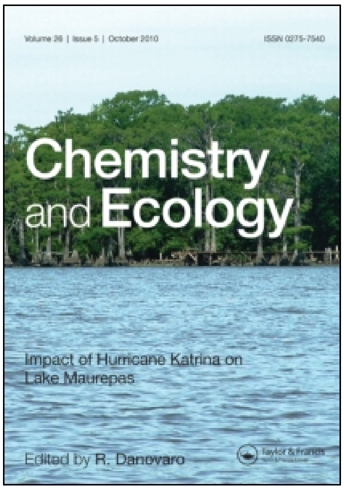

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Monitoring of the Fate, Transport, and Effects of Sewage Sludge Disposed at the 106-Mile Deepwater Municipal Sludge Dump Site

David Redford[a]; Douglas Pabst[b]; Carlton D. Hupt[c]
[a] Office of Wetlands, Oceans, and Watersheds, Washington [b] US Environmental Protection Agency, Region II, Marine and Wetlands Branch, New York, NY [c] Battelle Ocean Sciences, Duxbury, MA

To cite this Article Redford, David , Pabst, Douglas and Hupt, Carlton D.(1992) 'Monitoring of the Fate, Transport, and Effects of Sewage Sludge Disposed at the 106-Mile Deepwater Municipal Sludge Dump Site', Chemistry and Ecology, 7: 1, 51 — 74

To link to this Article: DOI: 10.1080/02757549208055432
URL: http://dx.doi.org/10.1080/02757549208055432

Chemistry and Ecology, 1992, Vol. 7, pp 51–74
Reprints available directly from the publisher
Photocopying permitted by license only

MONITORING OF THE FATE, TRANSPORT, AND EFFECTS OF SEWAGE SLUDGE DISPOSED AT THE 106-MILE DEEPWATER MUNICIPAL SLUDGE DUMP SITE

DAVID REDFORD,* DOUGLAS PABST** and CARLTON D. HUNT***

Office of Wetlands, Oceans, and Watersheds, US Environmental Protection Agency (WH-556F), 401 M Street S.W., Washington, DC 20460 US Environmental Protection Agency, Region II, Marine and Wetlands Branch, 26 Federal Plaza, New York, NY 10278** Battelle Ocean Sciences, 397 Washington Street, Duxbury, MA 02332****

(Received 5 December, 1991)

Since 1985, the US Environmental Protection Agency (EPA) has conducted monitoring studies to determine the transport, fate, and effects of sewage sludge dumped at the 106-Mile Deepwater Municipal Sludge Dump Site (106-Mile Site). This paper describes EPA's 106-Mile Site monitoring activities and the results from six oceanographic surveys of the Site. Surveys have been conducted to track sewage sludge plumes and monitor dispersion and settling characteristics; study plume toxicity and contaminant levels; search for sludge and sludge constituents in surface waters in the area of the Site up 74 km (40 nautical miles) away; maintain a stationary real-time current meter near the Site; deploy and retrieve approximately 50 sediment traps and 17 current meters on 10 arrays from Hudson Canyon south to Delaware Canyon, at depths ranging from 1500 to 2800 m; and deploy satellite-tracked drifters. Results of studies completed to date have provided field data on the chemical and physical behaviour of sludge discharge plumes. Short-term persistence of sludge particles in surface waters above the pycnocline was observed and advection of sludge material from the Site may be rapid, in many cases on the order of hours. A suggestion that removal of sludge material from the surface mixed layer at the Site occurs more from horizontal mixing and advection than from vertical transport processes is supported by the data. Finally, monitoring results have provided data for assessment of permit compliance and for development of additional monitoring to detect far-field transport and long-term impacts – monitoring efforts relative to these concerns continue.

KEY WORDS: 106-Mile Site, sewage sludge, effects monitoring, turbidity, biomass, sediments, DO, chlorophyll α

INTRODUCTION

The only ocean disposal site in the United States designated for dumping of sewage sludge is the 106-Mile Deepwater Municipal Sludge Dump Site (106-Mile Site). In 1984, the Environmental Protection Agency (EPA) designated the 106-Mile Site to receive municipal sewage sludge. Disposal operations were transferred from the 12-Mile Site (Figure 1), located in the New York Bight, beginning in March 1986. By late December 1987, all nine authorities from the New York/New Jersey Metropolitan area permitted to conduct ocean disposal of sewage sludge were using the 106-Mile Site.

During 1986 and 1987, EPA developed a monitoring plan for the 106-Mile Site that was designed to develop information on potential adverse effects of sludge on marine life and human health and to gain information regarding continued site management

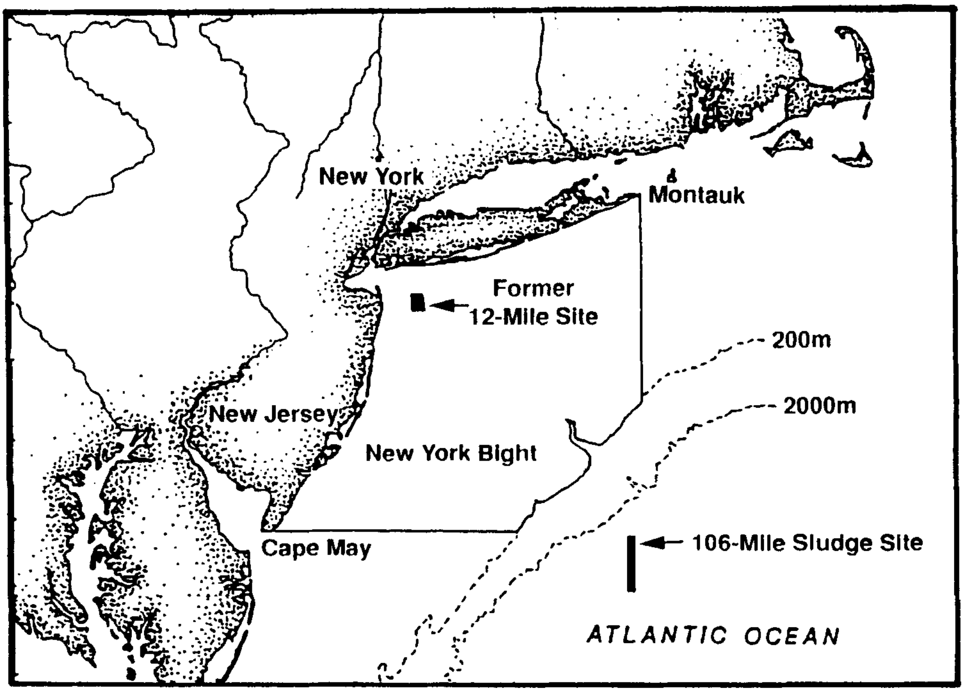

Figure 1 Location of the 106-Mile Deepwater Municipal Sludge Dump Site.

and permitting. The plan was completed in March 1988. Under this plan, EPA conducted baseline studies plus several surveys designed to evaluate near-field fate and short-term effects.

This paper highlights findings of initial monitoring studies conducted between 1986–1989 and examines the implications of results for the permitting process and for continued monitoring efforts. Continuing and expanded fate and effects studies, initiated in 1990, are briefly discussed. First, a historical synopsis is offered to frame the monitoring objectives.

Background

Designation of the 106-Mile Site resulted from the EPA decision to end municipal sludge disposal at the 12-Mile Site. When the 106-Mile Site was designated, the sewerage authorities involved negotiated a court-ordered schedule to shift operations offshore. Nine sewerage authorities used the Site from 1986 through 1990 (Table 1).

The general area of the Site had been used since 1961 for disposal of chemical wastes and other materials (Figure 1). [See also EPA (1989) for a discussion of the Site history.] The legally designated 106-Mile Deepwater Municipal Sludge Dump Site is approximately 100 square miles (statute) ($\approx$ 259 km^2), with boundaries at 38°40′00″ to 39°00′00″ north latitude and 72°00′00″ to 72°05′00″ west longitude. Its location is approximately ~ 222 km (120 nm) southeast of Ambrose Light, New York, and ~ 213 km (115 nm) from Atlantic City, New Jersey (Figure 1). The Site is seaward of

Table 1 Sewerage authorities disposing sewage sludge at the 106-Mile Site, 1986 through March 1991.

Sewerage authorities	*Abbreviation*
Bergen County Utilities Authority, NJ	BCUA
Joint Meeting of Essex and Union Counties, NJ	JMEUC
Linden-Roselle Sewerage Authority, NJ	LRSA
Middlesex County Utilities Authority, NJ	MCUA
Nassau County Department of Public Works, NY	NCDPW
New York City Department of Environmental Protection, NY	NYCDEP
Passaic Valley Sewerage Commissioners, NJ	PVSC
Rahway Valley Sewerage Authority, NJ	RVSA
Westchester County Department of Environmental Facilities, NY	WCDEF

the continental slope/shelf break, where the water depth ranges from about 2400 to 2700 m. Sludge disposal at the 106-Mile Site now proceeds according to permits issued in 1989. Approximately 8 to 10 million tons of wet sewage sludge were dumped at the Site annually from 1988 through 1990. Although the general characteristics of the sludge vary from plant to plant, the material being dumped at the Site is primarily biological sludge that also contains small amounts of debris, such as grit, paper and fibres. The sludges disposed at the Site are somewhat buoyant, comprising 2% to 4% solid material. The sludge contains trace levels of organic contaminants, such as aldrin, dieldrin, chlordane, heptachlor epoxide, DDT and its degradation products, and polychlorinated biphenyl (PCB). Metals, including cadmium, copper, chromium, and mercury, are also present at trace levels. The discharge of any floatable materials is prohibited.

The Marine Protection, Research, and Sanctuaries Act of 1972 (MPRSA) presents the US policy to regulate the dumping of all types of materials into ocean waters and to prevent or strictly limit the dumping of any material that would adversely affect human health, welfare, or amenities, or the marine environment, ecological systems, or economic potential. Acting under the MPRSA, EPA has published regulations and criteria for ocean dumping. The most recent revisions to these regulations were published in 1977 (40 CFR Parts 220–229). In November 1988, the United States Congress passed the Ocean Dumping Ban Act of 1988 (ODBA) that makes it illegal to dump sewage sludge and industrial wastes into the waters of the United States after 1991. Specific requirements of the ODBA and Federal agency response to the ODBA are considered later in this paper.

Under the MPRSA, the National Oceanic and Atmospheric Administration (NOAA), the United States Coast Guard (USCG), and EPA all have responsibilities. NOAA has a responsibility to conduct research. Surveillance of disposal operations are the responsibility of the USCG and EPA. This paper focuses on activities of EPA, which is responsible for (1) site designation – conducting disposal-site evaluation and designation studies and recommending modifications in site use or designation; (2) permits – regulating times, rates, and methods of disposal and quantities and types of materials that can be disposed and oversight/enforcement of permit conditions; and (3) monitoring – developing and maintaining effective monitoring programmes. These three interrelated functions are intended to prevent unreasonable degradation of the environment.

Acting under the MPRSA and the ocean dumping regulations, EPA developed a monitoring plan to determine whether (1) conditions of permits to dump sludge were met and (2) sludge dumping at the Site adversely affected the environment or human health. EPA's monitoring efforts have assessed not only whether permit conditions are being met, but also whether the conditions are sufficiently protective.

EPA's monitoring plan considered characteristics of the Site and the sludge to predict the possible impacts of sludge disposal. The 106-Mile Site monitoring programme was logically organized into different components, using a tiered approach. Tier 1 monitoring focuses on sludge characteristics and disposal operations, Tier 2 on near-field fate and short-term effects, Tier 3 on far-field fate, and Tier 4 on long-term effects. In theory, the tiers form a hierarchy where data collected in a lower tier act as the foundation for the design and extent of monitoring activities in the next tier. In practice, monitoring activities for higher tiers need not be delayed until *all* results are available from lower tiers.

Methods

Sampling for sludge characterization

Because of uncertainties in the available data on sludge characteristics as submitted in support of applications for disposal permits, EPA conducted an independent characterization. Sludge from the nine sewerage authorities was characterized by a variety of measures including toxicity to representative marine species (a fish, *Menidia beryllina* and a shrimp, *Mysidopsis bahia*), organic priority pollutants, metals (copper, lead, cadmium, and mercury), and other characteristics – settleable matter, total suspended solids, total solids, wet-to-dry-weight ratio, density of solid matter, and specific gravity. Samples were collected as one-time grab samples or composites taken during barge-loading operations in August 1988. Sampling and analytical deails for each chemical, physical, or toxicological measurement are provided by EPA (1991c). Analytical methods followed published EPA methods (EPA, 1986).

Near-field fate and short-term effects

The objectives of monitoring under Tier 2 were to assess the near-field behaviour, dilution, settling, transport, and short-term effects of sludges within the 106-Mile Site and in the immediate area surrounding the Site. To accomplish these objectives, monitoring focused on (1) short-term behaviour of sludge plumes, (2) near-field transport, and (3) short-term effects of the sludge in the Site and within its immediate vicinity (Figure 2). For convenience, short-term effects were defined as those effects occurring within 1 day of sludge disposal. The near-field is defined as being within the Site and up to approximately 5 km (3 nm) outside it.

To assist in evaluating sludge behaviour, the sewage sludge in the barges being monitored was sampled prior to departure for the 106-Mile Site; the samples were analyzed for selected physical parameters, selected metals, and other tracers of sludge. Spores of the microbe, *Clostridium perfringens,* were also enumerated. Samples from 10 sludge plumes were obtained during 1987 and 1988 (EPA, 1991a-c).

For these precharacterized sludges, sludge plumes were sampled in the environment for up to 12 h following disposal. The immediate fate of disposed sludge was estimated by a variety of plume-tracking observations, including deploying surface drogues directly into sludge plumes; marking the surface expression of the plume with dyes; using *in situ* transmissometry; measuring physical, chemical, and biological tracers of sludge; and monitoring visually the plume from survey vessels (OSV *Anderson* and R/V *Endeavor*) and an aircraft.

Survey/Activity/Date	Site Baseline Information			Tier I		Tier 2			Tier 3	Tier 4
	Chemical	Biological	Physical	Sludge Characteristics	Disposal Operations	Compliance Issues	Nearfield Fate	Short-Term Effects	Farfield Fate	Long-Term Effects
Survey										
1984	■									
1985a	■	■								
1985b	■	■								
1985c	■									
1986	■		■							
Mooring, 1986 to 1987			■							
Survey										
1987			■			■	■			
1988a			■			■	■			
1988b			■			■	■	■	■	
Mooring, 1989-1991							■		■	
1989a										■
1989b									■	■
1989c							■		■	
1990					■	■				
Development of Data Management Systems										
Historical Data, 1987		■	■	■						
Sludge Characteristics, 1988					■					
Disposal Operations, 1987-1991						■				

Figure 2 Summary of 106-Mile Site monitoring activities 1984 through 1991.

All of the above observation techniques are described in detail by EPA (1991a,b). To ensure the sewage sludge plume could be tracked, surface drogues tethered at 5 to 10 m depth were deployed in the centre of plumes immediately behind barges disposing of the sewage sludge. Visual observation of the drogue position relative to the surface signature of the plume plus other in situ measurements (described below) demonstrated that the drogues remained within the plumes over time. With respect to direct observation and sampling within the plumes, specialized sample-collection technology was developed (McDowell *et al.*, 1989). The system is an integrated water-sampling device designed to collect uncontaminated water samples while acquiring conductivity/temperature/depth (CTD) and turbidity data. The sampler is towed at speeds up to 4 kn to provide horizontal profiles and can be deployed to obtain vertical profiles. Continuous real-time profiles of turbidity were a major tool in defining the width and depth of a plume; the sludge plume was noted by changes in the transmissometry signal as compared to the background. The dimensions of the plume were described in relation to physical oceanographic variables (salinity, temperature, depth of the pycnocline) concurrently monitored by the CTD system. Water samples for chemical and biological sludge tracer analysis were collected from the centroid of the plume (as defined by the *in situ* transmissometry information) to ensure that the most conservative measurements of dispersion would be made. Chemical data from these samples were used to determine the rate of dilution of the disposal plume and, in addition, any exceedance of established regulatory endpoints. Most plumes dispersed beyond the ability to be tracked after 4 h; however, several were tracked for up to 12 h following disposal.

Monitoring activities for evaluating short-term effects were initiated during September 1988. These included several types of measures related to direct toxicity (EPA, 1991c). On board, rapid, chronic-toxicity tests were conducted using sea-urchin sperm and eggs. Tests used hourly samples of the plume, beginning with initial sampling immediately behind the barge. Additionally, on board, acute-toxicity tests were performed using the mysid shrimp, *Mysidopsis bahia*. Tests used plume samples taken 4 h after dumping to ensure compliance within the 4-h initial mixing period defined by the Ocean Dumping Regulations. On board acute-toxicity tests also were conducted using indigenous zooplankton (copepods). These tests also used plume samples taken 4 h after dumping. Finally, fish eggs were examined for genetic mutations and other abnormalities. Samples were obtained from hourly surface tows with a plankton net run transverse to the axis of the sewage sludge plume from 0 to 4 h following dumping.

There was also monitoring of ambient conditions indicative of biological function, specifically phytoplankton biomass, dissolved oxygen (DO), and pH. Chlorophyll α was measured in surface sea water both within plumes and at locations within 20 km of the Site. Measurements in plumes were made at hourly intervals. Tests were conducted in background conditions as well as in sludge plumes. pH and DO were measured in sewage plumes and in background sea water.

Analytical

For field studies, analytical methods followed those given in EPA (1991a-d). Where appropriate, published EPA methods were followed for all measurements. Trace metals sampling and analysis were conducted using stringent trace metal clean techniques. All sample analysis was conducted under intensive quality control procedures including analysis of procedural blanks, laboratory duplicates, matrix spike recoveries, and standard reference materials (SRMs) such as the National Research Council of Canada's sea water SRMs CASS-II or NASS-1. This set of quality control samples were run for each batch of twenty samples. Quality control results were within 20% of the expected values; specific results can be found in EPA 1991a,b,c. Analysis of the water samples was accomplished by complexing the metals with ammonium-1-pyrrolidine dithiodicarbamate (APDC) and diethylammonium diethyldithiocarbamate (DDDC) followed by double extraction into freon (Danielson *et al.*, 1982). *Clostridium perfringens* spores were enumerated using the method of Cabelli and Pedersen (1982).

RESULTS

Sludge characterization monitoring

The EPA in 1988 independently sampled and characterized sludge from the nine sewerage authorities that use the 106-Mile Site (EPA, 1991d). The data confirmed the notion that sludge is variable in composition and toxicity (Tables 2-4). Concentrations of chemicals were found also to vary relative to previous data provided by the sewerage authorities, primarily with respect to metals. Metal concentrations were found to be lower than those reported by the sewerage authorities in permit applications (Table 3). Organic compounds were found at notably low concentrations and were generally undetectable. The lower results obtained for the more recent samples are attributed in part to improved sample collection and analysis procedures and in part to improved sludge quality resulting from response to more stringent source control requirements. The toxicity of the sludge to representative test species, while variable among the sewerage authorities, was generally similar to previous results (Table 4).

Table 2 Summary of sewage sludge physical characteristics results from the August 1988 EPA Characterization Study [from EPA, 1991d]. The average concentration and coefficient of variation (%) for the triplicate analysis of each sludge are reported.

Authority[a]	*Non-filterable residual*[b] *(mg/l)*	*Total residual (mg/l)*	*Settleable solids (mg/l)*	*Specific gravity (g/cm*^{3}*)*	*Solids density (g/cm*^{3}*)*
PVSC	76,500 (5.0)	83,700 (6.2)	<4(–)	1.030 (0.22)	1.62
MCUA	27,800 (17)	41,100 (1.4)	<4(–)	1.013 (0.04)	1.59
BCUA	18,500 (19)	25,700 (1.7)	<4(–)	1.000 (0.29)	1.63
LRSA[c]	83,900 (13)	61,600 (8.9)	21,700 (36)	1.013 (0.99)	1.61
RVSA	53,300 (17)	63,900 (7.9)	<4(–)	1.016 (0.12)	1.64
JMEUC	19,400 (21)	32,200 (3.7)	<4(–)	1.003 (0.22)	1.59
NYCDEP	20,700 (2.0)	26,200 (2.0)	<4(–)	1.006 (0.08)	1.74
NCDPW	13,100 (11)	18,000 (3.3)	<4(–)	0.989 (0.11)	1.63
WCDEF	22,100 (4.4)	21,500 (4.4)	<4(–)	1.020 (0.22)	1.62

a Abbreviations for sewerage authorities are translated in Table 1.
b Nonfilterable residue is equivalent to the total suspended solids.
c Sample was heterogeneous and exhibited inconsistent behaviour during processing.

Table 3 Summary of sewage sludge trace-metal characteristics results from the August 1988 EPA characterization study [from EPA, 1991d] compared with mean results included in permit applications. Coefficient of variation shown in parentheses.

Authority[a]	*Cd* ($mg\,l^{-1}$)		*Cu* ($mg\,l^{-1}$)		*Pb* ($mg\,l^{-1}$)		*Hg* ($mg\,l^{-1}$)	
	1988	*Mean*[b]	*1988*	*Mean*[b]	*1988*	*Mean*[b]	*1988*	*Mean*[b]
PVSC	1.20	4.40[c]	42.0	57[c]	53.0	187[c]	0.29	0.45[c]
MCUC	1.90	2.96(48)	68.0	92(45)	6.3	17.8(121)	0.07	0.18(394)
BCUA	1.50	2.18(100)	25.0	42(100)	4.0	4.1(85)	2.00	0.13(131)
LRSA[c]	0.59	NA	80.0	NA	10.0	NA	0.31	NA
RVSA	0.08	NA	16.0	NA	2.6	NA	0.23	NA
JMEUC	0.67	2.12(42)	36.0	77(54)	9.1	26.3(90)	0.17[d]	0.17(35)
NYCDEP	0.20	0.16 to 8.5[e]	38.0	33 to 103[e]	13.0	2.3 to 113[e]	0.17	0.04 to 0.37[e]
NCDPW	0.14	0.30[c]	12.0	84[c]	3.9	8.6[c]	0.13	0.04[c]
WCDEF	0.19	0.61(89)	56.0	94(73)	9.2	17.4(165)	0.11	0.14(71)

[a] Abbreviations for sewerage authorities are translated in Table 1.
[b] Mean value from permit applications for sludge disposal at the 106-Mile Site.
[c] Single analysis available.
[d] 13 treatment plants.
[e] Range reported for 14 NYC treatment plants.
NA: Not applicable.

Table 4 Summary and comparison of sludge toxicity in August 1988 with information provided in permit applications. LC_{50} results are reported as the percentage of the whole sludge.

Authority[a]	*Menidia beryllina*		*Mysidopsis bahia*	
	August 1988	*Permit application*	*August 1988*	*Permit application*
PVSC	0.49	0.63	0.17	0.09
MCUA	5.95	1.95	2.11	2.80
BCUA	1.55	1.95	2.10	0.66
LRSA	0.53	0.96	0.06	0.20
RVSA	1.49	1.60	0.88	0.11
JMEUC	1.92	1.35	1.68	1.50
NYCDEP	1.59	1.30	2.25	1.41
NCDPW	2.33	2.87	0.92	1.40
WCDEF	0.91	1.47	1.17	1.16

[a] Abbreviations for sewerage authorities are translated in Table 1.

Short-term horizontal and vertical dynamics of discharge plumes

The various plume-tracking observations on plumes from 10 disposal operations at the Site during 1987–1989 showed that sludge was transported laterally and crossed Site boundaries. For example, surface drogues were used to mark a position within the plumes, and, by repeated marking of the position of the drogue, the movement of the near-field plume movement was evaluated. Data from these studies as well as from visually traced shallow sub-surface drogues show that sludge may remain within the Site for many hours or may be transported out of the Site within a few hours of disposal (Figures 3 and 4). The transport may be in any direction, depending on the local current regime at the time of disposal. Notably, the rate and direction of lateral transport can vary significantly on time-scales of less than 1 day and as a function of advective processes operating at spatial scales much smaller than the boundary (kilometres) of the Site (Figures 3 and 4).

Changes in beam attenuation from the *in situ* transmissometry were used to document suspended-particle behaviour in the vertical dimension over time following discharges (Figure 5). Such vertical profiles were used to estimate the

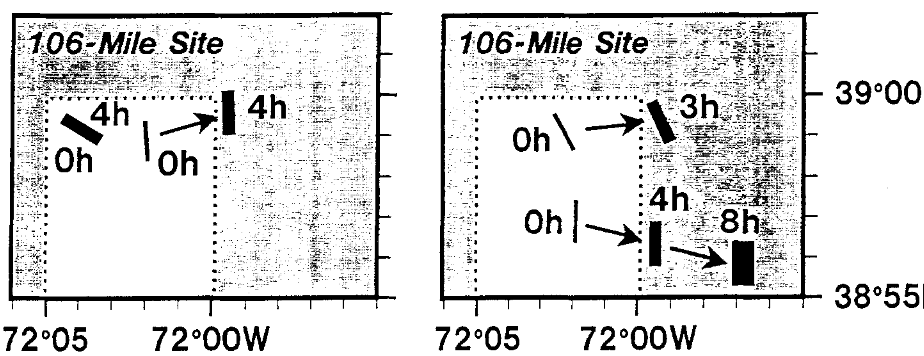

Figure 3 Summary of near-surface drifter trajectories from sewage sludge plume studies, September 1987. The direction of the plume movement is indicated by the arrow. The growth in the width of the plume is also shown at time intervals following disposal.

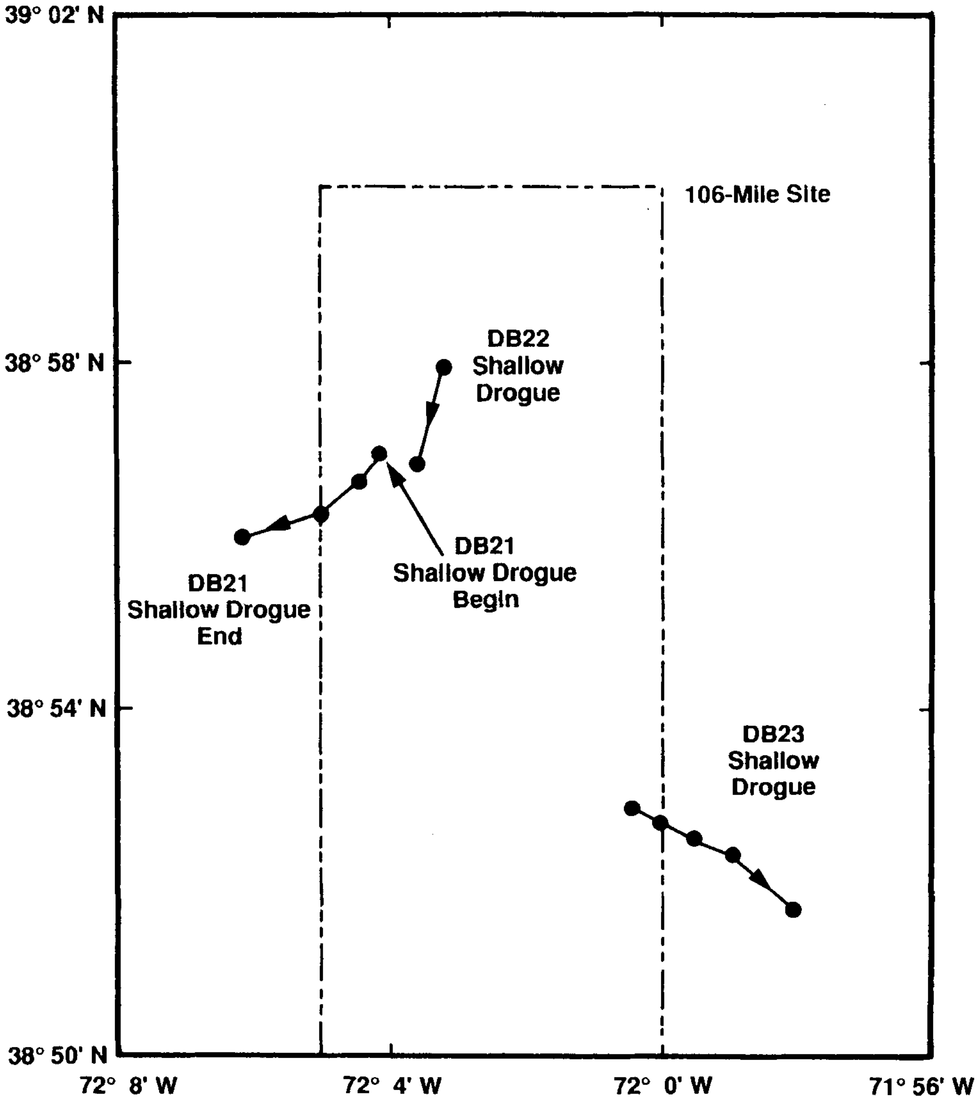

Figure 4 Movement of visually tracked mixed-layer drogues deployed during plume-tracking operations in October 1988. Plumes DB-21, DB-22, and DB-23 were tracked for 4, 2, and 12h, respectively.

vertical thickness of the plume, i.e., the depth to which increased turbidity due to the discharge was evident. In most cases, suspended particles from the discharge were evident between 10 and 20 m depth within minutes of discharge and remained detectable there for a few hours.

Based on numerous vertical profiles of turbidity, the sludge plumes did not appear to penetrate the summer pycnocline in significant quantities within the first 8 to 12 h following dumping. The pycnocline during September 1987 and 1988 was typical of summer conditions at the Site: a surface mixed layer with a sharp seasonal pycnocline

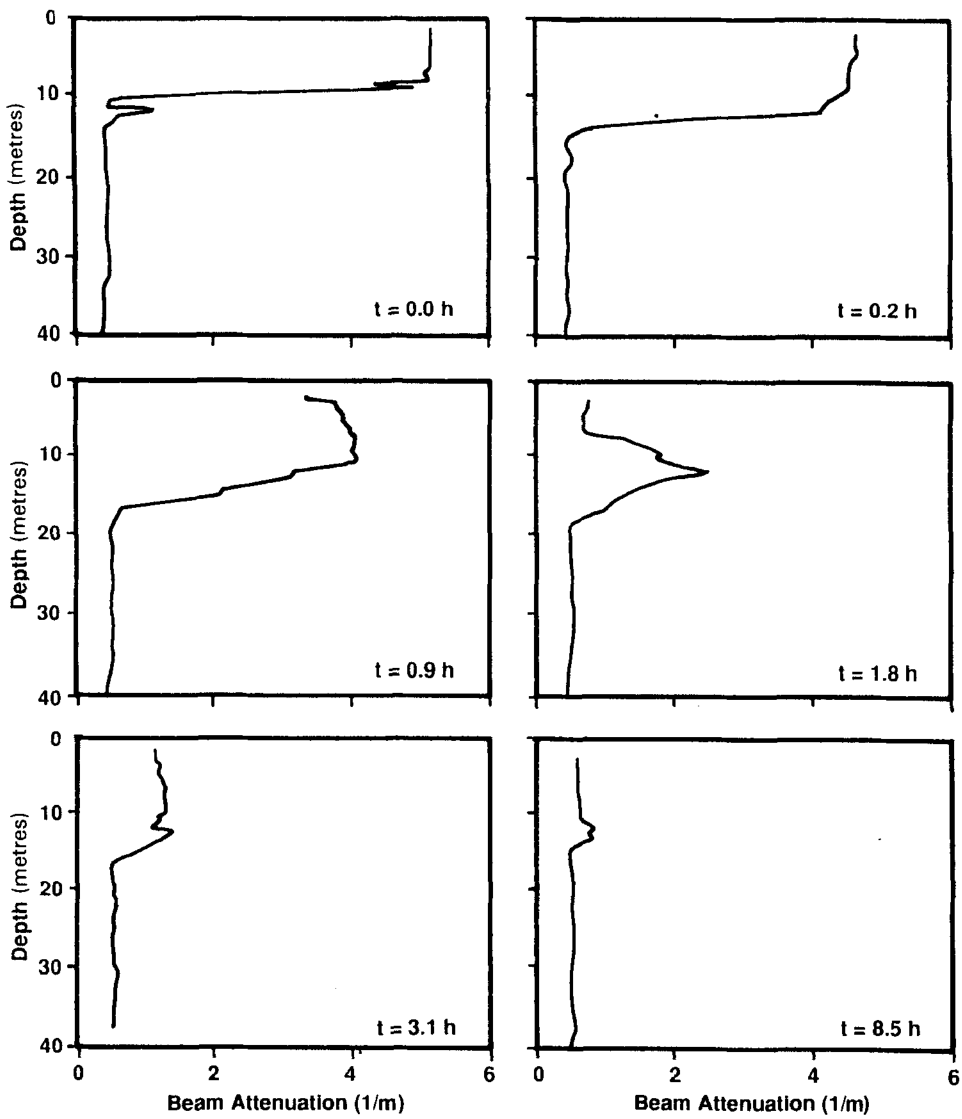

Figure 5 Composite of vertical turbidity (beam attenuation) profiles (from plume DB-3, September 1987) showing the depth of sludge penetration following disposal at the 106-Mile Site.

extended from roughly 20 to 40 m depth. High-resolution vertical profiling conducted within sludge plumes during the summer surveys found that the sludge generally remained within the upper 25 m of the water column (e.g., Figures 5 and 6). Additionally, profiling operations in the fall of 1988 that were designed to detect sewage sludge in the pycnocline in and near the 106-Mile Site also identified distinct subsurface turbidity maxima at depths above 25 m (EPA, 1991c). These turbidity features were confirmed to be sludge plumes through analysis of trace metals and *C. perfringens* Spores.

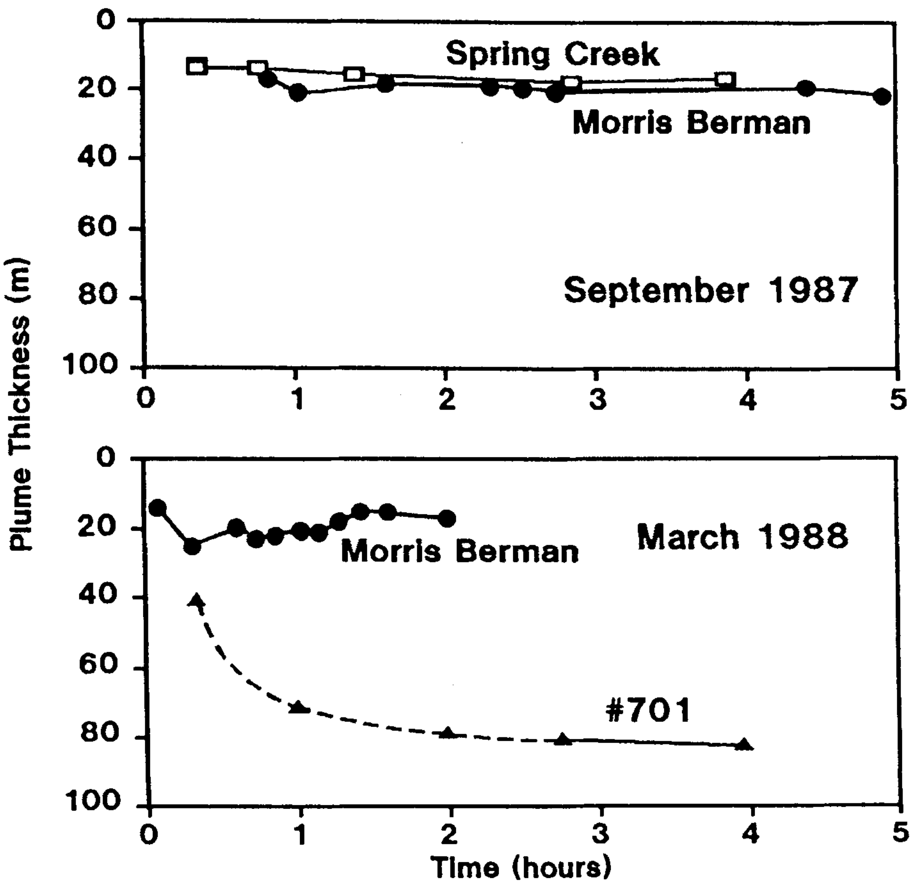

Figure 6 Comparison of sludge settling as a function of time for several sludge plumes surveyed in September 1987 and March 1988. The names of the barges discharging sludge are shown.

Sewage sludge-settling characteristics during the winter were found to be similar to those observed during summer, with the exception noted below. Profiling operations within six sludge plumes during a 3-day period in March 1988 revealed that sludge penetration was limited to the upper 25 m of the water column, although the mixed layer extended to roughly 50 m. During this survey, seas and winds were relatively calm and horizontal currents were weak (< 10 cm s^{-1}).

An exceptionally deep dispersion of a barge discharge occurred in March 1988, when a maximum depth of sludge particle penetration to about 70 m was documented (Figure 6). This occurred behind a barge (#701) suspected of having dumped at rates in excess of 68,900 l min^{-1} (15,500 gal min^{-1}), in exceedance of court-mandated dumping rates and well above dumping rates of other plumes that were tracked. This observation suggested that the rate of sludge disposal is a governing factor for plume dispersion in the vertical dimension. Interestingly, the extent of vertical dispersion in this one case exceeded the variability in short-term vertical dispersion observed across all other barge discharges monitored, including across different seasons and, accordingly, across strongly different physical conditions within the surface mixed layer at the Site.

Near-field chemical fate

The chemical and microbiological tracers chosen for the municipal sewage sludge were readily detectable in the environment in the plume centroid (as defined by *in situ* transmissometry information) immediately after discharge. Of significance, these included trace metals (such as Cu, Pb, Hg, Fe, Zn) and organic compounds for which there are water quality criteria (WQC). The surveys are fully described elsewhere (EPA 1991a-c), but the most notable results on metals are given below.

The results from near-field fate monitoring established that, under the conditions originally set for sludge disposal (i.e., the original court-ordered dumping rate of 15,500 gal min^{-1}), concentrations of sludge constituents frequently did not meet regulatory requirements. For example, data gathered in the late summer of 1987 demonstrated that the EPA WQCs for copper and lead (Figure 7) were exceeded, both inside the Site 4 h after disposal, and outside the Site boundaries. Similar results were found in the fall of 1988. Overall, WQCs were exceeded 4 h after disposal (Figure 8) in approximately 50% of the plumes surveyed during 1987 and 1988. Survey results also indicated that sludge dumping at 15,500 gal min^{-1} resulted in microbial spore tracer levels exceeding ambient levels 4 h after dumping. For example, both in 1987 and 1988, *C. perfringens* was detected in water collected 4 h or more after disposal in sewage plumes surveyed. *C. perfringens* was not detected in samples collected at background surface stations upstream of the 106-Mile Site.

Transport of sludge from the 106-Mile Site

Several pieces of evidence, including plume transport within hours of disposal and slow dispersion of the sludge, and substantial subsurface maxima in several transmissometry profiles in and near the Site indicated that sewage sludge tracers, therefore sludge, could be detected outside Site boundaries.

In addition, throughout the near-field environment, vertical transmissometry profiles exhibited a maximum situated within the seasonal pycnocline. Samples collected from within the seasonal pycnocline in March 1988 showed high concentrations of selected metals that approached or exceeded EPA marine WQCs (EPA, 1991b). During this period, surface currents at the Site were low, and thus the potential for build up of contaminants was high. Further monitoring of the particle maximum in the seasonal pycnocline was initiated in September 1988. Contaminant levels in the pycnocline both on site and in the environs of the 106-Mile Site were not generally elevated in this region during this survey, although indications of localized patches of sludge contamination were found both south-east and north-west of the Site (EPA, 1991c).

A factor of note affecting the transport of sludge is the partitioning between the solid and dissolved components of the sludge following disposal. Leaching of metals from sludge particles to the dissolved phase following disposal was observed during the winter 1988 survey. The partitioning to the dissolved phase was observed immediately following disposal and continued as the sludge dispersed. Generally, dissolved contaminants will move with the surface waters, whereas particulate phases are likely to undergo settling at slow rates. The effect of observed partitioning is likely to result in a net reduction in vertical transport of some contaminants in the immediate area over the short term and, thus, possibly dispersion over a wider area.

Finally, the direction(s) of longer-range advection via regional surface currents was assessed. A number of drogues were tracked after release within the boundaries of the Site. Trajectories measured in 1988 and 1989 (Figures 9, 10) generally suggested an initial southwest-ward movement parallel to the shelf break coast-ward

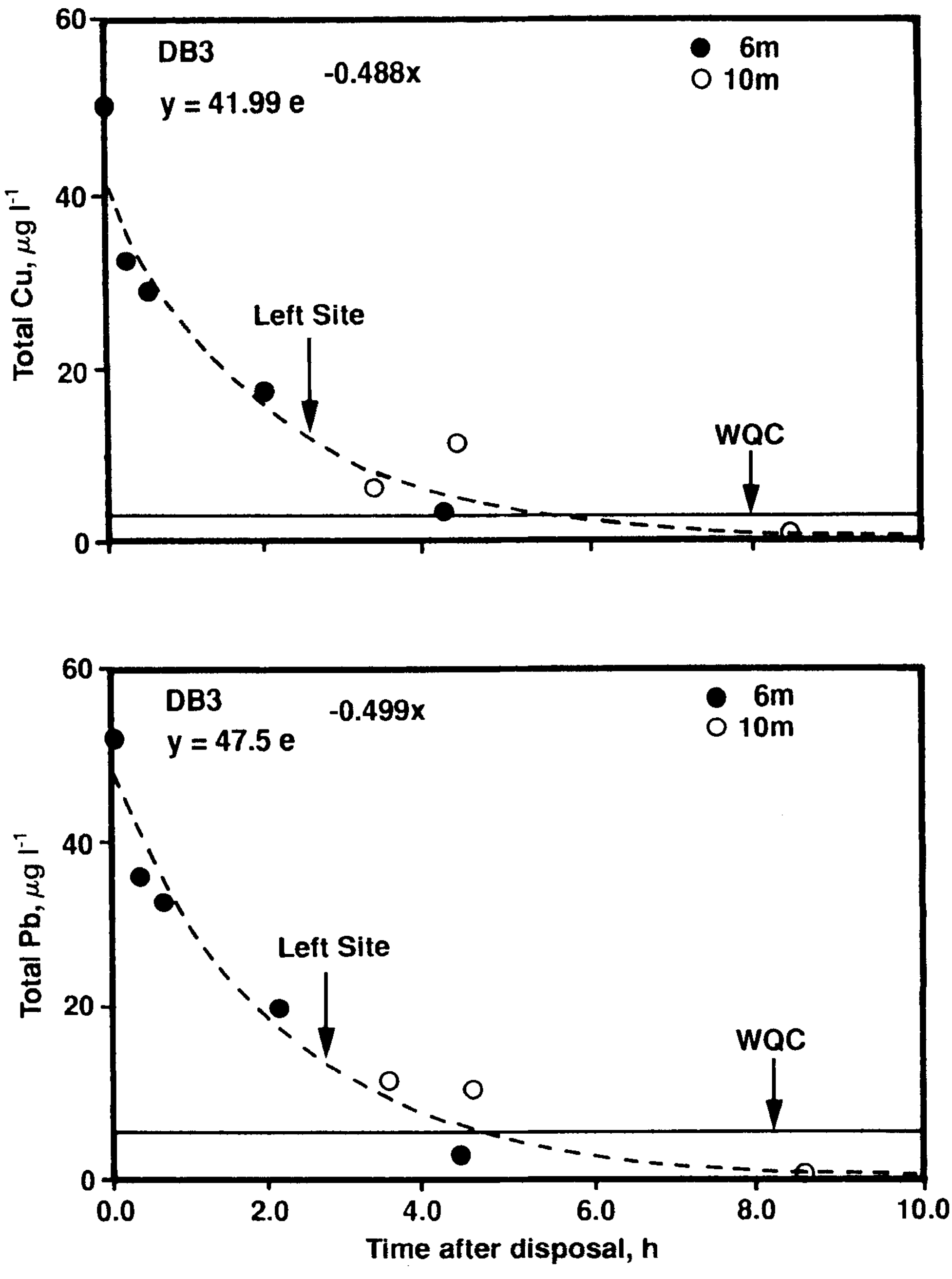

Figure 7 Decrease in copper and lead concentrations in plume DB-3, September 1987. Concentrations in the plume when it crossed the Site boundary are shown, as are the EPA chronic marine water quality criteria for these metals.

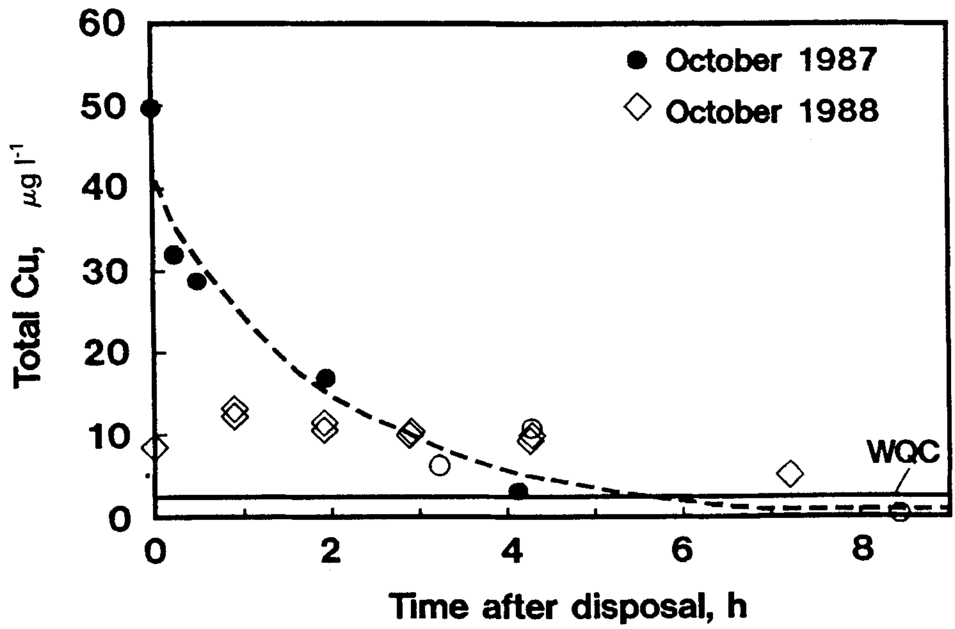

Figure 8 Comparison of copper dilution as a function of time against EPA chronic water quality criteria for plumes surveyed in September 1987 and 1988.

of the 106-Mile Site. Once the drogues reach the northern wall of the Gulf Stream in the general region of Cape Hatteras, they rapidly move to the east within the Gulf Stream.

Short-term effects

Several studies were performed to evaluate if disposal of sludge causes short-term biological effects. These studies involved measurement of potential causes of effects, such as changes in pH or dissolved oxygen (DO), or direct effects, such as toxicity to various marine test organisms or increases in phytoplankton biomass.

The monitoring results indicated that sludge was toxic to sea urchin gametes from 0 to 3h after disposal (Figure 11) but not 4 h after disposal. On board testing of sludge samples with mysid shrimp (two sludge plumes, $T = 4$ h after dumping) and indigenous calanoid copepods (one sludge plume, $T = 3.5$ h after dumping) revealed no acute toxicity.

No significant changes in the phytoplankton biomass as measured by chlorophyll α were observed. Chlorophyll α concentrations measured hourly in three plumes in September 1988 did not vary. However, phaeophytin concentrations, an indicator of degraded chlorophyll, were elevated in the plume samples relative to background concentrations. Because of an unchanging chlorophyll but higher phaeophytin concentration, a lower chlorophyll α/phaeophytin ratio was apparent downstream from the Site (EPA, 1991c). This ratio may serve as an additional tracer for the plume, but does not imply effects on phytoplankton biomass. Changes in productivity composition were not evaluated.

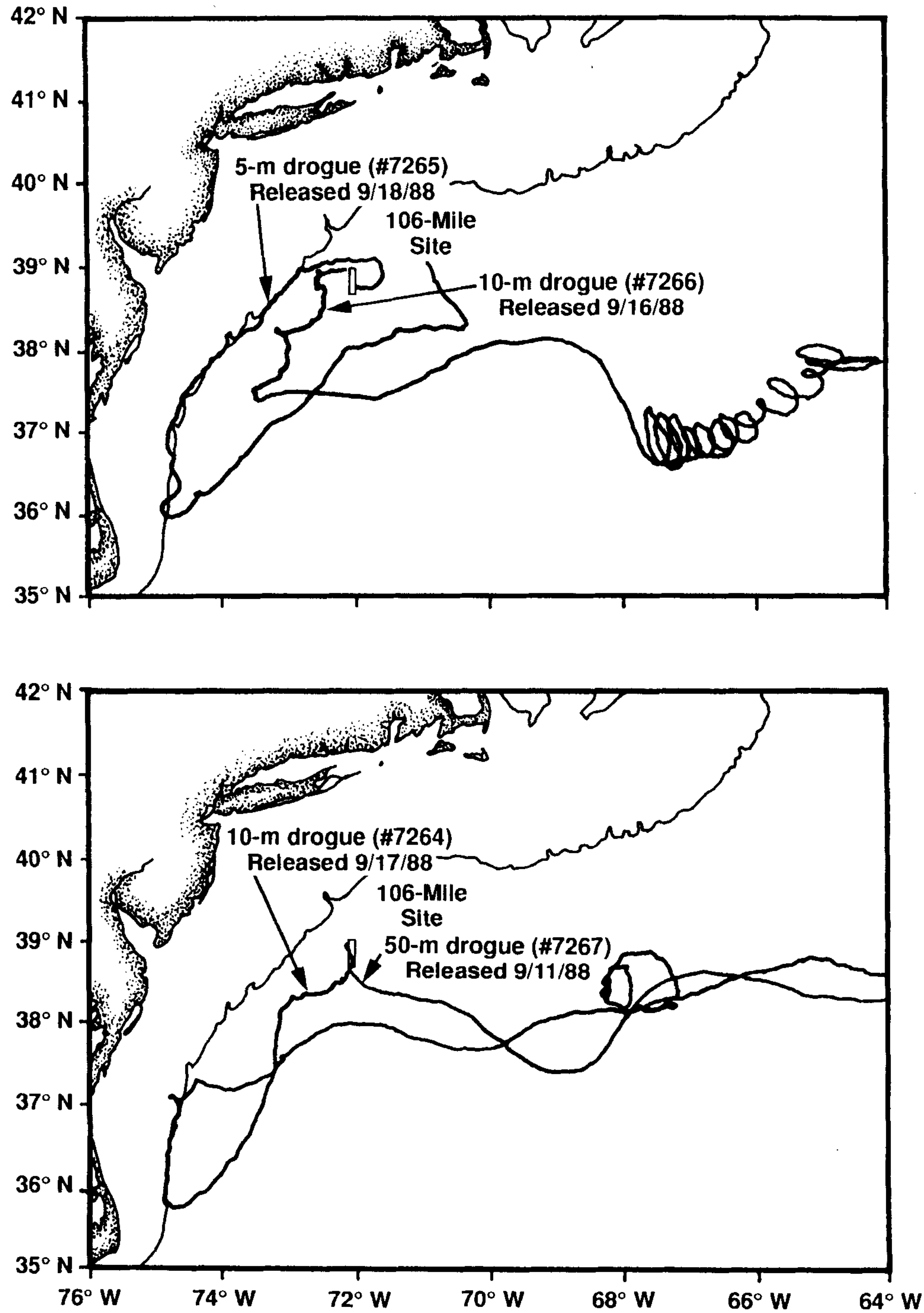

Figure 9 Trajectories of satellite-tracked drifters deployed during October 1988 plume-tracking operations. The depth of the subsurface drogue and date of deployment in the 106-Mile Site are shown.

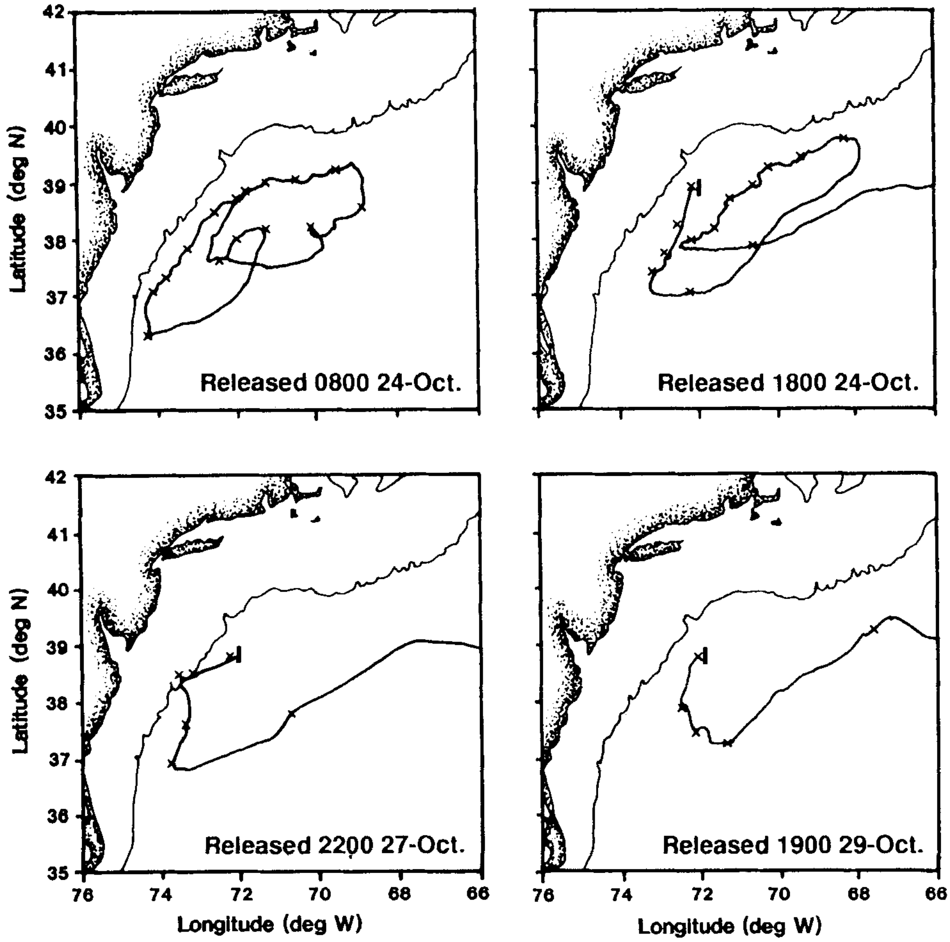

Figure 10 Trajectories of four near-surface satellite-tracked drifters released at the 106-Mile Site in September 1989. Tick marks indicate weekly intervals. Recirculation of the two drifters through the disposal site 60 to 80 days after deployment are shown.

Sampling for zooplankton and fish eggs found no effects that could be attributed to sludge. However, the collection period was near the end of the normal spawning period for pelagic fish, which limited the ability to determine effects. The samples collected for these studies also yielded floatable debris that included paper mulch, plastic pieces, pellets, spherules, plastic filaments, and tar balls. Such debris is not permitted to be dumped at sea and had not been expected in the samples. On evaluation of the characteristics of the material and information on the water masses in the area, it could not be determined whether these materials originated from the sewage sludge or were associated with continental shelf water that intruded over the Site. However, these results indicated that comprehensive monitoring for floatable debris should be a part of the ongoing sludge characteristics monitoring (Tier 1), and is conducted by the sewerage authorities using the 106-Mile Site.

Observations of DO in sludge plumes in the fall of 1987 and pH in the fall of 1988 found minor depressions following disposal but changes in DO concentration were

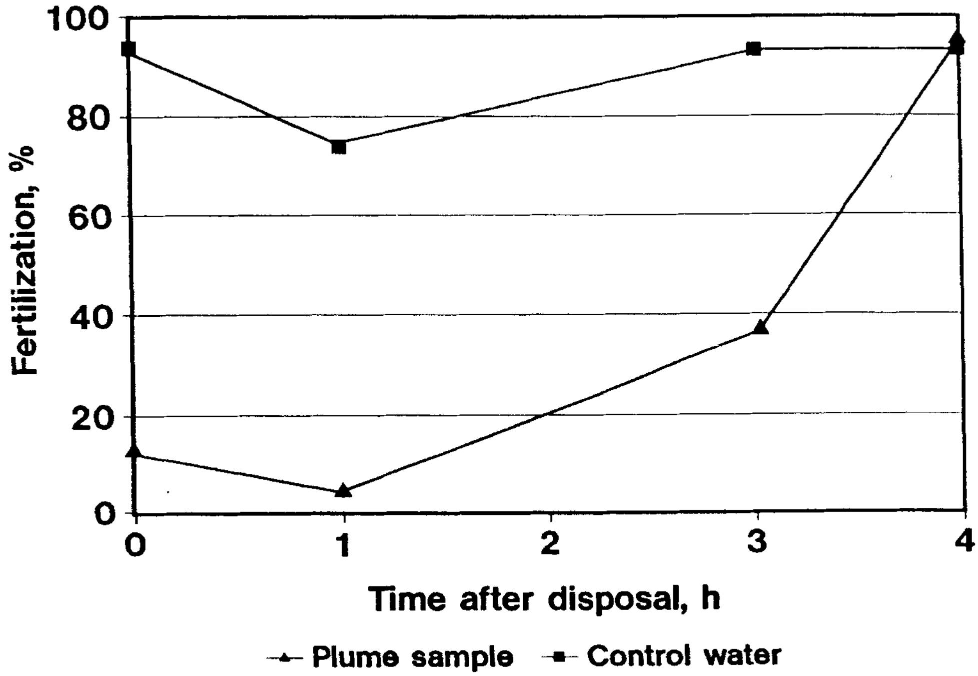

Figure 11 Results from sea-urchin fertilization tests conducted in October 1989. Control waters were obtained from approximately 10 nm (19 km) north of the 106-Mile Site.

at the limit of instrument resolution. The observed depression of DO could be predicted by simple mixing models and was not the result of depletion caused by chemical or biological oxygen demand. For example, if the DO content of the sludge and receiving water were 0 and 7 ml l^{-1}, respectively, the reduction in oxygen content of the receiving water at typical initial sludge dilution would be on the order of 0.002 ml l^{-1}. This level of depression is both immeasurable and insignificant from a biological perspective.

Results from the September 1988 survey showed that the pH of the sea water was not detectably altered in two of three plumes surveyed. The pH in a third plume decreased by approximately 0.2 immediately following disposal, and rapidly recovered to ambient levels.

DISCUSSION

Monitoring Results Relative to Some Predictions

The 106-Mile Site was selected for waste disposal in part because the receiving waters are dispersive (EPA, 1980). Major factors affecting the fate of wastes disposed at the

106-Mile Site were discussed by O'Connor in the National Oceanic and Atmospheric Administration (NOAA) report *106-Mile Site Characterization Update* (Pearce *et al.*, 1983; O'Connor *et al.*, 1983. O'Connor indicated that the initial dilution of sewage sludge in the wake of the barges dumping the sludge would be rapid. Other factors that were thought to control dilution of the sludge included the rate of disposal and the depth of the pycnocline.

Evidence from disposal of acid iron waste at the larger 106-Mile Site in the early 1980s indicated that, after the rapid mixing and dilution of the waste caused by the momentum of the barges is completed, additional dilution by oceanic processes would be slow (Fox and Kester, 19850; Fox *et al.*, 1986). Initial dilutions in the wake of the barges were predicted to be in the order of 5000:1 (Pearce *et al.*, 1983). It was also speculated that episodic high-energy events such as storms, would increase the rate at which dilution occurred.

Short-term variability in ocean currents was also predicted to cause movement of individual plumes away from the Site in all directions (Pearce *et al.*, 1983; O'Connor *et al.*, 1983). However, the long-term transport of the material was predicted to be toward the south-west in the direction of the long-term net current drift in the area. Simple modeling of the sludge dilutions that could be expected in the far-field suggested that dilutions could easily reach 500,000:1 or more. Because of these great dilutions, detection of sludge particles or constituents away from the Site was considered to be difficult. It follows that identification of parameters that could be clearly linked to sludge is one of the critical factors monitoring sludge in the far-field.

The information gathered during the EPA monitoring programme has resulted in improved understanding of many of the concepts and predictions offered by O'Connor *et al.* (1983) and others. To begin, the detection of sludge was easily and consistently accomplished on site for many individual disposal events. Both chemical and physical evidence of the presence of sludge for several hours after discharge was provided by the near-field/short-term monitoring studies. These studies were also able to identify tracers that could be used most effectively to detect sludge in the far-field. Among those identified as effective tracers of the sludge were *C. perfringens* spores, turbidity (i.e., total suspended solids), and trace metals such as copper and lead. Extraction of large-volume (100 l) samples from the sludge plume for quantification of organic compounds associated with sewage sludge [e.g., polychlorinated biphenyl (PCB), pesticides, and polynuclear aromatic hydrocarbons (PAH)] did not provide significant concentrations of these compounds after initial dilution (EPA, 1991a-c). Therefore, organic compounds were not conisdered to be effective tracers of sludge in the far-field. Those tracers found to be effective in tracing the sludge signal in the ocean were used to further evaluate the far-field transport and are discussed by Hunt *et al.* (1992).

A second feature relative to predictions was that the monitoring results provided a demonstration that, dumping rates being similar, sludge-settling characteristics were similar in winter and summer and generally did not penetrate the thermocline. Although not directly assessed in these studies, settling of the bulk of the sludge is likely to be controlled by flocculation of suspended particles. As a consequence, it is suggested that mixing and advective processes, rather that settling processes, appear to be the major factors controlling the short-term dispersal of the sludge.

Laboratory studies (Lavelle *et al.*, 1988) suggest that 10% to 20% of the sludge may settle at relatively high rates (> 0.3 cm s^{-1}). To address this prediction, EPA evaluated if there was a rapidly settling component of sludge directly under sludge plumes immediately after disposal. These traps captured sand, other black grit-like particles, plus large organic aggregates of sludge. These direct measurements of settling particles showed that a component of sludge could settle on the order of metres per hour.

A final point relative to plume behaviour predictions. Field data and subsequent modelling of plume dilution rates (below; EPA, 1991e) indicated that the rate of settling depends greatly on the dumping rate. Indeed, results suggested that vertical dispersion rates may vary more as a function of the volume rate of disposal than as a function of seasonal physical variability in ocean surface waters. This conclusion has direct implications for disposal practices, as discussed below.

Monitoring results relative to permits for sewage sludge disposal

Sludge-characteristics monitoring data, along with a review of quality of data provided in permit applications, were used to develop new requirements for monitoring sludge characteristics to provide necessary high quality data for the overall monitoring program. These requirements were incorporated into the permits issued for the 106-Mile Site in August 1989. The requirements included in the permits specify analytical methods, method detection limits, number and type of parameters monitored, frequency of monitoring, and quality control and reporting requirements.

Development of nomograph

Based on the specific observations of plume transport and measurements of chemical contaminants in 10 plumes, an empirical formulation was developed describing the dilution of the sewage plume centroid (EPA, 1991e). The formulation is based on the observed initial dilution behind a barge, the speed of the barge through the water, and the dilution required to meet the limiting permissible concentration (LPC) defined by the regulations within 4 h of sludge disposal. Using sludge characterization data from the EPA monitoring study and results from the plume-tracking studies, a simple nomograph was developed that relates dumping rates to the LPC. This nomograph (Figure 12) was used to establish the dumping rates under the permits issued by EPA in 1989 for use of the 106-Mile Site, and will be used to ensure that continued dumping at the Site complies with the WQC and LPC. This is being accomplished by quarterly review and recalculation of sludge disposal rates using the sludge characterization data required under the disposal permits.

In summary of these aspects of Tiers 1 and 2 monitoring, the studies accomplished several goals. First, they provided a field assessment and verification of a number of predictions of near-field fate and short-term effects from discharging. Most significantly, evidence was provided that a substantial fraction of sludge particles remains largely confined to the surface mixed layer above the pycnocline. Some results were perhaps surprising; for example, short-term persistence of metals in surface waters occurred and concentrations that were above EPA marine WQCs were documented. Based on the monitoring studies, modifications were made to the disposal permits and to the disposal practices that resulted in environmental conditions that were not in compliance with ocean disposal regulations. Finally, a simple method was devised to establish sludge dumping rates, given a specified dilution rate as determined from sludge toxicity tests.

Continuing monitoring studies

The accomplishments of Tiers 1 and 2 monitoring also include the development of a

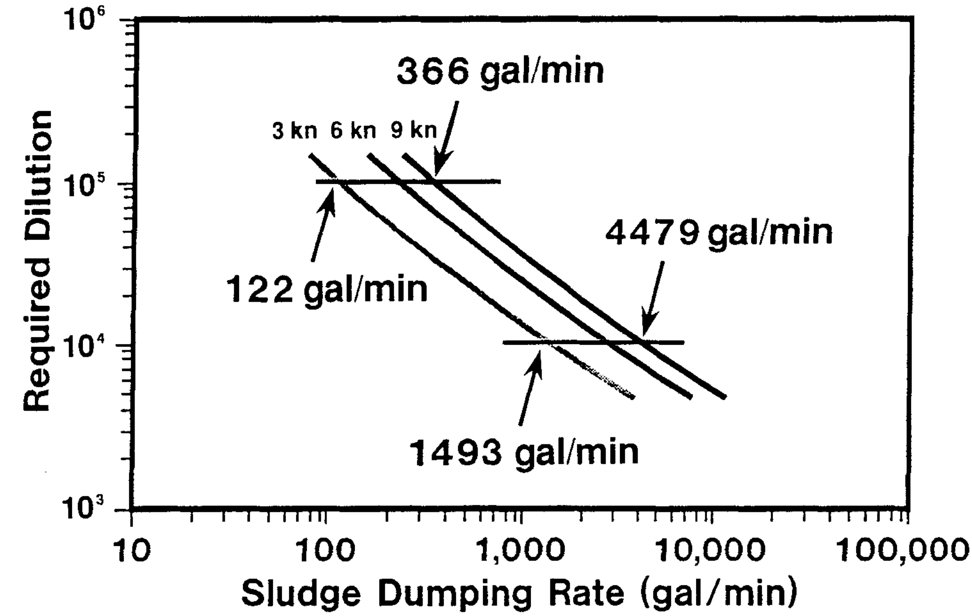

Figure 12 Nomograph of sludge dumping rates (in gallons per minute) versus sludge dilutions required to meet limiting permissible concentrations required by the ocean dumping regulations. Separate curves are shown for barge speeds of 3, 6, and 9 kn.

firm basis of information for initiating studies of far-field fate and long-term effects. The monitoring results, coupled with other recent studies, have created an appreciation of the dynamics of the physical setting and its influence. For example, prevailing physiographic conditions at the Site influence sludge movement as well as movement of contaminants originating from sources other than the sludge. The Shelf Edge Exchange Program (SEEP) has evaluated movement of particles from the continental shelf edge (Biscaye *et al.*, 1988; Walsh *et al.*, 1990). (The SEEP experiment is a two-phase study to examine (1) the fate of particles in the continental shelf water column and (2) the dynamics of the continental slope water column as these might effect the sedimentation of particles onto the slope.)

Relative to particle movement, Biscaye *et al.* (1988) conclude that, "In addition to the vertical flux of particles coming from near-surface waters of the slope, both fresh biogenic particulate matter and resuspended sediment derived from the shelf and upper slope are transported downslope and added to the burden of particles setting vertically to the slope and upper rise sediments." A major conclusion from the SEEP-I experiment according to Walsh *et al.* (1988) is that export of organic matter from shallow boundaries of the ocean to the interior regions of the ocean below the thermocline may be nearly equal to vertical losses from the surface water of the deep sea. SEEP results generally suggest a net flux of particles off the continental slope waters in the mid-Atlantic Bight are unlikely to be transported back on to the continental shelf.

The results of monitoring reported here support the same notion. There can be rapid advection of sludge plumes from the 106-Mile Site (Figures 3 and 4) and yet the water mass receiving the sludge appears to remain sea ward of the continental shelf

(Figures 9 and 10). Much of the sludge particles and contaminants also appear to remain above the pycnocline (Figures 9 and 10). Much of the sludge particles and contaminants also appear to remain above the pycnocline (Figures 5-7). Therefore, the probability for the advective transport of sludge away from the continental shelf (Figures 9, 10) seems most likely. Regardless of whether the sludge is entrained in surface currents and eddies or is carried below the thermocline by vertical settling, the results from the SEEP studies would suggest that the long-term fate of the sludge, thus the area most likely to be affected, would be primarily along the slope or upper rise, not toward the shelf.

Such information has in part helped to establish further guidelines on the nature, scale, and location for far-field/long-term monitoring. The Tiers 3 and 4 studies are indeed ongoing and include a variety of activities. In fact, the pace of studies has been accelerated, as affected by the Ocean Dumping Ban Act of 1988 (ODBA), passed by the United States Congress in November 1988.

Future monitoring in response to the ODBA

Passage of the ODBA makes it illegal to ocean-dump sewage sludge and industrial waste after 1991. The law also requires that a comprehensive monitoring program for the 106-Mile Site and environs be developed. In response to this ODBA requirement, a joint monitoring plan (EPA/NOAA/USCG) was developed and published (EPA, 1990). This joint plan updates the EPA plan and has increased the emphasis on the far-field/long-term fate of sludge and the far-field/long-term effects on human health and viability of living marine resources. Ongoing studies that are being conducted under the joint plan are summarized in Table 5.

Table 5 Studies being conducted at the 106-Mile Site under the joint EPA/NOAA/USCG monitoring plan of 1990 (EPA, 1990).

Monitoring tier	*Study area*	*Frequency*
1	Sludge characteristics	Ongoing
	Disposal operations	Ongoing
2	Near-field fate	As needed
	Expendable current profilers	Weekly
	Surface current measurements	Continuous
	Short-term effects	As needed
3	Far-field fate	
	Surface drifter studies	Weekly
	Sea surface temperature images	weekly
	Expendable bathythermographs sections	Weekly
	Hydrographic surveys	Seasonally
	Sediment traps mooring array	05/90 to 06/91
	Sediment sampling and analysis	Annual
	Modelling	As needed
4	Long-term effects	
	Bioaccumulation in benthic organisms	Annual
	Bioaccumulation in mid-water fish	Annual
	Shellfish disease studies	Ongoing
	Benthic organism community studies	Annual

Acknolwedgements

More than 30 individuals from the Battelle Ocean Sciences laboratories in Duxbury, Massachusetts, EPA Headquarters Office of Water, EPA Region II Marine and Wetlands Branch and Edison Laboratory, the City of New York, NOAA National Marine Fisheries Service, New Jersey Department of Environmental Protection, and Science Applications International Corporation have contributed to and participated in the planning, conduct of surveys, analysis of samples, and preparation of EPA reports cited in this paper. We wish to thank each for their dedication and commitment to research of the highest quality. The captains and crews of the EPA Ocean Survey Vessel (OSV) *Anderson* and the University of Rhode Island Research Vessel (RV) *Endeavor* were instrumental in accomplishing the field components of the 1986–1989 monitoring program. Their contribution to the studies is gratefully acknowledged. Dr. Jack Kelly of Battelle Ocean Sciences assisted in the preparation of this paper.

References

Biscaye, P. E., Anderson, R. F., and Deck, B. L. (1988) Fluxes of particles and constituents to the eastern United States continental slope and rise: SEEP-I. *Continental Shelf Research 8:*855-904.

Cabelli, V. J., and Pederson, D. (1982) The movement of sewage sludge from the New York Bight dumpsite as seen from *Clostridium perfringens* spore densities. Pp. 995–999 in *Oceans '82,* Institute of Electrical and Electronics Engineers, New York, NY.

Danielson, L. B., Magnusson, B., Westerlund, S., and Zhang, K. (1982) Trace metal determinations in estuarine waters by electrothermal atomic absorption spectrometry after extraction of dithiocarbamate complexes into freon. *Analytica Chimica Acta 144: 183-188.*

EPA (1986) Test methods for Solid Wastes. SW-846 (Third edition, November, 1986) Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington DC.

EPA (1980) Environmental impact statement (EIS) for the 106-Mile Ocean Waste Disposal Site designation. Final report to the U.S. Environmental Protection Agency, Oil and Special Materials Control Division, Marine Protection Branch, Washington, DC.

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

EPA (1990) Monitoring Research, and Surveillance Plan for the 106-Mile Deepwater Municipal Sludge Dump Site and Environs. Environmental Protection Agency, Office of Water. EPA 503/4-91/001. December 1990. 89 pp.

EPA (1991a) 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.

EPA (1991b) 106-Mile Deepwater Dumpsite winter 1988 survey. Environmental Protection Agency, Office of Water. EPA 503/4-91/009.

EPA (1991c) Final Report Summer 1988 106-Mile Site Survey. Environmental Protection Agency, Office of Water. EPA 503/9-89/009.

EPA (1991d) Characteristics of sewage sludge from the northern New Jersey – New York City area, August 1988. Environmental Protection Agency, Office of Water. EPA 503/2-91/003.

EPA (1991e) Determination of Sludge Dumping Rates for the 106-Mile site. Environmental Protection Agency, Office of Water. EPA 503/3-91/003. 62 pp.

Fox, M. F., and Kester, D. R. (1985) Pp. 171-185 in Kester, D. R., W. V. Bunt, J. M. Capuzzo, K. P. Park, and I. W. Duedall (Eds.), *Wastes in the Ocean,* Vol. 5. Wiley-Interscience, New York, NY.

Fox, M. F., Kester, D. R., and Hunt, C. D. (1986) Vertical transport processes of an acid-iron waste in a MERL statified mesocosm. *Environmental Science and Technology 20:* 62-68.

Hunt, C. D., McDowell, S. E., Shea, D., Trulli, W., Hillman, R., Redford, D., and Pabst, D. (1992) Transport of sewage sludge from the 106-Mile Site – Results from an October 1989 Survey. *Chemistry and Ecology*. This volume.

Lavelle, J. W., Ozturgut, E., Baker, E. T., Tennant, D. A., and Walker, S. L. (1988) Settling speeds of sewage sludge in seawater. *Environmental Science and Technology 22:* 1201–1207.

McDowell, S., Albro, C., and Willauer, C. (1989) An integrating profiling system assists EPA researchers in monitoring horizontal and vertical sludge plume movement at the 106-Mile Site. *Site Technology 30*(10):10-17.

O'Connor, T. P., Okubo, A., Champ, M. A., and Park, P. K. (1983) Projected consequences of dumping sewage at a deep ocean site near New York Bight. *Canadian Journal of Fisheries and Aquatic Sciences* *40* (Suppl. 2): 229-241.

Pearce, J. B., Miller, D. C., and Berman, C. (Eds.) (1983) Northeast Monitoring Program NEMP III 83-0002. *106-Mile Site Characterization Update.* NOAA Tech. Mem. NMFS-F/NEC-26. Department of Commerce, National Oceanic and Atmospheric Administration, National Fisheries Service, Woods Hole, MA.

Walsh, J. J., Biscaye, P. E., and Csanady, G. T. (1988) The 1983 – 1984 Shelf Edge Exchange Processes (SEEP) – I experiment: Hypotheses and highlights. *Continental Shelf Research* *8*(5–7): 435–456.