the ultimate areas for deposition of the sludge dumped at the 106-Mile Site were believed to be located outside of the 106-Mile Site boundaries and generally towards the southwest, in the direction of the net long-term current drift in this region.

As a result, beginning in 1988 and continuing through 1991, the focus of monitoring at the 106-Mile Site was directed in part towards improving the understanding of the far-field fate of the sludge. A September 1988 survey to assess surface water conditions within 15 nmi of the 106-Mile Site demonstrated that sludge was difficult to detect in the surface waters outside of the disposal site and that a general, area-wide increase in the concentration of sludge constituents was not occurring. However, on the several occasions when sludge could be detected in the far-field, the sludge was generally confined to the surface waters (< 30 m) and associated with the observed maximum in particle concentration (EPA, 1991c). Also, sludge constituents were not observed to increase consistently in the pycnocline as postulated during development of the EPA monitoring plan. These results and those from the near-field studies indicated that a substantial fraction of the sewage sludge was remaining in the surface ocean for periods of days or longer.

At about this time, information from laboratory studies designed to evaluate sludge settling rates (Lavelle *et al.*, 1988) indicted that the sewage sludge contained a fraction (< 20%) of material that could settle at rates in excess of 0.3 cm s^{-1} (11 m h^{-1}). However, the majority of the particles were found to settle at rates much slower than 0.3 cm s^{-1}. Recent work by Bonner *et al.* (1992) provides additional evidence that much of the sludge is likely to settle slowly after disposal.

A rapidly settling component of the sludge had not been detected during the near-field studies. This may have been due to the inability of the measurement techniques to detect very small amounts of rapidly settling particles. Because the laboratory studies suggested that a significant fraction of the sludge could reach the sea floor within days of disposal and because of growing public concern about the fate of the sludge, further studies to evaluate the composition of the sludge and to quantify the settling rates of this material were recommended as necessary studies to increase the understanding of the sludge transport. This recommendation and the need to accelerate implementation of planned far-field fate studies (EPA 1991a, b) were identified in March 1989 during a workshop on the 106-Mile Site (EPA, 1989).

To address these recommendations, a survey was conducted in October 1989 in and near the 106-Mile Site to (1) detect the presence of any large sludge particles that might settle rapidly follwoing disposal, (2) determine if sludge could be detected in surface waters at locations away from the immediate disposal site, and (3) determine if water-quality was degraded by assessing whether EPA water quality criteria were being exceeded outside of the 106-Mile Site boundaries. Additional laboratory studies were conducted in 1989 and 1990 to evaluate the qualitative characteristics of large particles found in the sludge and to determine settling rates under controlled laboratory simulations of sludge disposal (Bonner *et al.*, 1992).

This survey was conducted in two phases: Phase 1 evaluated the rapidly settling component of the sludge; Phase 2 examined the far-field fate of the sludge in the surface waters in the downstream direction outside of the 106-Mile Site. To conduct Phase 1, shallow-depth (< 40 m), short-term sediment-trap deployments were conducted to detect any rapidly settling components of the sludge. Laboratory analysis identified and quantified the material captured in the traps. Additional

follow-up studies of sludge obtained from municipalities disposing of sludge at the 106-Mile Site were conducted to further quantify the type and amount of the large particles associated with the sludge.

For the far-field fate studies, satellite-tracked surface drifters were used to establish the downstream direction of the surface currents in the vicinity of the 106-Mile Site and to establish sampling station locations. At these stations, vertical profiles of temperature, salinity, and turbidity were obtained from the upper 75 m of the water column. In addition, water samples were collected at three depths (15, 30, and 75 m) for analysis of sludge tracers such as trace metals, total suspended solids, *Clostridium perfringens,* and other potential indicators of sludge, such as xylem tracheid cells. Xylem tracheids are relatively large, elongated, tapering plant cells composed primarily of lignocellulose, which decomposes very slowly. They are ingested as vegetable material and pass through a mammal's digestive tract undigested. As a result, they are founded in fecal material and, for that reason, were believed to be potential tracers of sludge.

In addition, a towed transmissometry system was used to locate remnant plumes in the surface waters downstream of the 106-Mile Site.

METHODS

Rapid Settling of Sludge Particles

Sediment traps designed to descend through the water column at speeds of approximately 3 m s^{-1} were deployed to collect particles that settled rapidly. Each sediment trap unit consisted of paired traps (each 36 cm in diameter, or 0.1 m^2 in cross-sectional area) held within a frame and tethered to a surface buoy for flotation and a 20 lb (33 kg) weight (Figure 2). All trap components were made from or coated with polyethylene to minimize extraneous contamination.

The sediment traps were deployed directly in the axis of sludge plumes immediately behind (i.e. within 200 m of) barges dumping sludge. Traps were allowed to drift free during the deployment period. The maximum depth of the sludge plumes observed from transmissometry profiles obtained in the plumes indicated that the plumes did not penetrate to depths greater than 5 m immediately following discharge. Therefore, the sampling depth of the sediment traps was set so that the traps were located at 20 m depth, or at least 15 m below the base of the plume. Traps were deployed for periods of 0.8 to 1.9 h. All traps remained in the plume axis during the entire deployment period. One set of traps was deployed in a plume axis and immediately recovered to determine whether large particles were captured during the descent and retrieval of the traps through the plume. One additional set of traps was deployed away from the sludge plumes but within the 106-Mile Site and served as a control sample.

Upon retrieval, the water in the trap funnel (above the sample-collection vessel) was drained through a petcock. The sample collection tube was removed from the rest of the sediment trap frame. The water in the collection tube and any particles captured by the traps were emptied into acid-cleaned containers, and formalin was added to retard bacterial activity. Samples were then stored at room temperature for later analyses.

Figure 3 illustrates the deployment locations and drift of the sediment traps deployed behind the barges *Eileen* (E-1) and *Seatrader 1* (E-2).

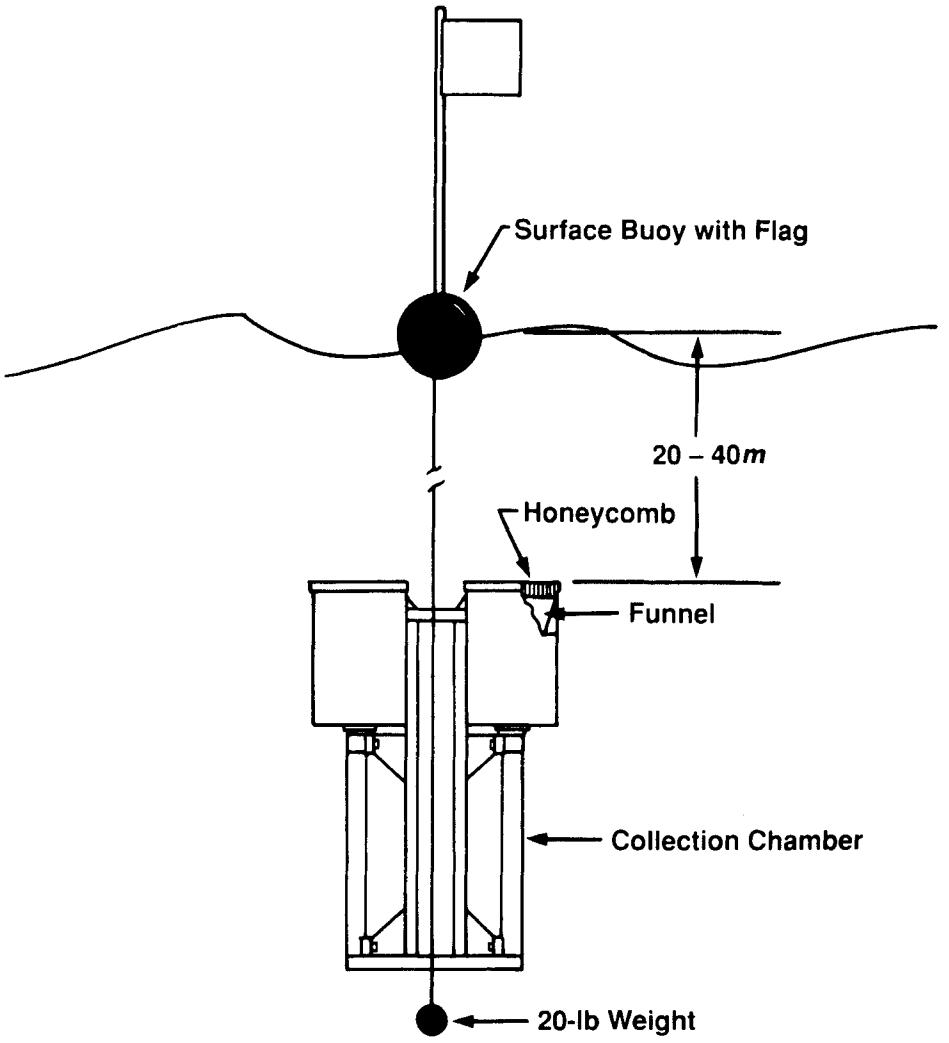


Figure 2 Sediment-trap configuration for sampling operations conducted during the October 1989 survey of the 106-Mile Site.

Sample analysis

Particles captured by the sediment traps were analyzed for type, number, and approximate size. The water retained in the storage bottle was decanted in the laboratory to minimize the resuspension of large particles that had settled during storage. The decanted liquid was filtered through 12-cm glass-fibre filter paper (2.5 μm), and the filter was dried in an oven for 24 h at 70 °C. The filter was then weighed. The large particles that remained in the sample container were then rinsed with deionized water and allowed to settle for approximately 2 min. The supernatant of

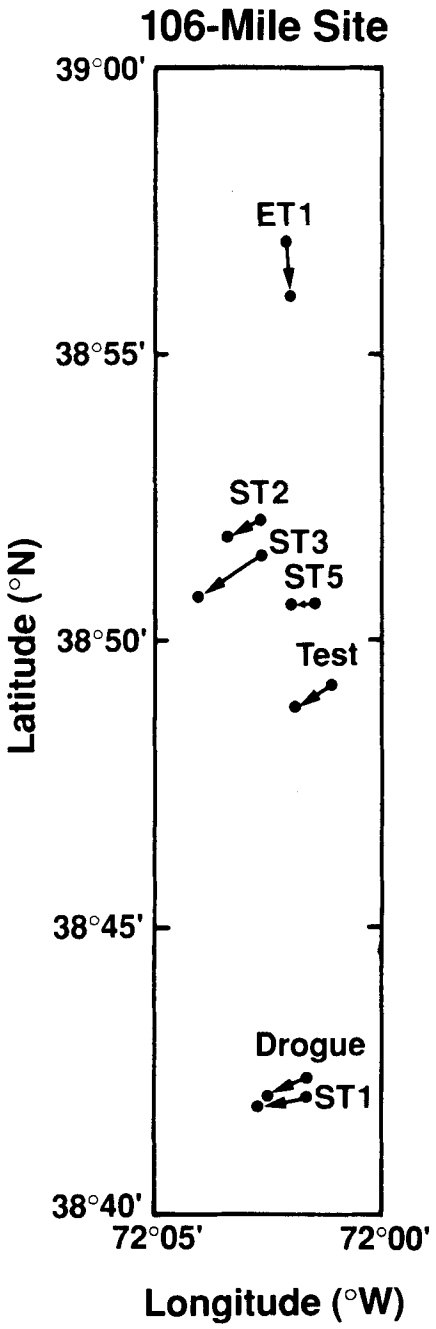


Figure 3 Deployment and retrieval location, and direction of drift for sediment traps and the drogue deployed during Phase 1 of the October 1989 survey of the 106-Mile Site.

this mixture was then decanted after a 2-min settling period and filtered as the first supernatant was. The remaining particles were then transferred to a deep Petri dish. After additional rinses, the particles in the Petri dish were transferred to a gridded Petri dish for further analysis.

Each filter sample was examined under a microscope, and all particles larger than 250 μm were removed and placed in the gridded Petri dish with the rest of the sample. The type and number of particles remaining on the filter paper were then recorded. The large particles in the Petri dish were counted, measured using a calibrated ocular micrometer, and classified according to their composition [e.g., flocculent (particles of different composition that clumped together), aggregate (particles of like composition that clumped together), plant material, mineral grains, grease, plastic, "coal", and unidentifiable.]

Laboratory studies of sludge

Twenty-one litre samples of sewage sludge were collected in the spring of 1990 from five sewerage authorities that were disposing of sludge at the 106-Mile Site (Table 1). The samples were obtained from holding tanks used to store sludge prior to loading barges or directly from the barges. Several techniques were tried for separating large particles from the remainder of the sludge, with limited success in each case. Techniques such as serial sieving through standard geological sieves (850–, 250–, 125–, and 63 μm) were found impractical because large amounts of a clear, fibrous material rapidly blocked the sieving process. Dilution of samples (10– to 100–fold) prior to sieving did not improve separation of large particles from the sludge. Three procedures that were slightly more successful were (1) diluting a known volume of sludge and allowing the large particles to settle, and (2) a reverse-flow concentration technique whereby the sludge was added in dilute form to a cylinder, (3) a gentle flow of water introduced at the bottom, and using air and water to strip the fibres and large particles from the sludge sample. Conceptually, the last two methods would carry the lighter particles up and out of the cylinder, while larger, dense particles would remain within the cylinder. The last technique proved to be the most effective. Unfortunately, large particles were observed to the entangled with the sludge, particularly the fibrous material previously mentioned, which decreased the effectiveness of the reverse-flow methods.

Table 1 Municipal facilities sampled for characterization of large particles, Spring 1990.

Facility	*Date sampled*
Bergen county utilities	May 31, 1990
Pasaic Valley Sewerage Commission (PVSC)	June 5, 1990
Rahway Valley Sewerage Authority (RVSA)	September 10, 1990
Westchester County Department of Environmental Affairs (WCDEA)	June 27, 1990
New York City Department of Environmental Protection (NYCDEP)	August 8, 1990

Even though quantitative results were not achieved for these samples, the exercise proved useful in that descriptive information related to the coarse fraction of the sludge was obtained. In addition, qualitative data on the minimum fraction of this type of material in the sludge was achieved.

Far-field Fate Measurements

Surface water movement

To determine the direction of the mean currents at the 106-Mile Site and thus the direction in which the sludge is transported during the far-field fate studies, four satellite-tracked surface drifters were deployed in the site over a 1-week period. The drifters, manufactured by the Charles Stark Draper Laboratories, consisted of a surface float containing a transmitter and a 7.5-m subsurface drogue suspended at 10 m. The positions of each drifter were tracked by Service Argos satellites, relayed to the Service Argos ground station in Landover, Maryland, and received by shore-based personnel at Battelle Ocean Sciences in near-real time. Shore-based personnel plotted drifter trajectory maps and transmitted them daily to the OSV *Anderson* by telefacsimile. In addition, thermal imagery of the ocean surface, available from the National Earth Satellite Service of the National Oceanic and Atmospheric Administration (NOAA) was used to derive quantitative information on sea surface temperatures (SST) and to indicate the locations of significant thermal features, such as continental shelf water, continental slope water, the Gulf Stream, and warm-core and cold-core eddies formed by Gulf Stream meanders. Maps indicating the boundaries of these thermal features were produced daily from October 13 through 31, 1989, and transmitted daily by electronic facsimile to the ship.

Shipboard personnel used the drifter trajectory maps and the thermal imagery information to determine the most probable direction of sludge transport away from the 106-Mile Site and then establish the positions of sampling stations (Figure 4) for evaluating the far-field transport of the sludge.

Vertical profiling and water sample collection

Three background stations (BK-1, BK-2, and BK-3), located to the east and north (upstream) of the 106-Mile Site, were selected to minimize the possibility of sampling sludge dumped at the 106-Mile Site. Three transects (A, C, and D), comprising a total of 21 vertical profiling stations, were located downstream of the 106-Mile Site. Transects A and C each consisted of eight stations (A-1 to A-8 and C-1 to C-8) spaced at 4 nmi intervals. Transect D consisted of five stations (D-2, D-4, D-6, D-8 and D-10) spaced at 8 nmi intervals. The stations were positioned to maximize the probability of detecting sludge carried from the 106-Mile Site into the far-field by near-surface currents.

At each of these stations, two major activities were conducted: vertical profiling for hydrographic/transmissometry information and water sampling. These operations were conducted using the Battelle Ocean Sampling System (BOSS). As described in McDowell *et al.* (1989), the BOSS is an integrated, *in situ* sensor package and sea water sampling system composed of a depressor which supports *in situ* sensors and a submersible pump, an electromechanical cable with an internal Teflon® tube for continuous delivery of water, a hydraulic winch and boom assembly, and a PC-based data acquisition and display system. The sensor package consists of a Sea-Bird, Inc., high-resolution conductivity/temperature/depth (CTD) profiling system. In addition, turbidity was measured with a 25-cm-pathlength SeaTech transmissometer. The sea water sampling system is composed of a submersible titanium pump that is connected to the ship's laboratory by 150 m of Teflon tubing within the profiling cable. The pump delivers water to the onboard laboratory at a minimum rate of 14 l/min^{-1}.

Vertical CTD/transmissometry profiles were made to depths of 75 to 90 m. From

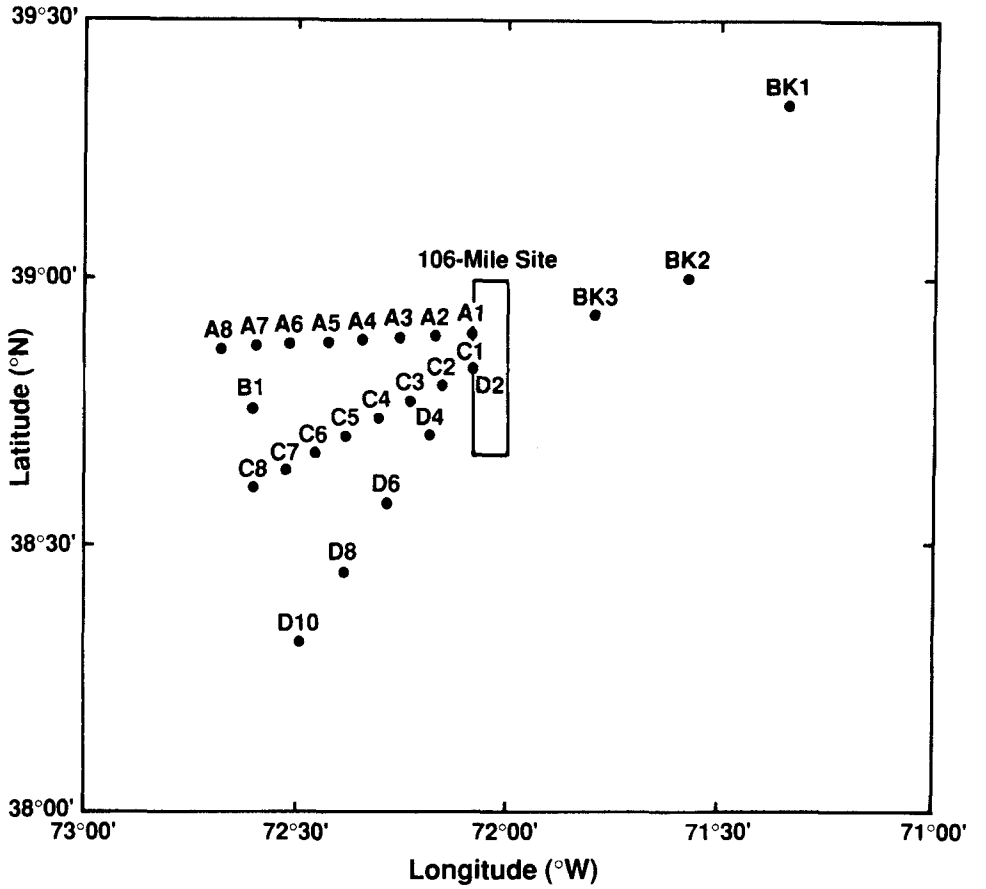


Figure 4 Map of the discrete stations sampled during the background (Phase 2) and the far-field (Phase 3) activities conducted during the October 1989 survey at the 106-Mile Site.

these profiles, the depth of the particle maximum was determined, and water samples were collected at two or three depths (at approximately 15 m, at the particle maximum in the shallow pycnocline, and at 75 m). Surface and pycnocline samples were collected at all stations. Samples for analysis of total trace metals, *C. perfringens, Salmonella* spp., chlorophyll *a,* xylem tracheids, and pathogens were obtained at these stations. At the three background stations and at 10 of the 21 far-field stations, samples were collected in duplicate from the three depths. These samples included trace metals (particulate trace metals and dissolved trace metals from the mixed layer and pycnocline; total trace metals from below the pycnocline), *C. perfringens, Salmonella* spp., chlorophyll *a,* xylem tracheids, and pathogens. In addition, particulate samples (from filtration of 400 l of water) for analysis of organic constituents were collected from the mixed layer and pycnocline at six of the 10 stations sampled at three depths. These data are not reported in this paper.

Horizontal transects

During transits between background and far-field stations, subsurface water

property data were acquired with a towed STD/transmissometer package. The towed system was composed of an Applied Microsystems STD-12 and a SeaTech transmissometer with a 25-cm pathlength. These instruments were mounted on the upper surface of a 3 ft wide depressor. The horizontal profiles provided improved areal coverage for detecting sludge signals in the far-field and increased the probability of finding any localized sludge concentrations in the surface water. The same data acquisition system used to acquire vertical profile data was used for horizontal profiling operations, but the STD sampling rate was 2 Hz instead 24 Hz. At this sampling interval and an average vessel speed of 7 kn, independent turbidity readings were acquired roughly every 3 m.

The sampling tows were conducted between all background stations and all but four far-field stations. The ship track followed during the profiling activities is shown in Figure 5. Towing depths were changed occasionally during several transits and ranged between approximately 15 and 30 m.

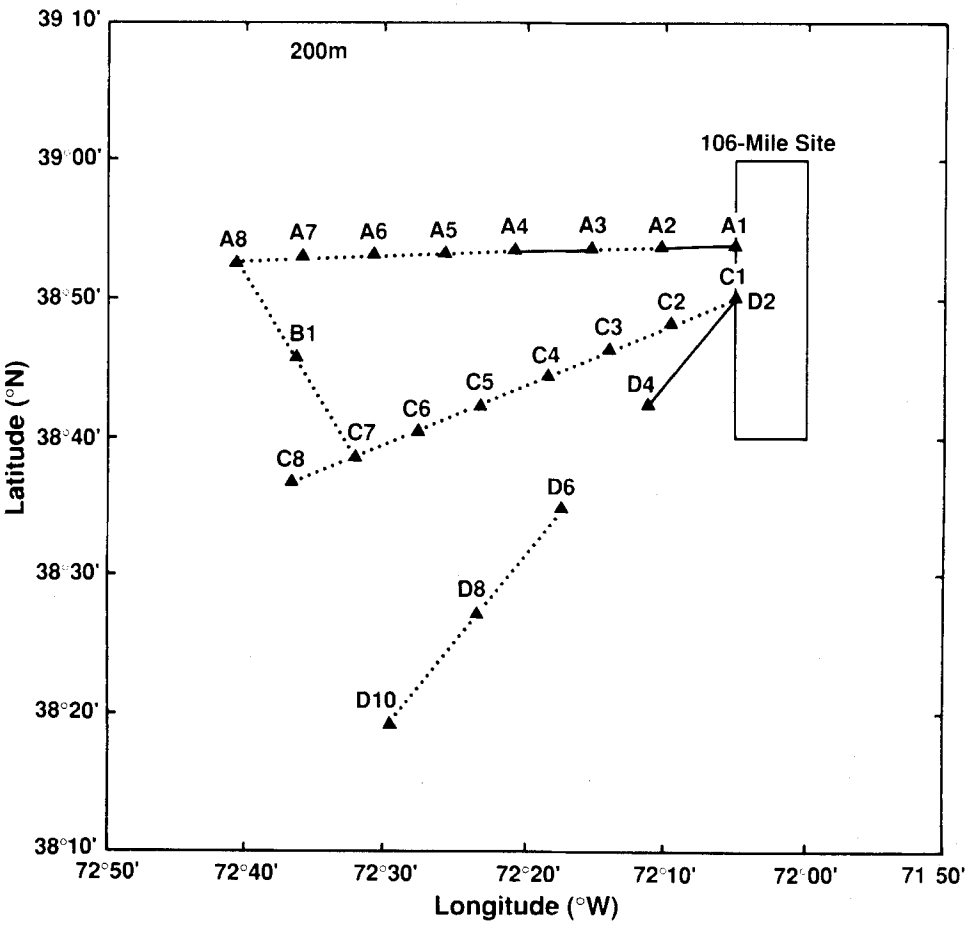


Figure 5 Map of the study area west of the 106-Mile Site indicating locations where horizontal transects of near-surface turbidity were acquired (dashed lines). Plumes were observed only along transects that are indicated by bold lines.

ANALYTICAL METHODS

Metals and Total Suspended Solids

Dissolved trace metal and total suspended solids (TSS) samples were vacuum filtered through acid-cleaned 47-mm diameter 0.4-μm pore-size Nuclepore filters. The total volume filtered for TSS concentrations was determined volumetrically; metals sample volumes were determined from the mass of the sample filtered. Nalgene 1000 ml polysulphone filter units, located in a Class-100 clean bench in the wet laboratory of the OSV *Anderson,* were used to separate the dissolved and particulate phases. The filtrate was transferred to tared acid-cleaned polyethylene storage bottles. All filters were then rinsed with three 10 ml rinses of deionized water adjusted to pH 8 with NH_4OH. Particulate samples were stored in cleaned, sealed polycarbonate Petri dishes. Samples for total trace metal analysis were acidified (HNO_3) on board the survey vessel to pH < 2, as were the samples for dissolved metal analysis.

TSS samples were filtered through pre-tared filters. The filters were rinsed three times with pH 8 deionized water to remove sea salt and stored in sealed Petri dishes for later mass determinations. In the laboratory, the samples were allowed to air dry in a Class-100 clean room prior to determination of the total mass on the filter.

Sea water samples for both total and dissolved trace metal analysis were extracted at pH 5 with a 1% solution of purified ammonium 1-pyrrolidine dithiocarbamate-diethylammonium diethyldithiocarbamate (APDC-DDDC) and Freon (Danielson *et al.,* 1982). Each sample was extracted three times with 5 ml aliquots of Freon; all Freon extracts were combined. The metals were back-extracted into 2 ml of 10% nitric acid. The nitric acid solutions were analyzed for cadmium, copper, iron and lead by graphite furnace atomic-absorption spectrometry (GFAAS), with Zeeman background correction and matrix modification, as appropriate, for the analyte of interest.

Samples for particulate trace metal analyses were placed in a 20 ml Teflon vial and digested with 5 ml of 3N nitric acid by sonicating for 1 h in a Class-100 clean hood. Metal concentrations in the acid digestates were determined by GFAAS with Zeeman background correction. Potential matrix interferences were minimized by using a standard curve prepared by the method of standard additions on one of the particulate samples. Matrix modification was used to reduce interferences during the analytical step.

Clostridium Perfringens and Salmonella spp.

C. perfringens and Salmonella spp.

Samples were processed immediately after collection and analyzed aboard ship within 48 h of collection. *Clostridium perfringens* spores were enumerated by the modified *C. perfringens* (m-*CP*) method documented by Bisson and Cabelli (1979). *C. perfringens* spores were collected by filtering aliquots sea water through 0.4 μm polycarbonate filters. The filters were cultured anaerobically on m-*CP* medium. Confirmation was obtained by exposing the incubated plates to ammonium hydroxide vapours, which turns *C. perfringens* colonies a magenta colour. The bacteria were quantified as the number of colonies per 100 ml of filtered sea water.

Sample analysis for *Salmonella* spp. in sea water was a multi-step procedure, a compromise between the need for sensitivity (because of expected low levels) and the need for selectivity. This procedure was developed from several sources and

involved four steps: sample concentration, sample enrichment, colony isolation/presumptive identification, and confirmation. The first three steps were conducted aboard ship, and the fourth was accomplished upon return to shore.

For each sample, a 1 l volume was concentrated by filtration on to 47 mm, 0.4 μm filters. The filters were transferred to a flask containing tetrathionate enrichment broth and incubated at 35°C for 96 h. After 24- and 96-h incubations, samples from the flask were streaked on to 100-mm-diameter Petri dishes containing XLD and BG agar to initiate the isolation and presumptive identification procedures. The Petri dish cultures were incubated at 35 °C for 24 h. After incubation, colonies typical of *Salmonella* (if apparent) were transferred to TSI slants, incubated at 35 °C for 24 h, and then refrigerated. Presumptive *Salmonella* isolates were identified to species by the API 20E system for confirmation. Because the procedure was complex, three control samples were carried through all the steps in the procedure several times during the survey. The three control analyses included a sterile buffer blank, a positive control (a *Salmonella* culture), and a negative control [an *Escherichia coli* culture].

Xylem Tracheids, Acanthamoeba spp., and Ascaris Eggs

Large sample volumes (approximately 38 l) were collected for analysis of xylem tracheids, *Acanthamoeba* spp., and *Ascaris* eggs. Stations selected for analysis of these parameters included two sets of background samples (BK-2 and BK-3), two series of samples taken behind the barges ($T=0_1$ and $T=0_3$; 0 indicates samples collected immediately behind the barge, the subscript is the sequence number for repeated samples at 0), and four series from the far-field stations (A-7, C-5, C-6, and C-7). The presence of high concentrations of the enteric bacterium *C. perfringens* (from shipboard analysis) was the single criterion used to select the far-field samples for these analyses.

In the field, each 38 l sample was filtered through a 64 μm-mesh net. The filtrate was discarded and the retained particulate material transferred to a glass jar and preserved with 10% formalin. In the laboratory, each sample was shaken to suspend the particulate matter in the jar. For most samples, the contents of the jar were filtered through a Millipore® filter with a surface area of 1257 mm^2. Millipore filters were found to be better than Whatman No. 1 filter paper because their surfaces were easily scraped with a spatula to remove the adhering particles and also allowed the samples to be concentrated in a smaller surface area.

Slides were examined for xylem tracheids and pathogens within 30 min of the filtering. To conduct the examination, a small drop of water was placed on about 50 mm^2 of the filter paper, and the surface of the paper was scraped with a square-edged chemical spatula. The scraped material, suspended in the water drop, was removed with a fine-pointed Pasteur pipette and placed on a standard 1 in by 3 in. glass microscope slide. A small amount of 1% methylene blue was added to the suspension on the slide, and the suspension was covered with a 24 by 50 mm glass cover slip. The slide was examined for tracheids and pathogens under low power (100X). Each filter underwent three such scrapings. The total scraped area of each filter was, therefore, 150 mm^2.

If the number of tracheids on a slide appeared to be relatively high (i.e., if several tracheids could be seen in a single field at the first observation), then the number of tracheids in each of five fields was counted. (The area of a field under low magnification was calculated to be 1.41 mm^2.) If there were very few obvious

tracheids, the whole slide (i.e., the area under the cover slip) was scanned. The area of the slide that was scanned was calculated to be 1200 mm^2.

The number of tracheids in the original 38 l sample was estimated by first calculating the number of tracheids on a slide and extrapolating that number to estimate the number of tracheids on the filter paper. Because the entire sample was filtered, the number of tracheids on the filter paper equalled the number in the original sample.

The technique used to distinguish the tracheids was also used to distinguish the eggs of the roundworms *Ascaris* spp. and the protozoan *Acanthamoeba* spp. Quantification of these pathogens was similar to that for the tracheids.

RESULTS AND DISCUSSION

Particle Settling

The number and type of particles captured by the sediment traps for each sampling event are shown in Table 2. Data from the trap deployed for background samples and from the trap deployed in a plume but recovered immediately are not included because particles were not observed in the sediment traps. Numerically, these were followed by plant material and unidentifiable particles. Interestingly, variously sized sand particles, small grease balls, and plastic materials were observed in all samples. The size distribution of the samples, regardless of the type material, is shown in Figures 6 and 7. Most particles (61 to 86%) were found to be less than 1 mm in diameter. Particles between 1 and 2 mm contributed 9 to 25% by number. A substantial number of the particles were larger than 3 mm; several particles from the *Seatrader* were larger than 10 mm. The total mass of the large particles averaged 13 $\pm$ 6 mg in six samples. This translates to an area-based distribution of approximately 130 mg m^{-2}. This concentration is an order of magnitude estimate of the input of the large particles immediately beneath the sludge plumes. This does not, however, represent the area-based mass that may reach the sea floor since oceanic processes disperse this material over a broader area.

The laboratory analyses of the trapped, rapidly settling particles did not include determination of their actual settling rates. However, from the known depth of the traps and the elapsed time that the traps were immersed, it is possible to estimate the minimum settling rate of the particles collected. For example, assuming that the base of the plume was at 5 m and that the trap was situated at 20 m depth, the vertical excursion of the particles was 15 m. Using the actual trap immersion time of event E1 (0.8 h), the collected particles must have settled at a minimum rate of 19 m h^{-1} (0.5 cm s^{-1}). Using an average water depth of 2500 m, these particles would have reached the bottom in a maximum of 5 days if their settling rates were not altered by physical or biological processes. Particles collected during the other sampling events must have settled at a rate of 8 m h^{-1} or more, resulting in estimates of bottom impact in roughly 13 days.

Theoretical settling rate estimates can be made with the Stokes rate law of particle settling equation described by Blatt *et al.* (1980):

$$v = \frac{(\rho_s - \rho_w)g}{18\,\mu}\, d^2$$

Table 2 Type and number of large particles in traps deployed in sludge plumes

Sample[a]	*Flocculent*	*Aggregate*	*Plant Material*	*Unidentified*	*Grease*	*Plastic*	*Sand*	*Coal*	*Other*	*Total*
Eileen Seatrader	> 148	5	26	> 42	1	27	42	–	–	> 291
$T0_1$	> 66	80	25	> 46	4	1	> 2	–	5	> 231
$T0_2$	> 88	93	32	54	10	–	12	–	–	> 290
$T0_3$	> 99	120	36	48	9	1	8	7	5	> 334

[a]$T0_n$ indicates the collection of samples immediately behind the barge at different times.

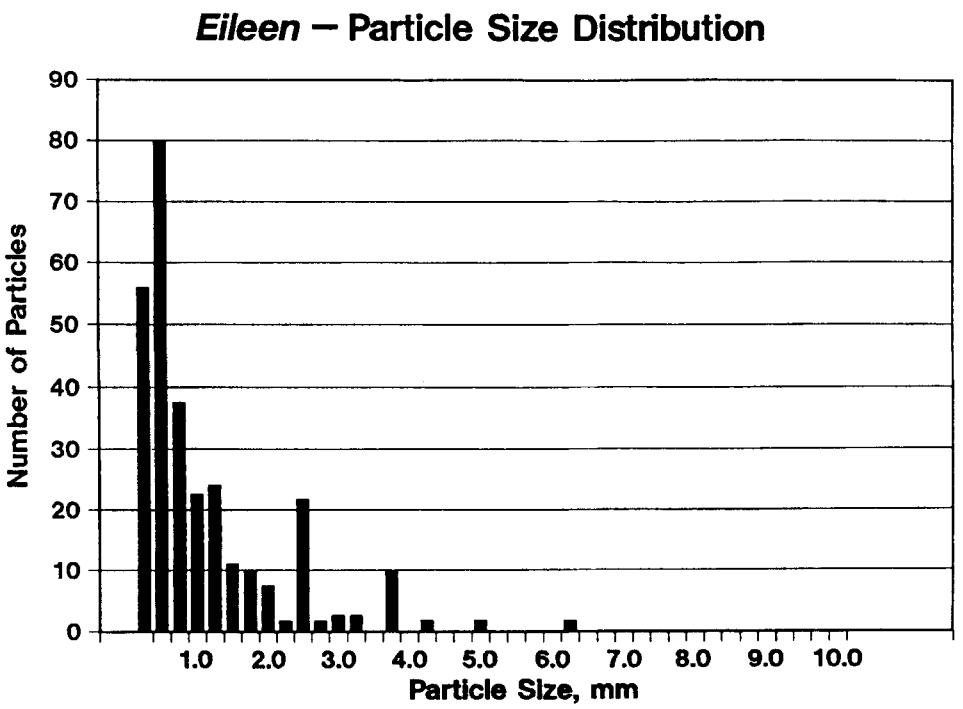


Figure 6 Size distribution of particles captured in the sediment trap deployed under the plume of the barge *Eileen*.

where v = particle velocity, ρ_s = particle density, ρ_w = water density, g = acceleration due to gravity, μ = viscosity, and d = particle diameter. Using the shortest trap deployment interval of 0.8 h, the observed diameter of particles from the sediment traps (range from < 250 >m to about 10 mm), and a viscosity of 0.0109 poise (Knauss, 1978) for sea water of 35 ppt and 20 °C, the settling rates of the particles with the greatest density (sand) can be used to provide an upper limit on the settling rates and hence, a lower limit on the settling rates and hence, a lower limit on the time required for the particles to reach the sea floor. For this estimation, ρ_s is equivalent to 2.65 g cm^{-3}, and the density of sea water under the prevailing conditions is about 1.025 g cm^{-3}. Given the values, a particle of 250 μm diameter would settle at a rate of about 5 cm s^{-1} (180 m h^{-1}), and these particles would travel the 15 m distance from the base of the plume to the sediment trap within about 5 min after disposal. They would reach the sea floor within 0.5 day. From the above estimates, it is clear that large, dense particles in the sludge will likely reach the sea floor within less than 1 week following disposal.

Laboratory Characterization Study

The results of the laboratory experiments used to confirm the type and amount of coarse, (and potentially) rapidly settling particles are shown in Table 3. The > 63 μm fraction of the sludge comprised from 12 to 17% of the mass of the sludge in the four

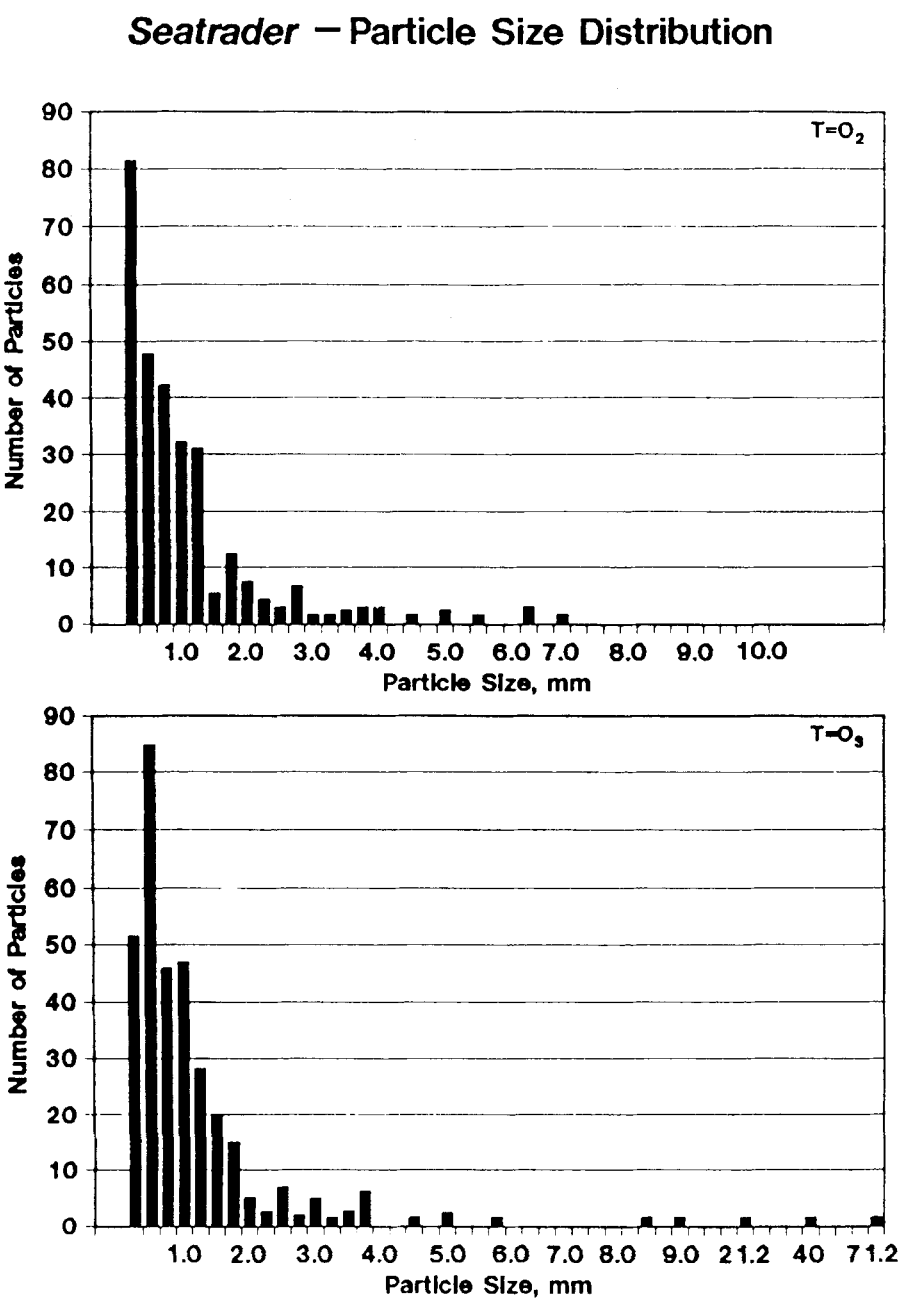


Figure 7 Size distribution of particles captured in the sediment traps deployed under the plume of the barge *Seatrader I* at $T=O_2$ and $T=O_3$.

Table 3 Percentage of large particles in sludge samples by size class microns (μm)

	Total Solids	*Size class*				
POTW	%	>850	850–250	250–126	125–64	<64
PVSC	7.5	6.0	–	5.3	2.0	86.7
WCDEF	2.5	–	7.9	3.2	6.2	82.7
RVSA	2.9	–	6.2	6.2	–	87.6
NYCDEP	1.1	–	4.0	1.7	11.6	82.7

samples for which reasonably good qualitative data were obtained. This is consistent with the results reported by Lavelle *et al.* (1988). Except for the Passaic Valley sample, particles greater than 850 μm were not observed. Generally, the mass of material was equally distributed among the three size ranges measured. Most of the material retained on the sieves or remaining after the lighter materials were removed by the reverse-flow methods was acellular fibrous material (not xylem tracheid cells) interspersed with grit and small zooplankton. Observation of the particles with 15 × magnification of a binocular microscope described the materials as black, irregular-shaped, gritlike particles; very fine- to medium-grained sand (frequently observed after combustion of the sample at 550 °C); pieces of vegetation; and light brown, light gray, and black particles (generally noted as sand). These types of particles were observed within all classes.

Water Mass Characterization

The *in situ* physical oceanographic and remote sensing measurements conducted during Phase 2 were used to characterize the near-surface water masses located in the area of the 106-Mile Site. These measurements provided information on the three dimensional water column structure and movement of the water masses that were identified.

Information on the water masses in the study area obtained with high-resolution, Advanced Very High Resolution Radiometer (AVHRR), sea-surface thermal (SST) imagery obtained from the NOAA-11 satellite was used to determine the approximate boundaries between the continental shelf water, the Slope Water, and the northern edge of the Gulf Stream in the region offshore of the US east coast. The locations of major features present during the survey period are shown in Figure 8. The shelf/slope front between the 100 m and 1000 m isobaths consisted of a well-organized series of regularly spaced, small-amplitude meanders. A large shelf water into the slope sea was observed opposite Chesapeake Bay near the western edge of the area, and a smaller streamer of cool shelf water (Churchill *et al.*, 1989) lay along the Gulf Stream front south of the intrusion. The small-amplitude meanders appeared to become disorganized and irregular as the period progressed, so that larger intrusions of shelf water appeared over the length of the front. Whether these intrusions were analogous to the shelf water plumes of Garvine *et al.* (1988) is not clear. The intrusions did not appear to be associated with eddies on the shelf/slope front.

Within the slope sea, the 106-Mile Site itself was covered by 20 °C water at the beginning of the monitoring period (October 11). Surface temperatures at the 106-Mile Site warmed to 21.5 °C over the next week, then cooled at 20 °C near October 30. In general, the slope sea had little discernible surface-temperature structure. A

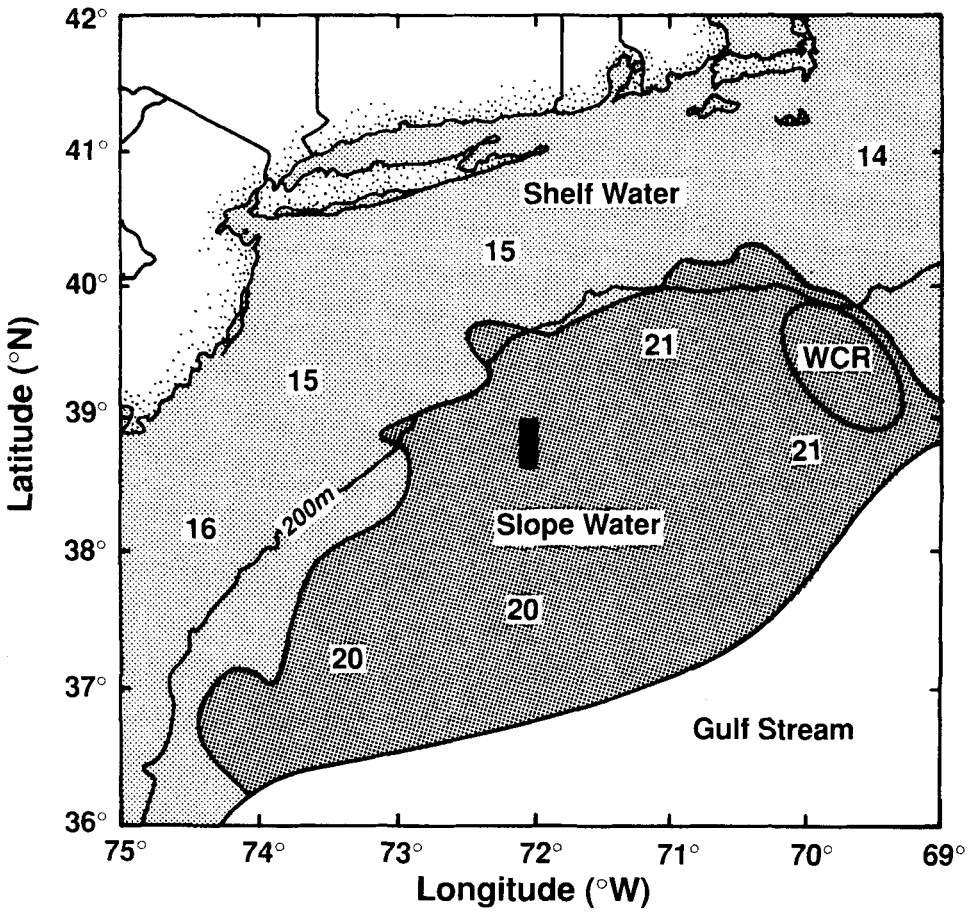


Figure 8 Graphical representation of the ocean frontal data for October acquired by satellite imagery during Phase 1 of the October 1989 survey of the 106-Mile Site. (Numbers shown are surface water temperature in °C.)

warm core ring (WCR) was visible approximately 250 km east of the 106-Mile Site throughout the period and moved approximately 76 km west-northwest over 19 days. No interaction with the 106-Mile Site occurred.

The Gulf Stream front appeared to be in a stable configuration, in that no large changes in its shape or position occurred during the study period. In the area generally west of 72° W, the Gulf Stream front was found close to or slightly south of the mean historical position determined by Robinson and Niiler (1967). East approximately 72° W, the Gulf Stream front was generally well to the north of the historical mean position but within the distribution of positions determined by Vasquez and Watts (1985).

Direct measurements of the surface flow in the vicinity of the 106-Mile Site were made with satellite tracked surface drifters. The trajectories of the four drifters deployed within the 106-Mile Site during October 1989 are shown in Figure 9. Daily

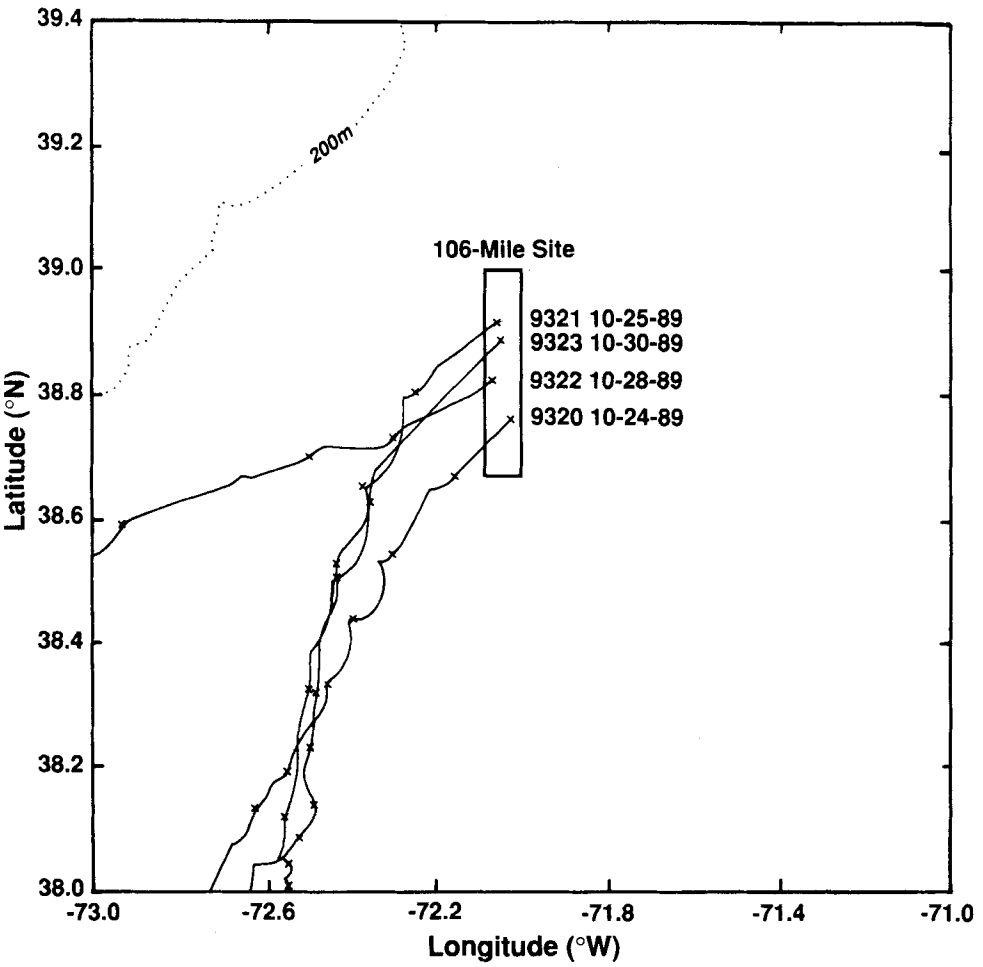


Figure 9 Argos drifter tracks for drifters deployed during the October 1989 survey of the 106-Mile Site. (x: Daily positions of each drifter)

time indicators along each trajectory are marked by an 'x'. Trajectories have been smoothed using a fourth-order cubic spline. This composite of drifter trajectories illustrates that three of the four drifters moved southwestward, while one (9322) moved more westerly.

Numerical analysis of the first 7 days of each trajectory revealed remarkable consistency among the drifters. Using the 7-day initial displacement of each drifter, the average speed and direction of each were calculated. Drifters 9320, 9321, and 0323 all moved at speeds ranging from 22.0 to 22.7 cm s^{-1} and directions between 192 and 213° T. Drifter 9322 moved toward 249° T at an average speed of 23.1 cm s^{-1}.

The EPA current meter array that has been moored to the west of the site since early 1989 provided good quality time-series measurements of currents and water temperature from a depth of 100 m throughout the survey period. Hourly time series of the north and east components of current velocity were numerically filtered to remove all but the low-frequency motions, to simplify interpretation of low-

frequency flow. Figure 10 presents a vector representation of the low-frequency flow at 100 m depth. At 2 h intervals along the time axis, a line is drawn representing the speed and compass direction of the current. Northward flow is represented by a vertical line extending upward; southwestward flow is represented by a line extending downward toward the left. The length of each line is scaled according to the current's speed. This figure clearly illustrates that the low-frequency (time-averaged) flow over the 13 day observation period was always toward the southwest. The calculated speed and direction of this flow were 26.4 cm s^{-1} and 242° T, respectively. These are very similar to the values obtained from the surface drifters, indicating a relatively coherent flow between the surface and the 100 m depth level.

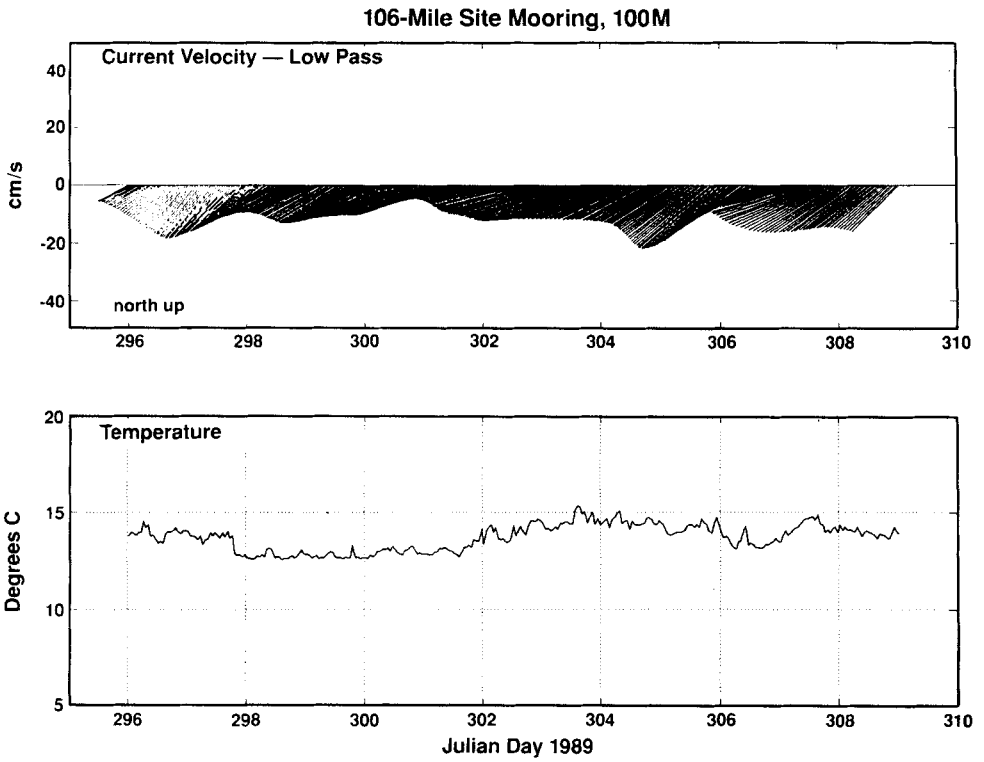


Figure 10 Time series of current vectors (upper) and water temperature (lower) measured at 100 m depth at the 106-Mile Site from October 22 to November 5, 1989. Each velocity vector indicates the direction and magnitude of the low-pass-filtered current.

Current shear information obtained from an expendable current profiler (XCP) deployed in the 106-Mile Site during the survey indicates that this southwestward movement was present to a depth of approximately 300 m. Current speeds measured by the XCP were less than 10 cm s^{-1} at depths greater than 50 m. Below 300 m, currents were generally weak ($<< 10$ cm s^{-1}). Under such weak flow conditions, the absolute accuracy of the XCP is questionable because by the XCP measures current shear rather than absolute current velocities. Consequently, a depth independent velocity adjustment of unknown magnitude must be made to each XCP profile to

interpret the XCP data as absolute velocities. This correction was not applied to the XCP data.

A typical vertical profile of temperature, salinity, density, and turbidity (percent light extinction) within the upper 75 m of the water column is shown in Figure 11. This profile is from Station C1 within the 106-Mile Site and is typical of the stations along Transect C, since temperatures, salinity, and density were very constant within a well mixed surface layer extending to a depth of roughly 40 m. Below this mixed layer, temperatures decreased rapidly within the seasonal thermocline, and salinities increased by roughly 0.5 ‰. The approximately 5 °C decrease in temperature between 40 and 50 m, combined with the moderate increase in salinity, resulted in a sharp pycnocline (density gradient) at the base of the mixed layer. Turbidity levels were relatively low and very constant over the upper 75 m. However, a slight increase in turbidity immediately above the pycnocline was evident. This feature is representative of normal conditions observed previously in and near the 106-Mile Site (EPA, 1991c, d).

Contour plots of individual water properties observed in the upper 70 m along Transect C are represented in Figure 12. This figure essentially presents the results obtained for a vertical slice along Transect C, with stations labeled at the top. The upper frame in Figure 12 presents temperature contours ranging from 14.8 to 20.4 °C with a contour interval of 0.4 °C. The salinity results (second frame in Figure 12) show that near-surface salinities were generally less than 35.2 ‰, whereas salinities below the thermocline were greater than 35.6 ‰. There was also a trend toward increasing salinities within the surface mixed layer toward the southwest (toward Station 8). The density (sigma t) results presented in the lower frame of Figure 12 illustrate that the pycnocline was essentially flat and located between roughly 35 and 60 m.

Turbidity values generally varied by only a few percent over the upper 70 m of the water column along this transect; values generally decreased with depth. The only anomalous results were observed at Station C6, where elevated turbidities were measured over the depth range of from 20 to 33 m. These relatively high turbidity values were associated with water that had higher salinities and slightly lower temperatures than did water in the upper portion of the surface mixed layer. Analysis of the temperature/salinity characteristics of this water indicates that it was different from waters both within the mixed layer and within the pycnocline along Transect C.

The vertical profile results obtained along Transect D were very similar to those observed along Transect C. An isothermal, isohaline, surface mixed layer extended to a depth of approximately 35 m, below which a sharp thermocline and pycnocline were evident. Turbidities were relatively constant within the mixed layer and then decreased through the pycnocline.

In contrast, the temperature and turbidity values along Transect A (Figure 13), made roughly 2 days after Transect C, exhibited greater variability within the surface mixed layer than had been observed along Transects C and D. The depth and thickness of the thermocline and pycnocline were also more irregular along Transect A. Salinities were quite homogeneous along the transect, as had been observed along Transects C and D.

Comparison of the three transects reveals that the mixed layer along Transect A was warmer and more saline than it was along the two transects located farther to the south. Temperature/salinity characteristics of the near-surface waters along the three transects indicate that these water properties were dissimilar between the transects and apparently associated with the horizontal advection of slightly different

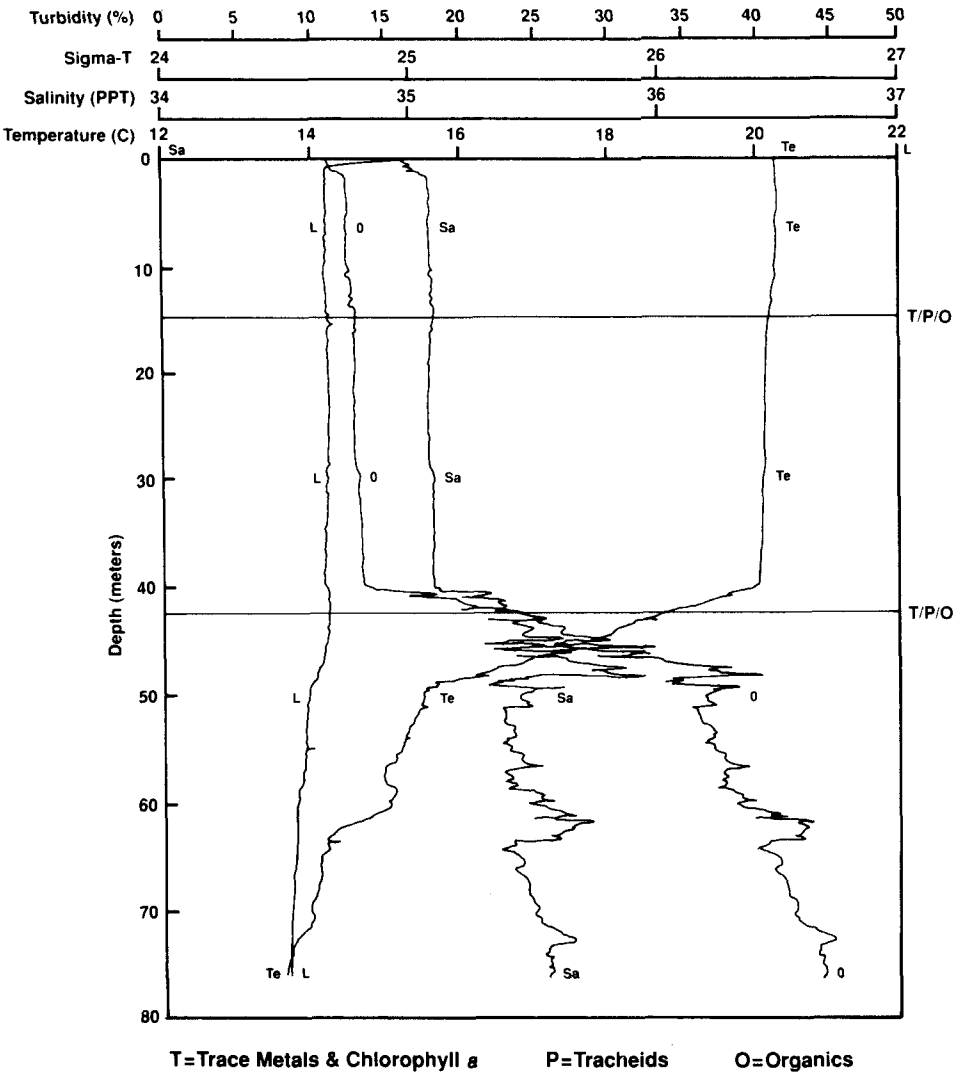


Figure 11 Vertical profile of water properties acquired at station C1 on October 27, 1989. The following codes are used on the figure: transmissometry (L), temperature (Te), salinity (Sa), and density (D). The depths and type of discrete samples that were collected are shown by the horizontal lines labled with T, P, O as coded above.

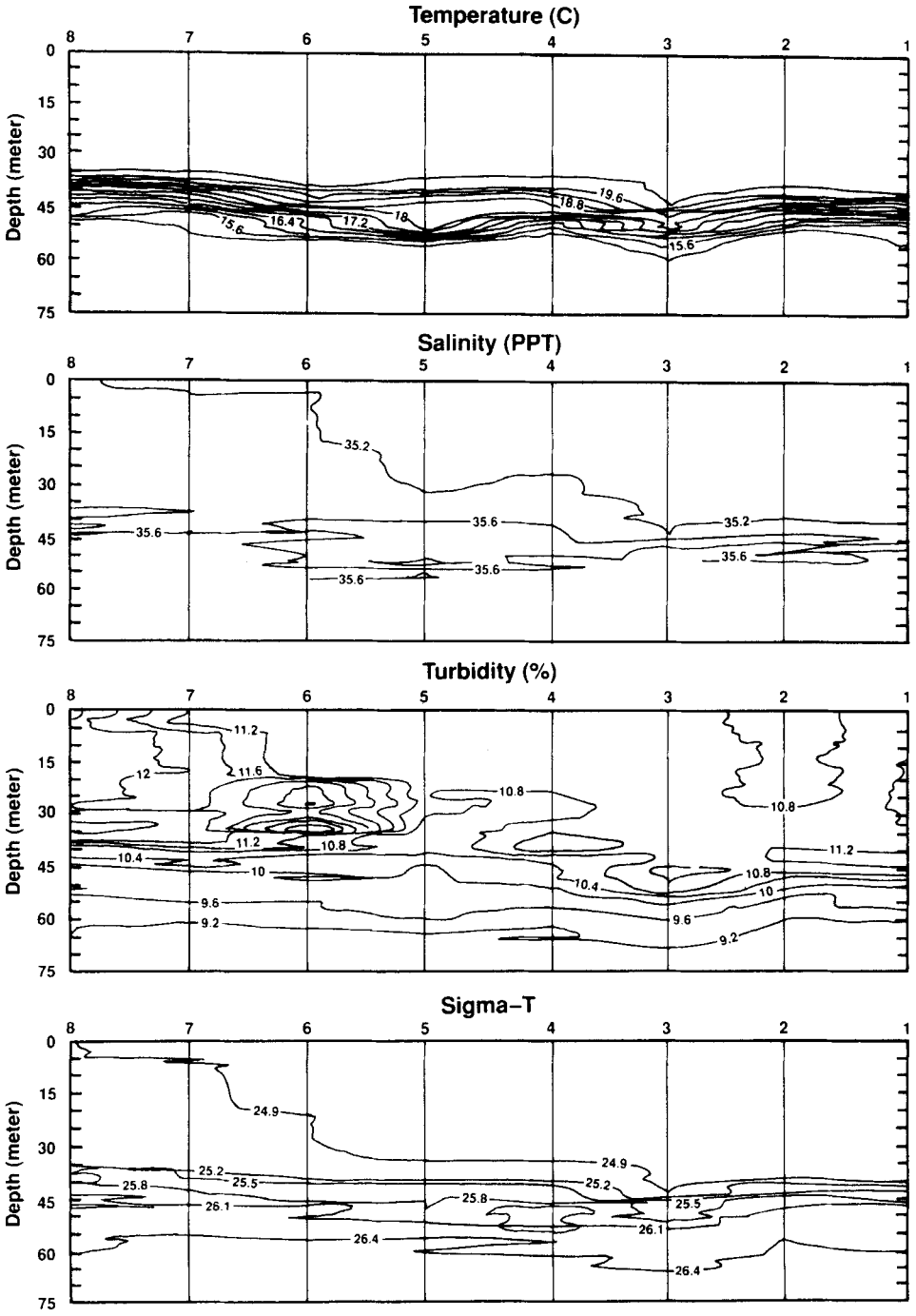


Figure 12 Vertical contour plots of water properties observed along Transect C on October 27–29, 1989. Stations 1–8 are indicated along the horizontal axis of each plot.

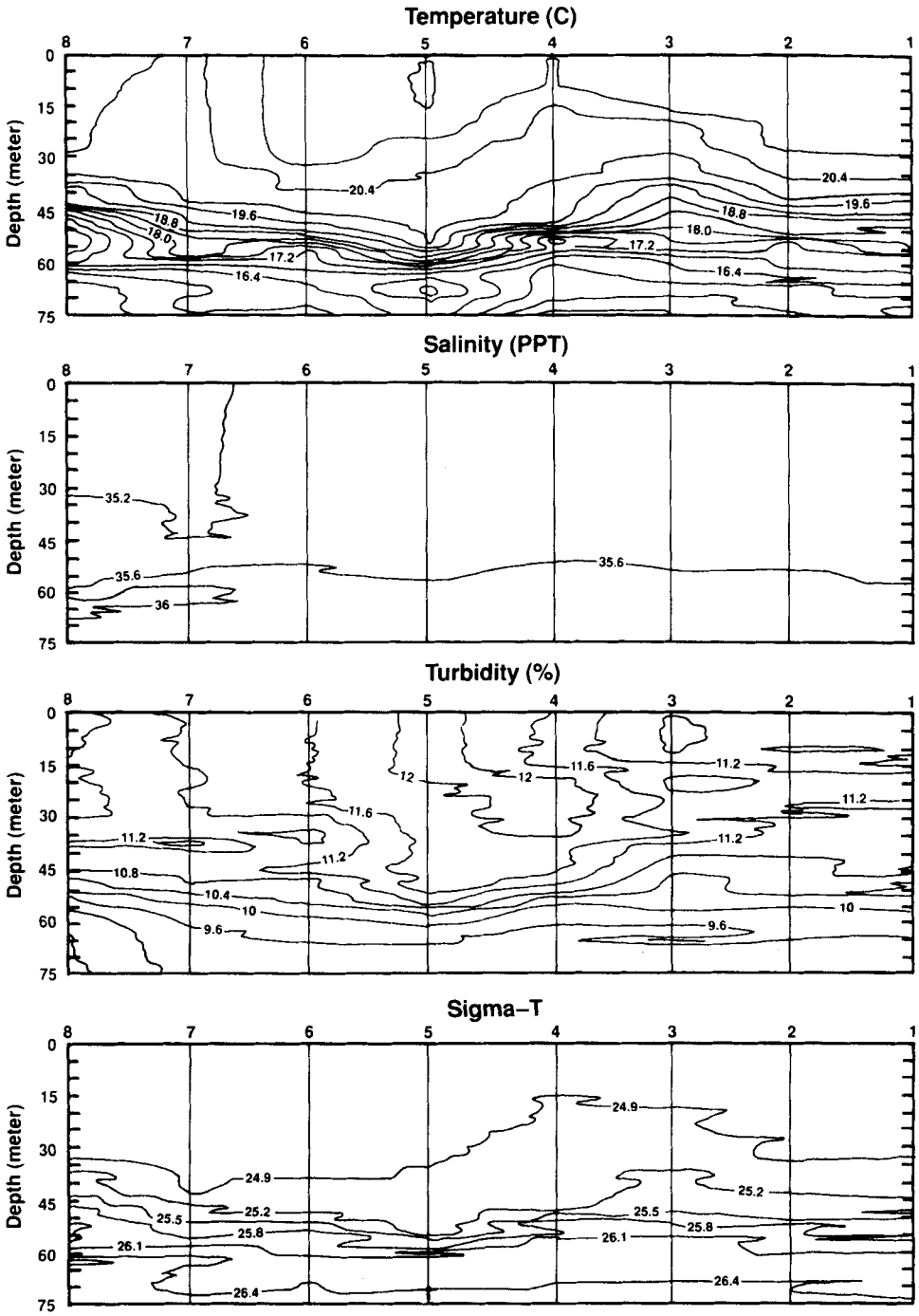


Figure 13 Vertical contour plots of water properties observed along Transect A. Station 8 was made on October 28, 1989, whereas Stations 1–7 were made on October 29–30, 1989.

water masses, rather than a result of rapid, local changes in water properties due to atmospheric effects (e.g., heating, cooling, evaporation, or precipitation). The near-surface turbidities at Stations A4 and A5 were higher than those observed elsewhere along the three transects.

The satellite-imagery data indicated that the surface water masses in close proximity to the 106-Mile Site during the period from October 27 to 30 were composed of relatively homogeneous slope water and, therefore, void of the relatively cool, fresh water from the continental shelf and relatively warm, saline water from the Gulf Stream or WCRs. The water property data acquired at the 21 stations along the three transects discussed above agree with this assessment of the water masses in the area. In general, the physical characteristics of the upper water column in the vicinity of the 106-Mile Site were typical for autumn conditions. A surface mixed layer having temperatures near 20 °C and ranging in thickness from 30 to 50 m was present throughout the study area. Below the surface mixed layer existed a strong, seasonal thermocline in which temperatures decreased from 20 °C to roughly 14 °C over a vertical distance of approximately 30 m. As is common in this region during late summer and early autumn, the near-surface, seasonal thermocline created a strong pycnocline at the base of the mixed layer.

Sludge Fate – Horizontal Tows

Near-surface measurements of turbidity made within sludge plumes at the 106-Mile Site and during preliminary far-field studies in 1988 showed that sludge plumes were identifiable from the high turbidity found in the plumes, in contrast to the relatively clear background waters of the region (EPA, 1991c, d). The distinct nature of these plumes and the relatively long period during which they had been observed to remain as recognizable features during the previous studies were examined by turbidity measurements on all three transects discussed above. During the survey, background turbidity values were consistently low on all transects at depths ranging from 12 to 32 m. This depth range corresponds with the middle and lower portions of the surface mixed layer. No distinct high-turbidity values were observed along Transect C. Distinct regions of high turbidity also were not detected between Stations D10 and D6 or between Stations A8 and A4.

In contrast, the turbidity data acquired between Stations D4 and D2 (Figure 14) do, however, reveal three distinct patches of relatively high turbidity that separated by equal distances of roughly 4.1 km. The northeastern-most patch was located roughly 6 km southwest of the 106-Mifle Site, and, using a 22 cm s^{-1} estimate of the current speed, this patch was estimated to have left the 106-Mile Site approximately 8 h before the transect measurements. Using this current speed estimate, the 4.1 km separation between the patches represents an advective time interval of 5 h between the patches.

Turbidity measurements made along Transect A (Figure 15) revealed high-turbidity areas between Stations A1 and A2 (Figure 15) and between Stations A3 and A4. The single plume observed between Stations A1 and A2 was roughly 600 m wide and located 2 km from the 106-Mile Site. At a translation speed of 22 cm s^{-1} toward the southwest, this plume was estimated to have left the 106-Mile Site roughly 4 h earlier (around 1700 h on October 29). The near-surface turbidity data acquired between Stations A3 and A4 suggested that there were three plumes within 2 km of Station A3. These plumes had lower turbidities and were significantly narrower (ranging from 300 to 600 m in width) than the plume observed between Stations A1

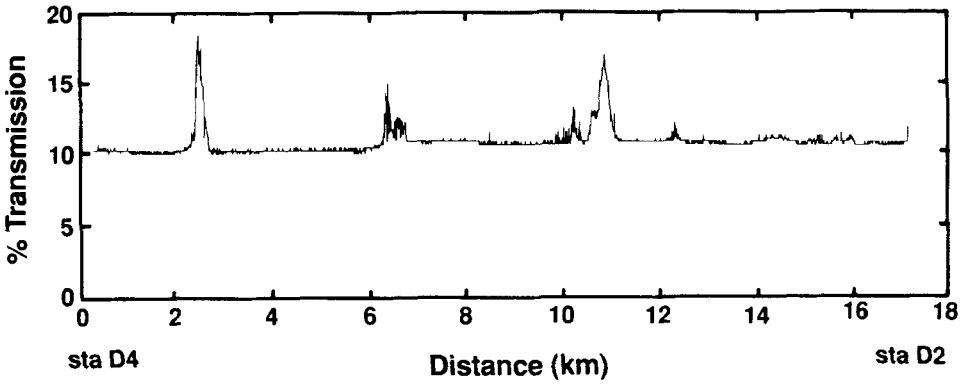
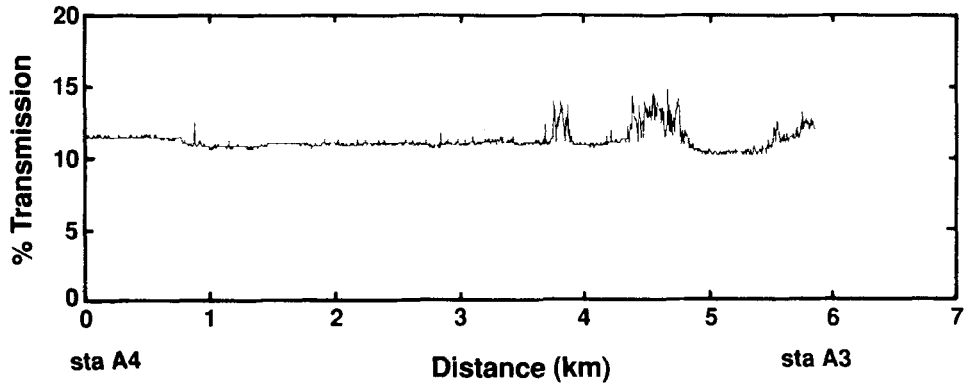


Figure 14 Plot of observed turbidity, expressed as percent light transmission (high values represent high turbidity), along the horizontal transect between Stations D2 and D4 (See Figure 13 for locations).



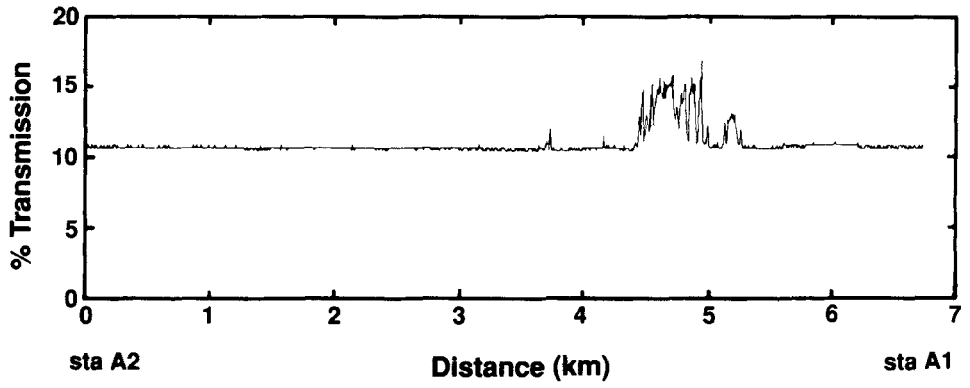


Figure 15 Plot of observed turbidity, expressed as percent light transmission, along the horizontal Transect between Stations A1 and A2 and between A3 and A4 (See Figure 13 for locations).

and A2. The three plumes between Stations A3 and A4 were located within 14 to 16 km of the 106-Mile Site and may have exited the boundaries of the 106-Mile Site 18 h earlier (around 0600 h on October 29) at an average current speed of 22 cm s^{-1}.

Accurate records of actual sludge dumping at the 106-Mile Site are available from the Ocean Dumping Notification Forms (ODNF) that barge-towing companies must submit to EPA for each dumping event. These forms provide such information as the time, location, sludge between source and volume, and dumping rate for each dumping operation. Analysis of the ODNFs on file at EPA indicated that 21 dumping events (Table 4) occurred during the 10-day period from October 21–30. During this period there were from one to four barges dumping in the 106-Mile Site on any given day. From the navigation records provided with the ODNFs, the number of north–south plume segments in the east and west sides of the 106-Mile Site (dumping occurs in two oval lanes circumnavigating the 106-Mile Site) were determined to be 34 and 44, respectively. The average number of plume segments created per day over the 10 day period was eight (78 plume segments divided by 10 days), although the number of plumes per day ranged from two to 15.

Table 4 Summary of sludge dumping operations at the 106-Mile Site from October 21 through 31, 1989. A total of 21 dumps were made during this period.

Date	*Sea* Conditions	# Barges dumping per day	# Plumes in West lanes	# Plumes in East lanes
10–21	Rough	2	4	0
10–22	Rough	4	7	4
10–23	Calm	1	8	0
10–24	Calm	3	9	6
10–25	Rough	4	2	10
10–26	Calm	1	2	0
10–27	Calm	1	2	0
10–28	Calm	2	0	11
10–29	Calm	2	0	5
10–30	Rough	1	0	8
Total		21	34	44

Only two barges dumped sludge during October 26 and 27 before the sampling of Transect C began. On the morning of October 26, the barge *Spring Creek* dumped two north–south plumes in the western lanes of the 106-Mile Site. From 1645 to 2245 h on October 27, the barge *Udalls Cove* created two other plumes in the western lanes of the 106-Mile Site. These plumes were created a few hours before measurements were made on Transect C; hence, the plumes may not have reached the western boundary of the 106-Mile Site to allow detection along the transect. Nondetection of plumes along Transect C suggest that the plumes from the *Spring Creek* were diluted in the two days following disposal to turbidity levels that were not detectable by the towed transmissometer. Dumping activities increased after October 27 with three barges dumping sludge in the 106-Mile Site on October 28 and two barges dumping on October 29. The plumes observed on the D and A transects are most likely relate to dumping from these barges.

Sludge Fate – Tracers

Total suspended solids

TSS concentrations determined for surface waters (15 m depth) and within the observed particle maxima at the background and selected stations along the far-field transects were similar to background TSS concentrations found in the surface water near the 106-Mile Site during previous EPA studies. Concentrations during previous surveys ranged between 0.16 and 0.90 mg l^{-1} (EPA, 1991c, d). Concentrations at the background stations during the October 1989 survey ranged between 0.14 and 0.26 mg l^{-1}. Slightly lower concentrations were found at 15 m relative to the particle maxima located near the pycnocline. TSS concentrations observed at the farfield stations were generally similar to those at the background stations. TSS in samples from Stations C8, D10, and A5 were higher than typical background levels. The higher concentrations are consistent with the higher turbidity signals found at these stations.

Trace metals

The total cadmium, copper, iron and lead concentrations observed at background stations (Table 5) were consistent with concentrations reported by previous studies (EPA, 1991c, d; Battelle, 1992). Cadmium concentrations increased slightly between 15 and 75 m (Table 5). In contrast, the copper and lead and data indicat that the water column above the pycnocline may have had slightly higher concentrations of these metals than the water collected from 75 m. Trends in the iron data are less distinct.

Table 5 Total metal concentrations (μg l^{-1}) found at the background stations during the October 1989 survey compared with previous results. Concentrations are the mean (standard deviation) of results from the three background studies.

Depth	*Metal concentration (μg l^{-1})*			
(m)	*Cd*	*Cu*	*Fe*	*Pb*
15 (October 1989)	0.0052	0.12	0.14	0.013
	(0.0003)	(0.005)	(0.005)	(0.003)
35–40	0.0032	0.12	0.17	0.016
(October 1989)	(0.0018)	(0.02)	(0.03)	(0.008)
75–80	0.013	(0.08)	0.24	0.009
(October 1989)	(0.008)	(0.00)	(0.03)	(0.001)
Historical Surface[a]	0.007	0.14	0.21	0.012
	(0.007)	(0.04)	(0.15)	(0.003)
Pycnocline[a]	0.005	0.15	0.26	0.011
	(0.002)	(0.06)	(0.31)	(0.001)

[a] From Battelle (1991).

Comparison of the average concentration of cadmium and copper at each depth from the background stations with the average calculated for each depth at the far-field stations indicates that these metals were not elevated downstream of the 106-Mile Site (Figure 16). However, the mean iron and lead concentrations (approximately 0.28 and 0.030 μg l^{-1}, respectively) in the surface and 35 m depths were about twice that of the background stations. The standard deviation of the mean of these two metals in the downstream samples, 0.30 and 0.31 μg l^{-1}, respectively, was also much larger than that found for the control stations. High variability was not observed in the downstream cadmium and copper results. In

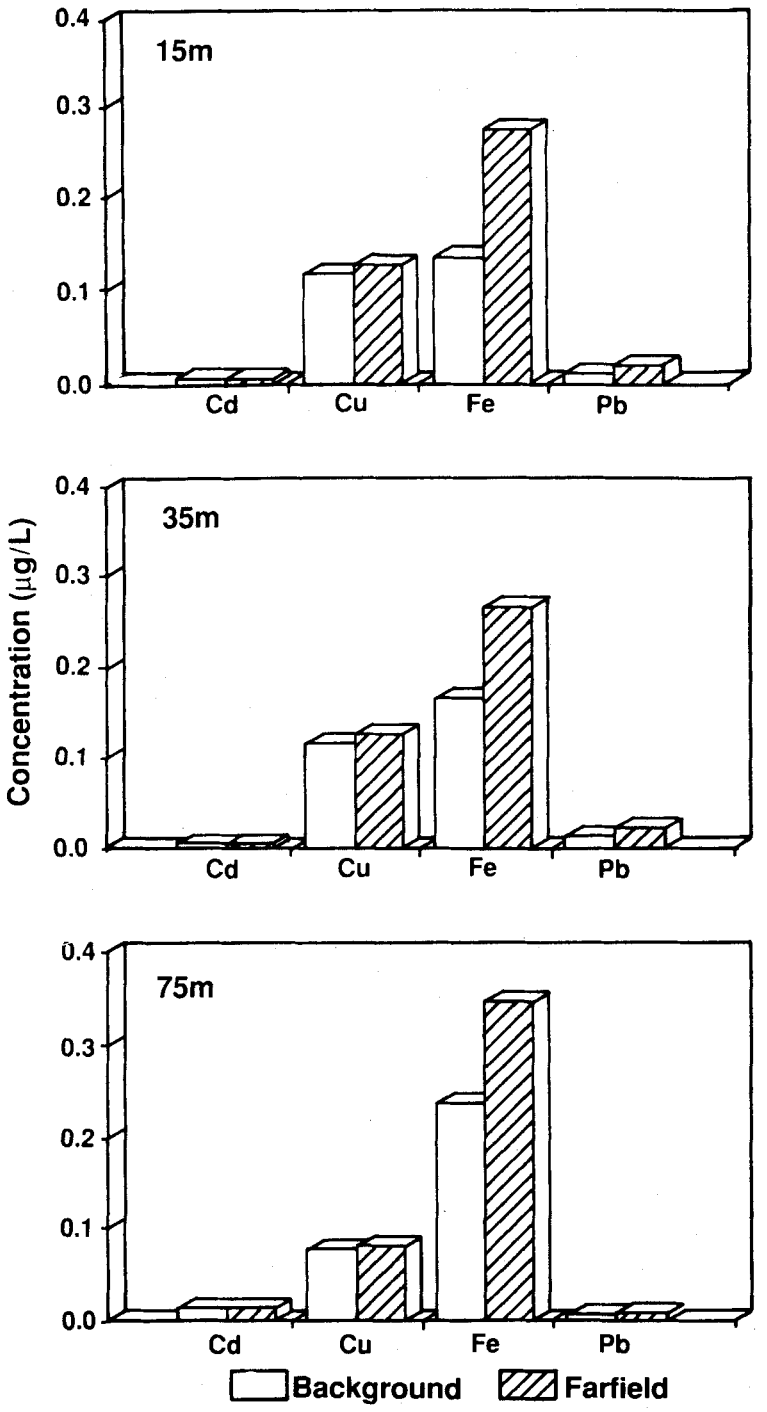


Figure 16 Average metal concentrations at three depths at the background stations compared with average concentrations at the far-field stations.

addition, close examination of the metals concentrations at the individual far-field stations revealed a striking pattern in that a lower threshold in the metals concentrations was apparent in the samples from both 15 m and the pycnocline. These threshold values were the same as the average metals concentrations observed at the background stations (Table 5). Superimposed on this threshold concentration were metals concentrations that are distinctly higher than the background values (at least two times the standard deviation of the mean of the background samples). In contrast, cadmium, copper and lead concentrations in the far-field samples from 75 m were nearly identical to those found at the background stations.

To determine the spatial pattern in the distribution of the metals, the concentrations in samples from 15 m depth and in the pycnocline (35 m) were mapped and contoured. The lowest contours chosen were 0.005, 0.12, 0.15, 0.025 $\mu g\ l^{-1}$ for cadmium, copper, iron and lead respectively. These values represent the background concentrations. The contours were increased by 0.001, 0.01, 0.1, and 0.02 $\mu g\ l^{-1}$ intervals for cadmium, copper, iron and lead respectively. These contours represent the standard deviation in the background concentrations, except for iron and lead for which the intervals are approximately 10 and 20 times the standard deviation of the background concentrations. Lead and iron in the surface samples (15 m) show marked areas of high concentrations to the southwest of the transect near the 106-Mile Site along the outer limit of transects C and D (Figures 17 and 18). Both metals show higher concentrations along the northwest boundary of the 106-Mile Site. Copper exhibited a similar but less well defined pattern. The cadmium results did not show clear areas with high concentrations. Station C6 particularly shows elevated metal concentrations in both the surface and pycnocline samples.

Samples from the pycnocline show the area of high metals concentrations to the southwest of the 106-Mile Site along transect C. Iron, copper and cadmium also display areas of high concentration along transect A. These areas are not seen in the lead data. As found for the surface water, and cadmium concentrations were relatively uniform and did not reflect any areas of significantly elevated concentration.

These results clearly indicate that a fraction of the sewage sludge remains in surface waters downstream of the 106-Mile Site. Even though evidence of elevated metals concentrations relative to background levels were found, the concentrations were well below EPA marine water-quality criteria for chronic exposure. Thus, no impairment of marine life is expected from the metals being discharged at the 106-Mile Site.

C. perfringens and Salmonella

C. perfringens spores were below detectable limits at all background stations. The absence of detectable levels of *C. perfringens* from any background samples, regardless of depth, implies that this water had not been affected by dumping. In contrast, elevated *C. perfringens* counts were obtained at a number of the far-field stations (Figure 19). The highest counts, ranging from 4.0 to 19.5/100 ml, were found at stations C-5, C-6, and C-7. Detectable *C. perfringens* concentrations were found in near-surface samples and samples from the pycnocline but not in samples from below the pycnocline. Transect C was located along the prevailing direction of surface water movement. Thus, these data confirmed movement of sludge toward the southwest. Levels at adjacent stations, C-8 and C-4 to C-1, were significantly lower or not detected. Stations C-5, C-6, and C-7 also show a change in the vertical distribution of the spores. Station C-5, closer to the dumpsite, had higher counts at

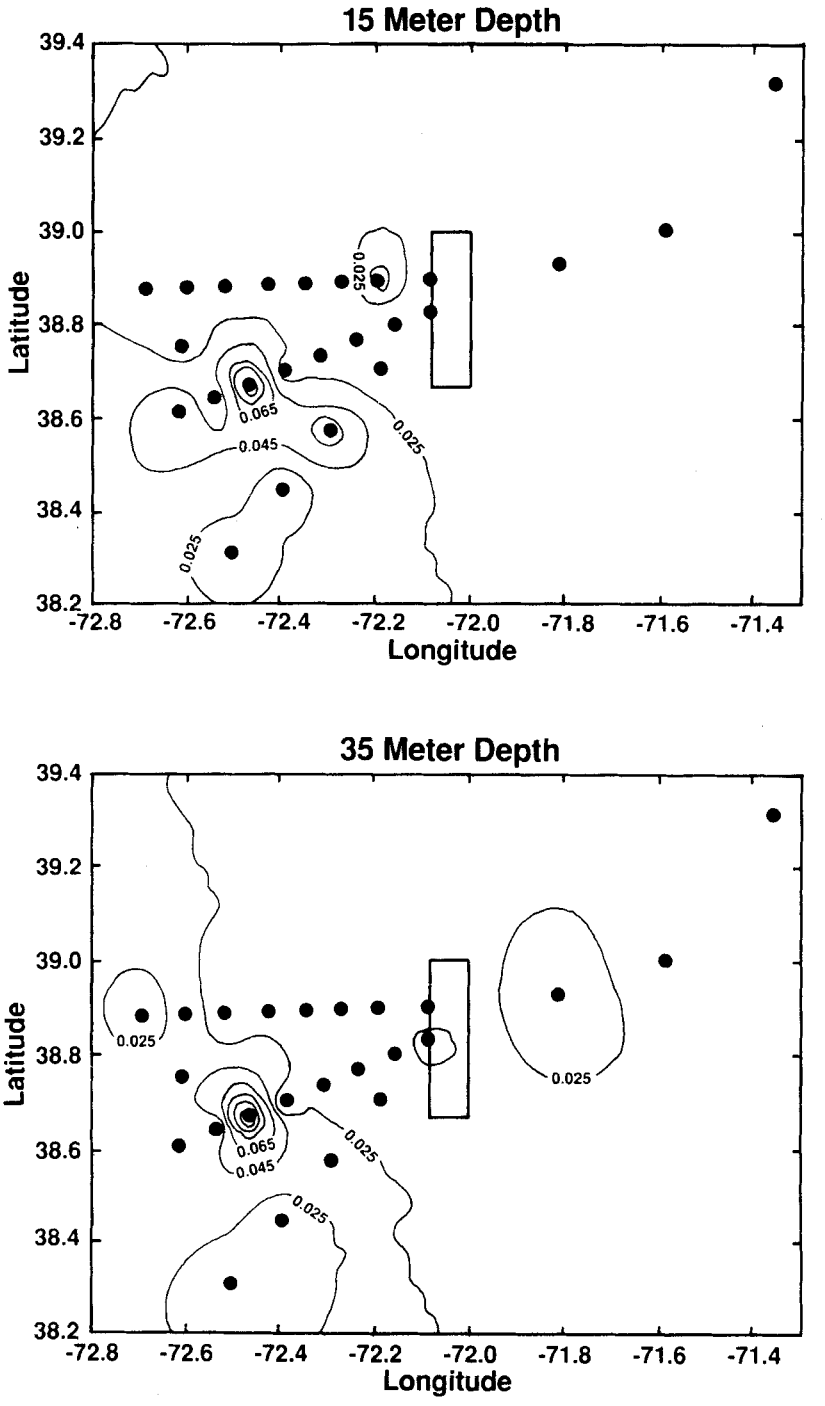


Figure 17 Contour plot of total lead concentrations at 15 m and 35 m depth near the 106-Mile Site. October 1989.

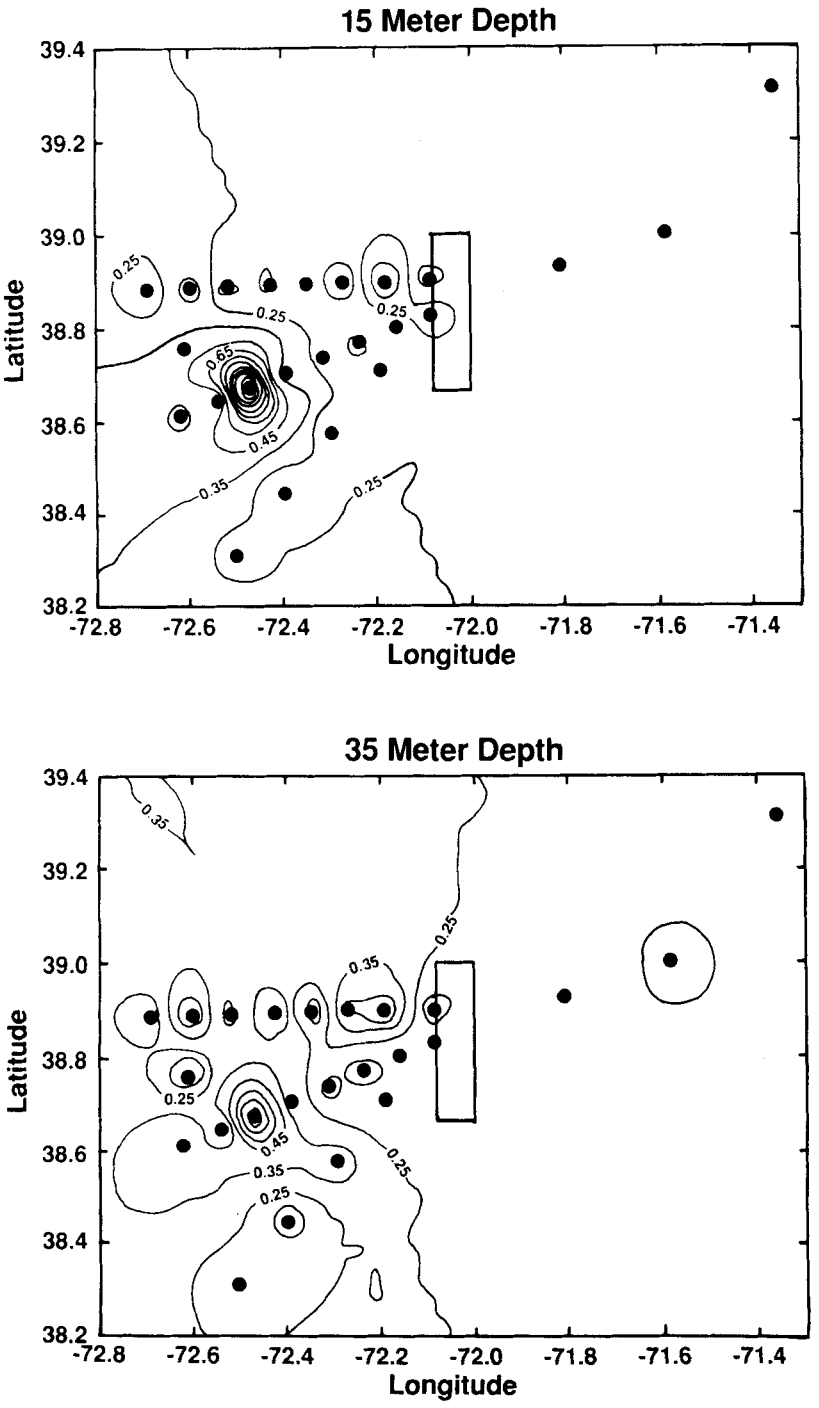


Figure 18 Contour plot of total Iron concentrations at 15 m and 35 m depth near the 106-Mile Site. October 1989.

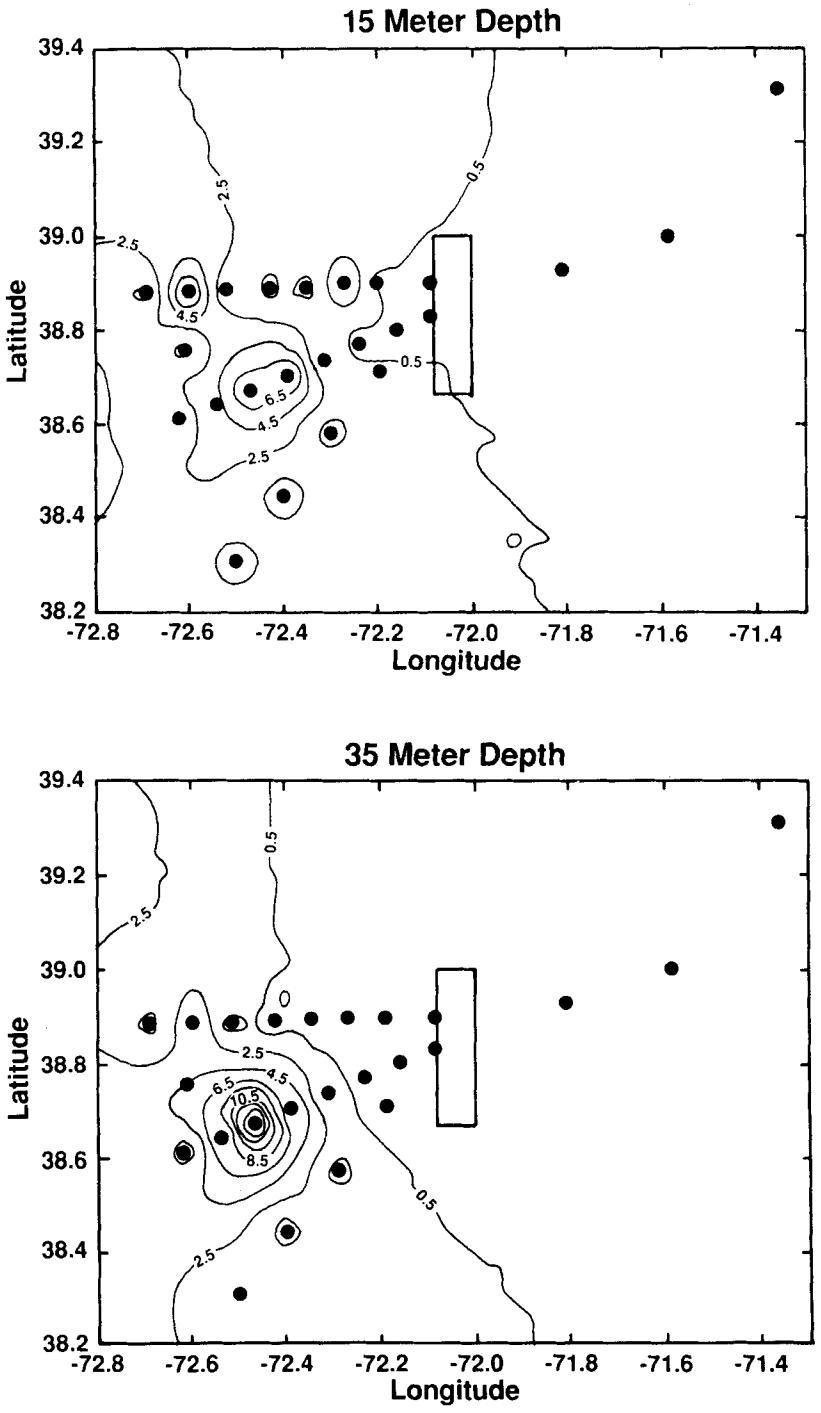


Figure 19 Distributions of *Clostridium perfringens* in surface water near the 106-Mile Site. October 1989.

the surface than at the pycnocline. At stations C-6 and C-7 this pattern is reversed, with higher counts at the pycnocline than at the surface. The surface sample from C-6 was actually sampled from approximately 24 m depth (rather than 15 m depth) in a distinct high-turbidity feature. Other stations with elevated counts were A-7 and A-3, which also are surrounded by stations with no detectable levels, except for station A-6, which was slightly elevated over background levels. The spatial distribution of the *C. perfringens* indicates heterogeneity in the distribution of the spores and suggests that the discharge of sludge does not result in a general area-wide increase in sludge related components. Rather, the distribution appears to be more related to the specific dumping events and the physical transport of the surface water within the 106-Mile Site that received the sludge.

No *Salmonella* were detected in any of the background or far-field samples. The lack of *Salmonella* is not surprising, given its sensitivity to environmental conditions.

Xylem tracheids, acanthamoeba spp., and ascaris

Xylem tracheids were measured to determine the feasibility of using them as a sludge tracer at far-field stations. Therefore, except for those samples collected in the immediate discharge and at the background stations, the sampling sites selected for analysis were based on the identification of elevated *C. perfringens* counts.

The highest observed tracheids concentrations occurred in the two sets of samples taken within sludge plumes immediately behind the discharging barges (Table 6). Tracheid concentrations in the plume ranged from over 48,000 to over 202,000 per 38 l sample.

Table 6 Estimated number of xylem tracheids in 38 litre water samples collected at the 106-Mile Dump Site during the Fall 1989 survey.

Station number	*Replicate*[a]	*Number of tracheids observed*	*Estimated number of tracheids per 38 litres*
$T = 0_1$[b]	1	47	67,000
	2	34	48,500
$T = 3$[b]	1	107	152,600
	2	142	202,500
	1S	0	0
A-7	2S	0	0
	1P	0	0
	2P	2	17
	1S	0	0
C-5	2S	1	8
	1P	0	0
	2P	3	25
	1S	1	8
C-6	2S	0	0
	1P	0	0
	2P	0	0
	1S	0	0
C-7	2S	2	17
	1P	0	0
	2P	1	8
	1S	0	0
BK-2	2S	0	0
	1P	0	0
	2P	0	0
	1S	0	0
BK-3	2S	0	0
	1P	0	0
	2P	1	8

[a] Numbers represent replicates; letters indicate surface (S) and pycnocline (P) samples.
[b] Samples from sludge plume immediately behind a discharging barge.

Several tracheids were seen on slides made from samples collected at Stations A-7, C-5, C-6, C-7, and BK-3. No tracheids were observed in samples from station BK-2. The relatively few tracheids seen in the far-field samples did not at first appear to justify expending much effort on the collection and processing of the samples when the *Clostridium* counts provides the same information. As an afterthought, however, it seemed that the number of tracheids estimated to be in the water immediately behind the barges was very high, possibly too high to be the result of the ingestion of plant material from which these cells are derived. As an experiment, a small piece of toilet tissue was soaked in tap water for several minutes, then placed on a microscope slide in a drop of water. A small amount of methylene blue was added to the drop, and the toilet tissue was macerated. A cover slip was applied to the material and the slide was viewed at 10X magnification. The material on the slide was identical in form to what was observed behind the barges. As a result of this experiment the most probable source of these fibers was attributed to toilet tissue. In addition, other plant cells, including fibres, vessel cells, and phloem sieve tube cells, could be seen in the toilet tissue sample. Those types of cells were often seen during the examinations for tracheids but were not counted. Although not qualified, the total complement of material making up toilet tissue could probably be effective as a sludge tracer, especially considering the amount of toilet tissue in the discharges. It may also be an effective tracer of sludge reaching the sea floor and thus, may be useful for mapping the extent and distribution of sludge on the sea floor.

No *Ascaris* eggs or *Acanthamoebae* were observed on the slides. This may in part be related to the laboratory technique used for assessing the tracheids. The analysis for tracheids required a very small fraction of the total sample. In the samples collected immediately behind the barges, the mass of tracheids, fibres, and other debris was often enough to obscure the eggs even if they were present on the slide. Furthermore, the technique probably would not have been adequate for *Acanthamoebae.*

SUMMARY AND CONCLUSIONS

Physical oceanographic measurements revealed typical autumn hydrographic conditions near the 106-Mile Site during the October survey. The salinities of the surface waters were typical of slope water (35.5 ‰) and were of relatively uniform temperature (20 °C). The surface waters were characterized by a shallow pycnocline extending from 30 to 50 m depth. No intrusions of continental shelf water were observed nor were warm-core rings influencing the hydrography and currents of the area during the survey. The entire region of the 106-Mile Site had a stable and coherent current flow towards the southwest. Near-surface current speeds were approximately 22 cm s^{-1}. This flow was demonstrated by the movement of satellite tracked surface drifters deployed during the survey and also by the short-term movement of drifting sediment traps deployed within the 106-Mile Site during the survey. A moored current meter and an expendable current profiler indicated that this flow extended to at least 100 m and likely to 300 m.

Background turbidity levels determined by both hydrographic profiles to 75 m and horizontal tows (surface 15 to 30 m) were low and similar to those observed on previous surveys. A general, area-wide increase in turbidity was not observed downstream of the 106-Mile Site. Thus, the hydrographic conditions, current velocities, and water clarity were nearly ideal for evaluating the transport and fate of

sludge dumped at the 106-Mile Site.

Data obtained during the October 1989 survey demonstrated that sludge plumes remain as distinct features in the near-surface waters. Horizontal tows conducted at 15 m depth identified distinct areas of high turbidity that could be linked to barge activity in the 106-Mile Site within the previous 12 to 18 h. Thus, this tracking technique proved highly effective for evaluating the fate of the plumes. Chemical and biological tracers of sewage sludge (*C. perfringens,* trace metals, xylem tracheids) were detected in the near-surface waters (to a depth of 35 m) at locations up to 40 km downstream of the 106-Mile Site. Concentrations were well above background levels but below applicable marine water quality criteria. No evidence of sewage sludge was found in samples collected from 75 m depth (below the seasonal pycnocline). Thus, much of the sludge was found in the near-surface waters, where it appears to remain for many days, possibly weeks, and is removed by natural processes. The trajectories of the surface drifters deployed during the survey did not cross the continental shell/slope break. Thus, results suggest that transport of sludge on to the continental shelf is unlikely.

Finally, large, rapidly settling particles were found immediately below sewage sludge plumes in the 106-Mile Site. These particles reached a depth of 20 m within 1 h after disposal. Estimated settling rates of these large particles (18 to 180 m h^{-1}) imply that these particles are likely to reach the sea floor within 1 to 13 days of disposal. Laboratory studies of the type and size of large particles found in the sludge samples verified that approximately 13 to 20 percent of the sludge may be in the form of large particles that are likely to settle rapidly to the sea floor.

Acknowledgements

The information presented in this paper is the result of the efforts of the staff at Battelle Ocean Sciences with support from Science Applications International Corporation. Field support was provided by Ms. Deborah West, Mr. Dion Lewis, Ms. Julie Seavey, Ms. Lisa Ginsberg, Ms. Heather Trulli, Ms. Nancy Padell, Mr. Charles Willauer, Mr. Carl Albro, Mr. Kevin King, and Mr. Paul Dragos of Battelle. Mr. Tom Brosnan of the New York City Department of Environmental Protection, and Ms. Bridgette Farren of the Environmental Protection Agency, Region III provided additional field support. The staff of the chemistry department at Battelle Ocean Sciences conducted the laboratory analyses; *C. perfringens* and pathogen analyses were provided by Dr. Robert Duncanson and Ms. Dale Saad of MTH Environmental Associates; physical oceanographic data reduction was provided by Mr. Albro and Mr. Dragos. The assistance and support of the captain and crew of the OSV *Anderson* are gratefully acknowledged. The sludge sampling and large particle characterizations were conducted by Mr. Steve Dowhand of SAIC and Ms. Karen Foster of Battelle. Ms. Stacey Martinis and Ms. Carol Costa provided secretarial assistance. This work was conducted by Battelle Ocean Sciences under contract to the United States Environmental Protection Agency (Contract No. 68-C8-0571). This paper has been reviewed and approved for publication by the US EPA. The contents do not necessarily reflect the official views and policies of the US EPA, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

References

Battelle (1992) 106-Mile Site Monitoring Data Summary Report. A final report submitted to the U.S. Environmental Protection Agency, Office of Water, under Contract 68-C8-0105. Work Assignment 2–46, 270 pp.

Bisson, J.W., and Cabelli, V.J. (1979) Membrane filter enumeration method of *Clostridium perfringens*. *Appl. Environ. Microb.* **37:** 55–66.

Blatt, H., Middleton, G. and Murray, R. (1980) *Origin of Sedimentary Rocks*. Second Edition. Prentice-Hall, Inc., Englewood Cliffs, NJ. 782 pp.

Bonner, J., Ernest, A., Hernandez, D.S., Autenrieth, R.L., and Redford, D. (1992) Transport of sewage sludge in a mixed water column. *Chemistry and Ecology*. (This volume).

Churchill, J., *et al.* (1989) Velocity and hydrographic structure of subsurface shelf water at the Gulf Stream's edge. *J. Geophys. Res.*, **94:** 10791–10800.

Danielson, L.B., Magnusson, B., Westerlund, S. and Zhang, K. (1982) Trace metal determinations in estuarine water by electrothermal atomic absorption spectrometry after extraction of dithiocarbamate complexes into Freon. *Anal. Chem. Acta* **144:** 183–188.

EPA (1989) Proceedings of the Ocean Dumping Workshop 106-Mile Site. Environmental Protection Agency Office of Water. EPA 503/9/9-89/009, 53 pp.

EPA (1991a) Final Draft Monitoring Plan for the 106-Mile Deepwater Municipal Dumpsite. Environmental Protection Agency Office of Water. EPA 503/4-91/007, 79 pp.

EPA (1991b) Final Draft Implementation Plan for the 106-Mile Deepwater Municipal Sludge Site Monitoring Program. Environmental Protection Agency Office of Water. EPA 503/4-91/008, 56 pp.

EPA (1991c) Final Report Summer 1988 106-Mile Site Survey. Environmental Protection Agency Office of Water. EPA 503/3-91/001, 118 pp.

EPA (1991d) Final Report for Nearfield Monitoring of Sludge Plumes at the 106-Mile Deepwater Municipal Sludge Site: Results of a Survey Conducted August 31 through September 5, 1987. Environmental Protection Agency Office of Water. EPA 503/4-91/004, 83 pp.

Garvine, R.W., *et al.* (1988) The morphology of shelfbreak eddies, *J. Geophys. Res.*, **93:** 15593–15608.

Knauss, J.A. (1978) *Introduction to Physical Oceanography*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 338 pp.

Lavelle, J.W., Ordogan, E., Baker, E.T., Tennant, D.A. and Walker, S.L. (1988) Settling speeds of sewage sludge in seawater. *Environ. Sci. Technol.* **22,** 1201–1207.

McDowell, S., Albro, C. and Willauer, C. (1989) An integrated profiling system assists EPA researchers in monitoring horizontal and vertical sludge plume movement at the 106-Mile Site. *Sea Technology,* **20:** 10–17.

Redford, D., Pabst, D. and Hunt, C.D. (1992) Monitoring the fate, and effects of sewage sludge disposal at the 106-Mile Deepwater Municipal Sludge Dump Site. *Chemistry and Ecology*. (This volume)

Robinson, A.R. and Niller, P.P. (1967) The theory of free inertial jets, I. Path and structure, *Tellus* **19:** 269–271.

Vasquez, J., and Watts, D.R. (1985) Observations on the propagation, growth and predictability of Gulf Stream meanders, *J. Geophys. Res.* **90:** 7143–7151.