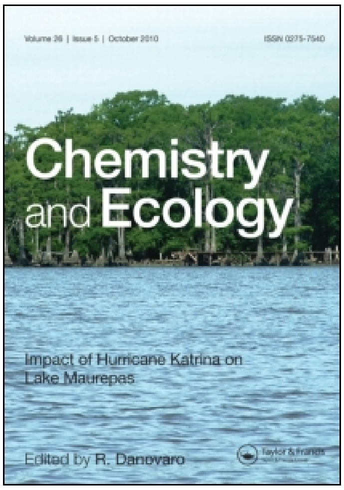
This article was downloaded by:
On: *15 January 2011*
Access details: *Access Details: Free Access*
Publisher *Taylor & Francis*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



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

Transport of Sewage Sludge in a Mixed Water Column

J. S. Bonner[a]; A. N. Ernest[a]; D. S. Hernandez[a]; R. L. Autenrieth[a]
[a] Civil Engineering Department, Texas A&M University College, Station

To cite this Article Bonner, J. S. , Ernest, A. N. , Hernandez, D. S. and Autenrieth, R. L.(1992) 'Transport of Sewage Sludge in a Mixed Water Column', Chemistry and Ecology, 7: 1, 139 — 159
To link to this Article: DOI: 10.1080/02757549208055438
URL: http://dx.doi.org/10.1080/02757549208055438

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Chemistry and Ecology, 1992, Vol. 7, pp 139–159 © 1992 Gordon and Breach Science Publishers S.A.
Reprints available directly from the publisher
Printed in Malaysia
Photocopying permitted by license only

TRANSPORT OF SEWAGE SLUDGE IN A MIXED WATER COLUMN

J.S. BONNER, A.N. ERNEST, D.S. HERNANDEZ, R.L. AUTENRIETH

Civil Engineering Department, Texas A&M University College Station

(Received 23 October 1991; in final form 12 March 1992)

Sewage sludge from four publicly-owned treatment works was sampled and characterized in terms of parameters affecting transport at the 106-mile deep ocean disposal site as part of the US Environmental Protection Agency's site monitoring programme. Samples from treatment plants in Passaic Valley, Rahway, and Elizabeth, New Jersey and New York City were characterized in terms of dynamic size distribution, suspended solids and density. The transport characteristics of sludge particles were measured using a 2 metre computer-interfaced laboratory settling column. Experiments were conducted at constant salinity (35 ppt) while varying hydrodynamic mixing, sludge type and concentration using a modified factorial experimental design. Hydrodynamic power dissipation was varied so that the vertical dispersion and rms fluid shear rate ranged between 0–6 cm^2s^{-1} and 0–30 s^{-1} respectively. Results indicate that at least 80% of suspended sludge particles will eventually settle under mixed conditions. The average settling velocities ranged between 0.05–4.05 × 10^{-3} cm s^{-1}. Shear rates above 15 s^{-1} inhibited sludge settling due to aggregate breakup and boundary effects, but at a lower shear rate, differential settling and fluid shear were the dominant transport mechanisms. Sludge dilution (1/500–1/5000) had a limited effect on the settling rate. Results from this study can be used to calibrate particle transport models to determine the fate of sludge disposed at an ocean disposal site.

KEY WORDS: Sewage sludge, transport, water column, suspended particles

Downloaded At: 14:24 15 January 2011

INTRODUCTION

The 106-Mile Deepwater Municipal Sewage Sludge Disposal Site (106-Mile Site or DWD106), located just beyond the seaward limit of the continental shelf of the Northeast United States (Figure 1), has been designated for disposal of sewage sludge on a 5 year interim basis by the United States Environmental Protection Agency (EPA). The EPA has monitored the 106-Mile Site since 1986 and has issued nine permits for sludge dumping. It was estimated that the site would receive 8.1 million (wet) metric tonnes of sludge in 1990 (Battelle, 1990). Under the EPA monitoring studies of sludge disposal, it has been shown that a portion of the sludge remains in the surface layer immediately after disposal and will settle relatively slowly under quiescent oceanographic conditions (Battelle, 1988a,b). However, Lavelle *et al.* (1988) observed sludge-settling velocities as rapid as 0.3 cm s^{-1} for a coarse fraction. This fraction of particles was greater than 64 μm in diameter and constituted 14.6% to 47.3% by weight of the sludge from several sewage treatment plants, including ones using the 106-Mile Site. Also, recent results from 106-Mile Site indicate that the sludge contains a rapidly settling fraction of the particles that may reach the ocean floor near the disposed site. So it is unclear what fraction of the sludge dumped at the 106-Mile Site remains in the surface layer and what fraction settles, and what role flocculation and oceanic turbulent mixing and shear play in sludge settling velocities.

The 106-Mile Site is a rectangular area of 9.3 × 37 km bounded by 38°40′N, 39°00′N, 72°00′W and 72°05′W, with water depth varying from 1700 m in the

Downloaded At: 14:24 15 January 2011

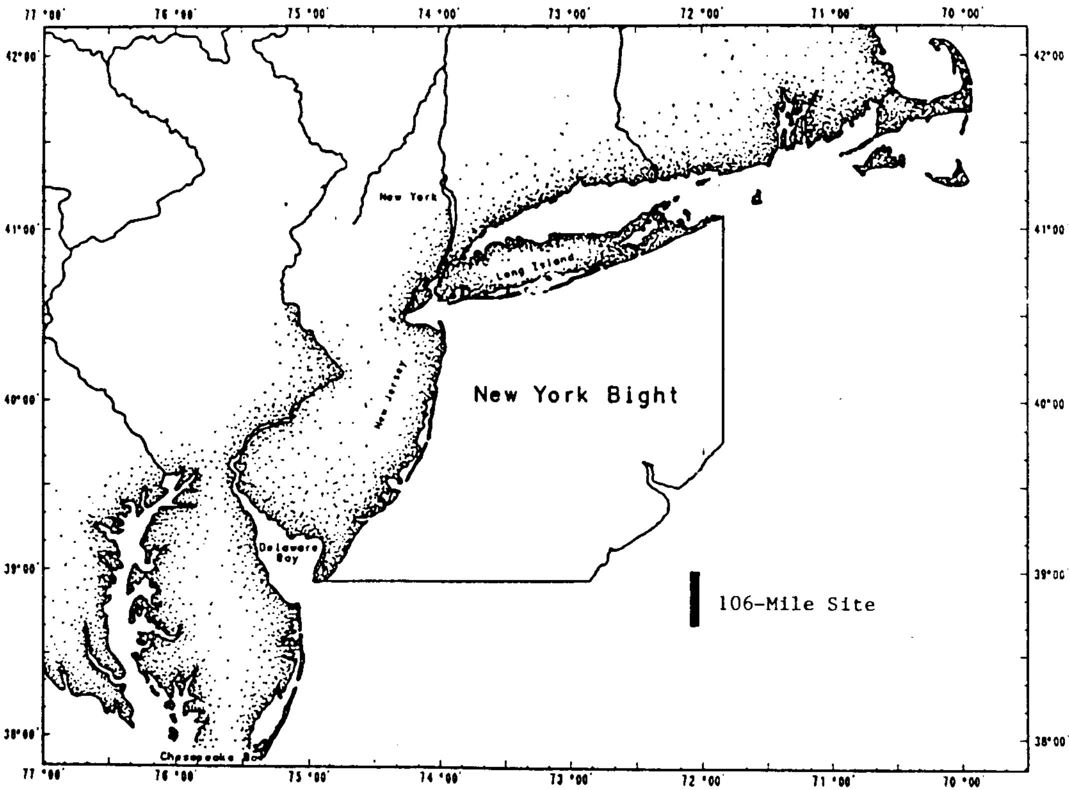


Figure 1 Location of 106-Mile Site.

northwest section to 2750 m in the southeastern section. Between October and May, the water column is almost isothermal to a 100 to 200 m depth where the permanent thermocline exists (Ingham *et al.*, 1977). A seasonal thermocline develops between 20 to 40 m and is present from May to October. The Site has been characterized as a highly dispersive environment in which suspended and dissolved solids are strongly mixed and transported from the dump site. Field studies performed on acid iron waste disposal at the 106-Mile Site determined the primary fate of this waste to be dispersion and vertical transport through the water column (Fox *et al.*, 1986).

Depending on several factors (such as release method, barge speed, and oceanographic conditions), sewage sludge released in the ocean may become finely divided. After disposal, the concentration of the particles and the amount of turbulent mixing and shear in the ocean itself may cause the particles in the waste plume to flocculate, and thereby change their settling characteristics. If small particles do not flocculate, they may be hydrodynamically dispersed and advected away from the disposal site. Sludge that flocculates, however, will form larger particles and may settle more rapidly. On the other hand, the large particles in the coarse fraction may settle rapidly and reach the sea floor in the net downstream direction. Most of the relevant studies indicate that some fraction of the material will settle (Faisst, 1978; Hunt and Pandya, 1984; Morel and Schiff, 1980; Lavelle *et al.*,1988).

Laboratory studies conducted under quiescent conditions to determine particle settling velocities (Kranck, 1980; Lavelle *et al.*, 1988; Li and Ganczarcyk, 1987) show that Stokes Law, which assumes spherical particles of constant diameter and density, does not adequately describe settling velocities in a flocculating system (Lick, 1982; Faisst, 1978; Zaneveld *et al.*, 1982). In aquatic environments, suspended particulate material will tend to approach an equilibrium size distribution as a function of particle characteristics and system hydrodynamics (Farley and Morel, 1986). Gibbs and Hopkins (1984) estimated that the time required to reach this equilibrium decreases with increased particle concentration and fluid shear. It was speculated that this was due to the increased collision and flocculation rates experienced under these conditions. The majority of models proposed to account for the particle agglomeration processes during settling (Lawler, 1979, Hunt and Pandya, 1984) are based on the original particle collision rate theories derived by Smoluchowski (1917) and extended by Friedlander (1964), Swift and Friedlander (1964) and Ives (1978). For particles between 1μm and 100μm, fluid shear and differential settling are the dominant collision mechanisms (Ives, 1978; Lawler, 1979; Lawler *et al.*, 1983). As a result, quantification of the fluid shear level, or mixing intensity (Camp and Stein, 1943), is necessary to accurately predict the vertical transport rates of particles in this size range.

The purpose of this study was to quantify sludge settling velocities under laboratory simulated oceanic conditions with sludge dilutions found at 106-Mile Site. We examined the flocculation and settling characteristics of sewage sludge and provided an indication of the transport and fate after release of sludge at 106-Mile Site. To achieve these goals, the settling studies were conducted on four types of sludge collected from Publicly Owned Treatment Works (POTWs), using the 106-Mile Site for sludge disposal. The POTWs examined were: Passaic Valley Sewerage Commissioners, Newark, New Jersey (PVSC); New York Department of Environmental Protection, Ward Island, New York (NYCDEP); Rahway Valley Sewerage Authority, Rahway, New Jersey (RVSA); and Joint Meeting of Essex and

Downloaded At: 14:24 15 January 2011

Union Counties, Elizabeth, New Jersey (JMEUC).

The specific objectives of this work were to:

1. characterize the four different types of sludge being disposed at the 106-Mile Site in terms of particle density, particle size distribution, suspended solids, and turbidity;
2. conduct settling studies to determine their bulk settling rates as a function of shear rate, sludge type, sludge concentration, and salinity; and
3. determine the flocculent and settling characteristics of the sewage sludge;
4. provide a preliminary assessment of the transport and fate of sewage sludge after its release at the 106-Mile disposal site.

To accomplish our goals we included the effects of flocculation, mixing, shear, and dilution in our experimental approach. Results from these experiments indicated that hydrodynamic shear forces cause a significant increase in the rate and extent of particle flocculation. This increased the relative amount of settleable material and enhanced the vertical transport of sewage sludge. Our results indicate that at least 80% (volume based) of all types of the sewage sludge will settle under test conditions.

EXPERIMENTAL METHODS

Downloaded At: 14:24 15 January 2011

The sludge settling studies were performed at constant salinity (35 ppt) using a 2 m laboratory-scale mixed settling column with controlled hydrodynamics (Figure 2). Hydrodynamic power dissipation was varied so that the vertical dispersion ranged between 0–6 cm^2s^{-1} and the rms fluid shear rate was between 0–3 s^{-1} for angular velocities from 0 to 21 rpm. An electronic particle counter, a Suspended Solids Instrument (CEM, Corp., AVC-80), and a turbidimeter (HACH) were used to observe the changes of sludge particles both initially and during the settling studies. The particle counter was used to obtain particle-size distributions as a function of time and depth in the column, and suspended solids were taken to confirm the observed settling trend of volume fraction concentration. Details concerning methods and procedures are presented in Ducharme (1989), Ernest *et al.* (1991b) and Hernandez *et al.* (1991).

The diameter of the settling column is 38 cm with a wall thickness of 1 cm (Figure 2). A 2 m long hollow glass shaft, with polyvinyl chloride (PVC) impellers at 18-cm intervals is rotated by a computer-controlled Dayton Permanent Magnet Gearmotor. Ducharme (1989) and Ernest *et al.* (1991b) conducted dye studies to characterize the hydrodynamics of the column as a function of shear rate (G) at different motor speeds. Hydrodynamic shear was determined by using Camp-Stein equations based on the power dissipated in the system which was a measured parameter. Power was determined by measuring the torque applied to the impeller shaft as a function of time and angular velocity. Angular velocity was determined by measuring the displacement of a potentiometer mounted on the shaft connected to the motor as a function of time. The product between angular velocity and torque yields power dissipation which is used to determine shear for a given system. These were used to simulate the conditions found at 106-Mile Site.

Sensors (photocells) mounted vertically on the side of the column were aligned with light-emitting diodes (LED) to form a transmissometer at the same depth as each sample port. The resistance of the photocell changes as particles through the transmissometer path. The level of attenuation is directly related to the particle

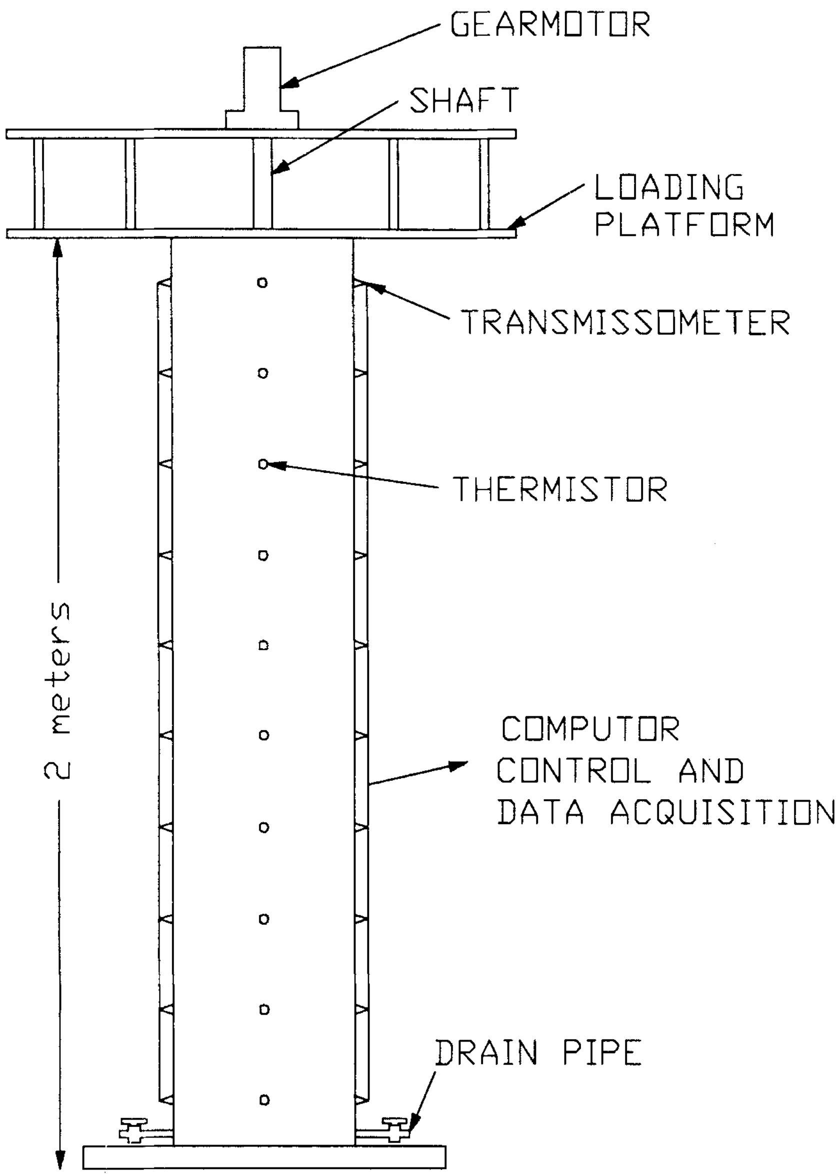


Figure 2 Settling column.

Downloaded At: 14:24 15 January 2011

concentration and is measured and recorded via a computer data-acquisition system (Ducharme, 1989).

Ten sampling ports were spaced at 18 cm intervals from the top to the bottom of the column and were made from 3 mm glass tubing with a 1 mm inner diameter that extends inward one-half the radius of the column. Samples (50 ml) based on a logarithmic time series were drawn from each sample port on the column during the settling study. These samples were analyzed for particle-size distribution, suspended solids, and turbidity. An electronic particle counter (Coulter Counter, Coulter Electronics Limited) was used to analyze the dynamic size distribution (a histogram of volume concentration as a function of particle size in micrometers). A 140 μm aperture was used, permitting valid measurements of particles in the 2.8 to 84 μm range, including large flocs.

Suspended solids and turbidity measurements were performed on samples drawn from the column to confirm the observed pattern of the size-distribution data measured with the Coulter Counter. The suspended solids analysis was performed by using a Suspended Solids Instrument. The procedure outlined from CEM Corporation was followed. To determine turbidity, a 20 ml sample was pipetted into the sample cell and placed in the sample chamber of a HACH model 2100A Turbidimeter. Suspended solids were monitored in the column until they were no longer detectable. Two methods were used to determine the densities of the four sludge types. The first method used was a calibrated linear density-gradient procedure (Bonner *et al.*, 1991) that has a calibrated range between 1.0 and 1.2 g ml^{-1}. To determine the density of denser sludge, a standard pycnometer procedure was used.

These particle transport experiments were organized using a limited factorial experimental design (John and Quenouille, 1977) based on shear rate, sludge dilution, and particle type at constant salinity. Detailed investigation on salinity at the 106-Mile Site shows it to be relatively constant (Ingham *et al.*, 1977), which would be expected for a deep ocean disposal site. As a result, three experimental series under four conditions were scheduled.

The sludges used for these settling studies were taken from four different POTWs located in the northeastern United States. Table 1 lists the location of the sludge and the types. The particle concentration used in the settling column was determined by the Coulter Counter for the dilution ratios. The values for shear rate and salinity were established on typical ocean conditions. Sludge type, shear rate and sludge dilution were varied within the Experimental Series I, II and III, respectively, while salinity was held constant (Table 1). The three experimental series were a design which reduced the number of experiments while at the same time keeping the integrity of the experimental picture. Experiments 2 and 10 were duplicated in order to validate the results.

RESULTS AND DISCUSSION

The sludge was characterized in terms of particle density, mean particle size, particle size distribution standard deviation, total volume fraction, total number concentration, suspended solids, and turbidity from the initial conditions of Experimental Series I. The average densities of NYCDEP, RVSA, and JMEUC sludges were in the same range, between 1.048 and 1.055 g ml^{-1} (Table 2). The PVSC sludge was out of the range determinable by the density-gradient procedure, so the

Downloaded At: 14:24 15 January 2011

Table 1 Experimental Design.

Experiment no.	*Shear rate s^{-1}*	*Sludge dilution (V_{sl}/V_w)*	*Salinity (%)*	*Type*
Series 1. Variation in Sludge Type				
1	10	1/1000	3.5	PVSC
2	10	1/1000	3.5	NYCDEP
3	10	1/1000	3.5	RVSA
4	10	1/1000	3.5	JMEUC
Series 2. Variation in Shear Rate				
5	5	1/1000	3.5	PVSC
6	10	1/1000	3.5	PVSC
7	15	1/1000	3.5	PVSC
8	20	1/1000	3.5	PVSC
Series 3. Variation in Sludge Dilution				
9	10	1/500	3.5	NYCDEP
10	10	1/1000	3.5	NYCDEP
11	10	1/2000	3.5	NYCDEP
12	10	1/5000	3.5	NYCDEP

pycnometer procedure was used to determine the density of 1.28 g ml^{-1}. The largest mean size diameter and standard deviation were found in RVSA and JMEUC sludges with mean sizes of 26.67 and 26.40 μm and standard deviations of 17.83 and 14.63 μm, respectively. The total volume fraction (particle volume/fluid volume) represents the raw sludge concentration for the sludge type. RVSA and JMEUC sludges have the two highest total volume fractions, 36.0×10^3 and 36.3×10^3 ppm, respectively, while NYCDEP had the lowest at 12.1×10^3 ppm and PVSC sludge had an intermediate concentration of 30.7×10^3 ppm. However, PVSC had the highest total number concentration of particles with 108.2×10^6 (numbers per ml) sludge sample, and RVSA and JMEUC had similar counts, 38.2×10^6 and 36.9×10^6 (numbers per ml), respectively. Due to the high total number concentration and average density of PVSC sludge, it had the highest suspended solids. PVSC sludge also had the highest turbidity reading of 37.6 NTU due to the high number concentration per ml of sludge.

The initial particle-size distributions for each sludge type are shown in Figure 3. Each of the eight data points on the curves indicate size classes that were condensed from the Coulter Counter's 256 output channels. Thirty-two channels were combined to create each size class represented in Figure 3. The PVSC and NYCDEP sludges had similar size distributions (Figure 3i,ii) respectively, and the RVSA and JMEUC sludges also displayed similar distributions.

Each settling study was characterized by a dynamic particle-size distribution. Data from Experiment 2 (NYCDEP sludge) are presented in Figures 4i–iv. These show volume fraction as a function of time and particle diameter. The dynamic particle-size distributions show that a decrease in the total particle volume was due to flocculation and vertical transport. Figure 4ii clearly indicates an increase in volume fraction for particles with diameters greater than 70 μm. From the initial particle-size distributions (Fig 3ii), the particle volume fraction for the 80 μm size category was zero. However, during the first half-hour of settling, the volume fraction increased to over 1 ppm in the 80-μm range.

Experiments 2 and 10 were replicates performed on NYCDEP sludge at a dilution of 1/1000 and a shear rate of 10 s^{-1} to verify the settling study procedure. The temporal profiles of volume fraction (Figures 5i and ii) from both experiments were

Downloaded At: 14:24 15 January 2011

Downloaded At: 14:24 15 January 2011

Table 2 Physical characteristics of the Sludge Types from Experimental Series I.

Sludge type	*Average density* ($g\ ml^{-1}$)	*Mean size* (μm)	Standard deviation (μm)	Total volume fraction ($\times 10^3$ ppm)	Total number concentration ($\times 10^6\ ml^{-1}$)	Suspended solids	Turbidity (NTU)
PVSC	1.282	16.48	10.72	30.7	108.2	72	37.6
NYCDEP	1.048	17.85	10.01	12.4	26.1	27	4.7
RVSA	1.052	26.67	17.82	36.0	38.2	50	15.3
JMEUC	1.055	26.40	14.63	36.3	36.9	40	16.0

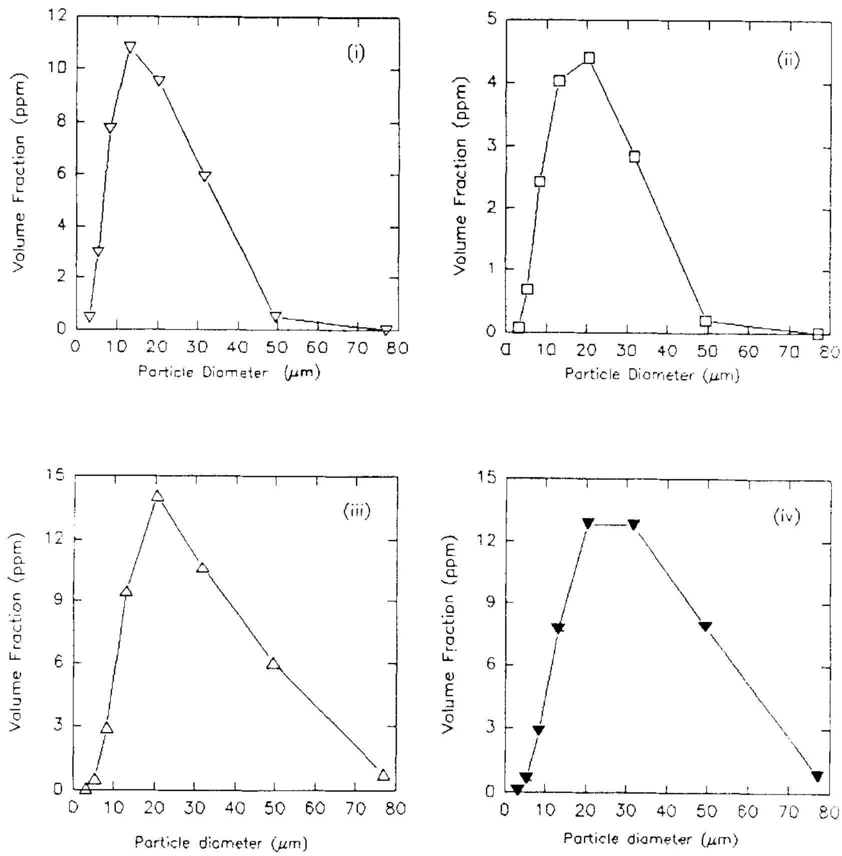


Figure 3 Initial size distribution.

compared. The average bulk settling velocities were determined to be 1.84 and 2.91×10^{-3} cm s^{-1}, for Experiments 2 and 10 respectively, with the average of 1.94×10^{-3} cm s^{-1}. The data suggest that the volume fraction settled slightly faster in Experiment 10 although the difference between the two experiments was not statistically significant. From Figure 5ii, the particle mass in terms of volume fraction settled slightly faster in the first 5 hrs of Experiment 10 and had a slightly higher bulk settling velocity. The slight differences in the replicated results may be due to sample measurement errors, variability in set experimental conditions and temporal shifts in the sludge characteristics due to storage. Measured shaft angular velocity (which determines shear rate) was 7.02 to 6.92 rpm for Experiments 10 and 2, respectively with a standard error of 1.4%. However, the standard errors for the average bulk settling velocities were between 8.5% and 9.2%. Under the same hydrodynamic conditions, 90% mass was removed from the column after a 48 hr settling period in Experiment 10, while 95% mass settled out in Experiment 2 for the same settling period. Measured characteristics of the sludges remained constant over the storage period.

Downloaded At: 14:24 15 January 2011

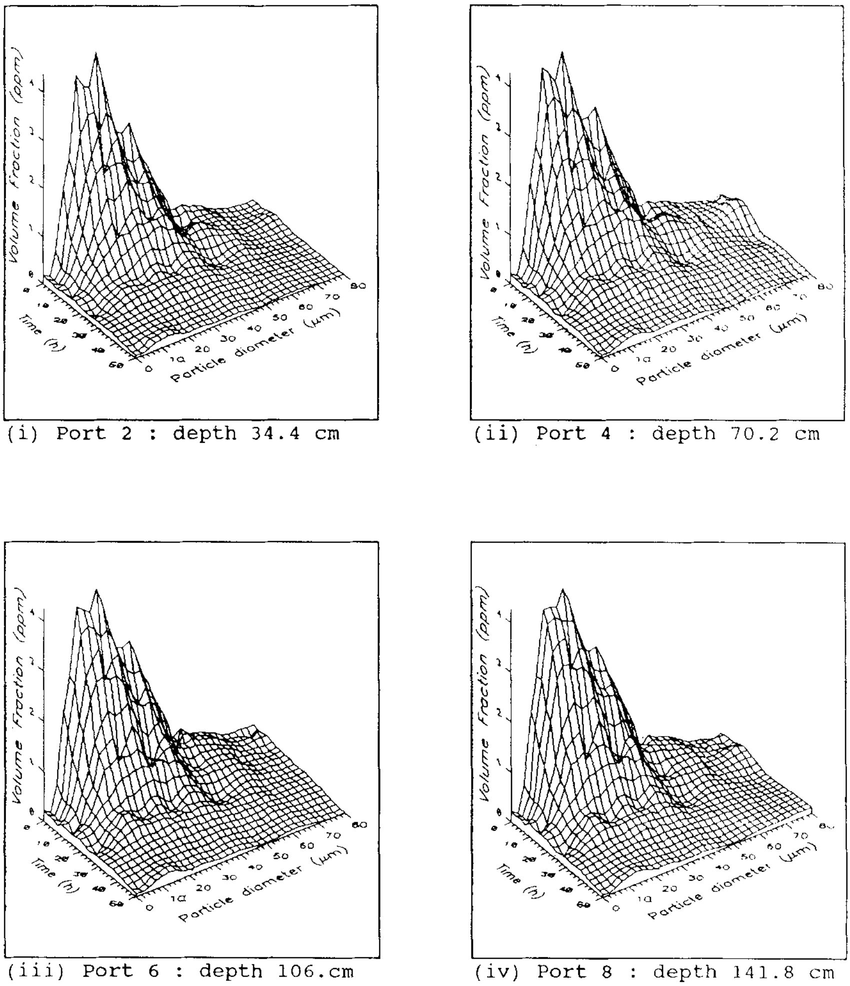


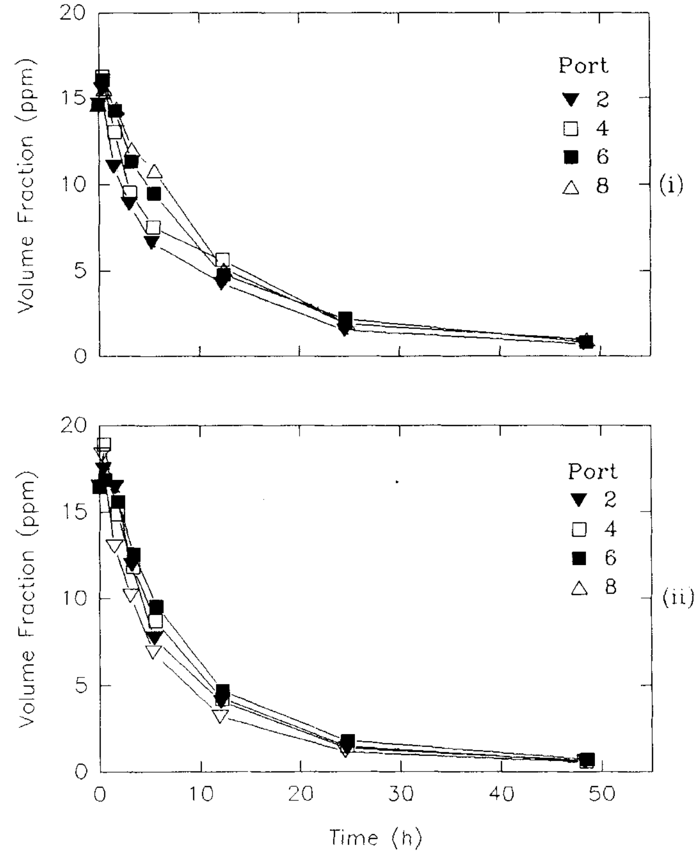
Figure 4 Dynamic size distribution for NYCDEP sludge (G = 10 s^{-1}, Dilution = 1/1000).

Downloaded At: 14:24 15 January 2011

Series 1: Variation of sludge type

Experiments were performed on four different sludge types at a shear rate of 10 s^{-1} and a sludge dilution of 1/1000 to determine the variability of transport characteristics between sludge types. The physical characteristics of RVSA and JMEUC sludges were very similar (Table 2, Figure 6). Because they had the largest initial mean particle diameter, they were expected to have the highest settling velocities. In addition, due to the physical similarity between the RVSA and JMEUC sludges, their estimated bulk settling velocities had almost identical patterns throughout the depth of the column. Although PVSC sludge had the highest total number concentration, suspended solids and turbidity, it had the lowest bulk settling velocity.

Particle-size distributions from Experimental Series 1 were taken from port 8 (Figure 6). Figures 6i–iv display the reduction of volume fraction for PVSC NYCDEP, RVSA, and JMEUC sludge, respectively. Because PVSC and NYCDEP



Downloaded At: 14:24 15 January 2011

Figure 5 Temporal variation of NYCDEP sludge concentration versus time at different depths in the column (G = 10 s^{-1}, Dilution = 1/1000).

sludge had small mean particle sizes, not all the particulate material was able to settle in the 48 hr experimental period, resulting in a small residual volume fraction in the water column. However, RVSA and JMEUC sludge (Figures 6iii and iv), respectively, showed complete removal (0 ppm volume fraction) by the end of the experiment. These results also illustrate the occurrence of flocculation where the distribution shifted toward the larger class size. The increase of volume fraction was observed between 50 and 80 μm for Experimental Series 1.

Series 2: Variation in shear

Experiments were conducted with shear rate varied at a sludge dilution of 1/1000 using PVSC sludge in 35 ppt sea water. At shear levels of 20 s^{-1}, no settling was measured over the time scale of the study. It was concluded that high fluid shear and

Downloaded At: 14:24 15 January 2011

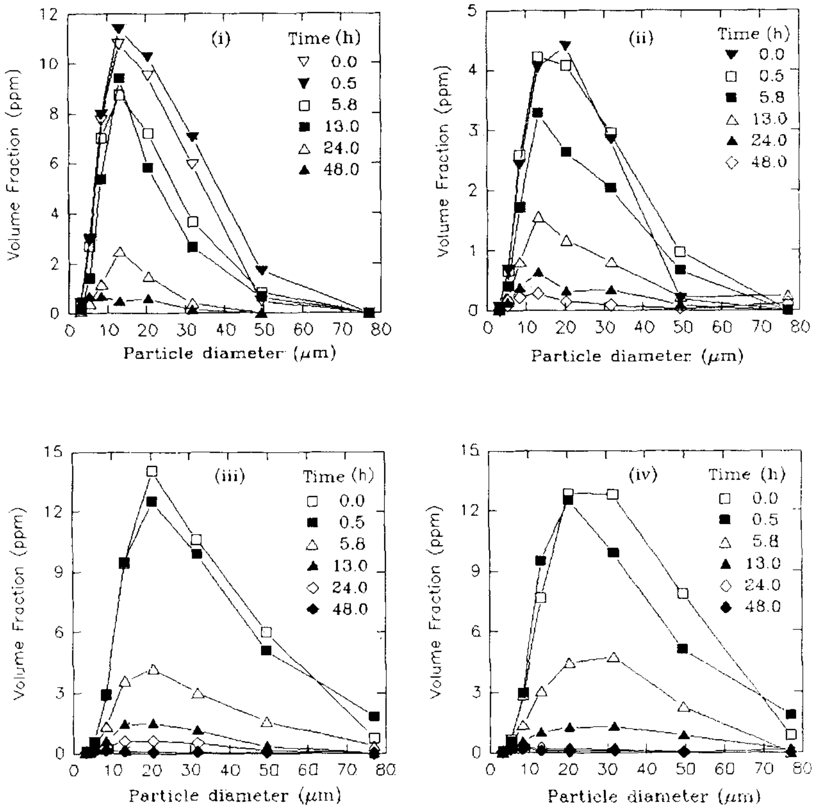


Figure 6 Dynamic size distribution for all four sludges (G = 10 s^{-1}, dilution = 1/1000).

dispersion were the dominant factors controlling transport at this shear rate. These factors influenced floc breakup and resuspension of particles from the bottom boundary. To confirm this conclusion, an experiment at 30 s^{-1} was added following Experiment 12. These data supported the concept that floc breakup and resuspension occurred in the settling column at shear rates in excess of 20 s^{-1}. In this experiment, the sludge material that had previously settled to the bottom boundary of the column was distributed throughout the water column after a 1 hr duration and the size distribution shifted to the initial condition.

Shear rate and dispersion increase with increasing hydrodynamic power dissipation. The bulk vertical settling velocities also increased with increasing shear from 5 s^{-1} to 10 s^{-1} due to enhanced flocculation. According to Smoluchoski (1917), this would be expected in the absence of floc breakup. However, at shear rates higher than 10 s^{-1}, bulk vertical settling velocities decreased because increased dispersion levels caused floc breakup. However, at shear rates higher than 10 s^{-1}, bulk vertical settling velocities decreased because increased dispersion levels caused floc breakup. The Smoluchoski theory assumes that flocculation is directly related to fluid shear, and this was observed at shear rates lower than 10 s^{-1}. However, at shear rates greater than 10 s^{-1}, the power dissipation levels drove particle shear forces that overwhelmed the flocculation mechanism and caused floc breakup, which lowered the bulk settling velocities. Further, vertical variations in the settling velocities were observed to decrease as shear increased with increasing depth, except for shear rates higher than 20 s^{-1}. In fact, the vertical trend of increasing settling velocity with depth was reversed. This phenomenon can be attributed to the breakdown of concentration gradients caused by increased dispersion and the increasing dominance of floc breakup and resuspension. Fluid shear was the primary transport mechanism that drove the settling process.

Series 3: Variation of sludge dilution

Experiments were conducted on NYCDEP sludge with 35 ppt sea water at four different sludge dilutions (1/500, 1/1000, 1/2000, and 1/5000) with a constant shear rate of 10 s^{-1}. The sludge dilutions had a volume fraction range from 2.9×10^3 to 27.9×10^3 ppm for the 1/5000 to 1/500 sludge dilutions, respectively. The data suggest that sludge dilution in the above range appeared to have a limited effect on settling velocity within each depth of the column. The bulk settling velocities at individual depths in the column varied by less than 15% over the range of dilutions. Although the variability of the results is not statistically different, the greatest bulk settling velocities were obtained at sludge dilutions of 1/2000. It is expected, however, that at sludge dilutions greater than 1/10000, the dilution effects would reduce flocculation and cause a reduction in vertical transport.

Bulk settling velocities

All the experiments are summarized in Table 3 and Figure 7. This Table presents the results of the bulk settling velocities with corresponding mass loss rate for each experiment performed. Here, bulk settling velocity is obtained by regressing the log of the volume fraction versus time and multiplying the slope by depth of the column. The JMEUC sludge showed the highest water column loss rate, while PVSC had the lowest. Figure 8 shows the average bulk settling velocities and portrays the effects on vertical transport lumped into the empirical bulk settling coefficient; it clearly shows the variation in settling velocity on four different sludge types. Data from Experimental Series II summarizes the effects of shear on vertical transport. The shear rate of 10 s^{-1} enhanced flocculation and in turn increased the settling velocity, while at higher rates the settling velocities were inhibited due to floc breakup and resuspension caused by high dispersion levels. Data from Experimental series 3 illustrates the limited effects caused by sludge dilution on NYCDEP sludge. The error bars on these data in Figure 8 indicate a standard error of 10%.

Particle transport model

Development and Calibration. A particle transport model (Ernest *et al.*, 1991a, 1991b, 1991c) was applied to synthesize observed data gathered from the settling studies and incorporated into a modelling framework. The model consists of the classical advection-dispersion equation with the addition of two flocculation

Downloaded At: 14:24 15 January 2011

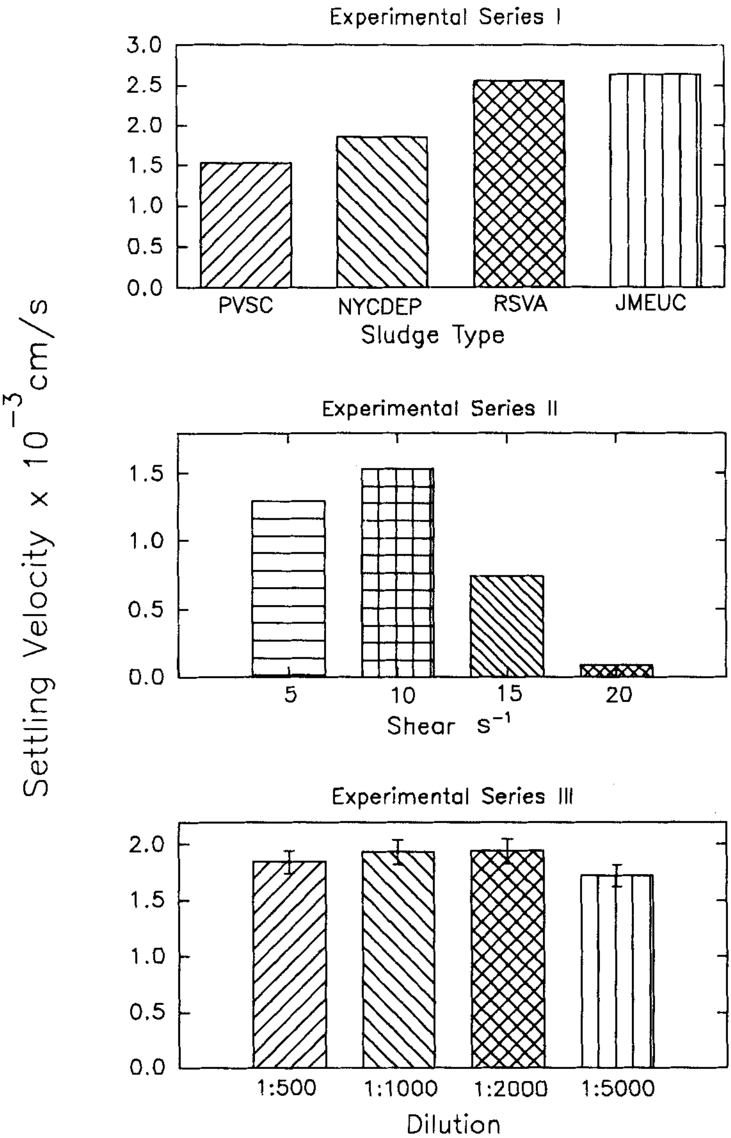


Figure 7 The effect of sludge type, shear rate, and dilution on the mass removal rate.

Downloaded At: 14:24 15 January 2011

Table 3 Mass loss rate for all experiments.

Experiment no.	*Sludge type*	*Shear (s)$^{-1}$*	*Sludge dilution*	*Mass loss rate (day)$^{-1}$*	*Bulk average settling velocity* $\times 10^{-3}$cm s^{-1}
Series 1. Variation in sludge type					
1	PVSC	10	1/1000	1.30	1.53
2	NYCDEP	10	1/1000	1.62	1.93
3	RVSA	10	1/1000	2.13	2.56
4	JMEUC	10	1/1000	2.17	2.64
Series 2. Variation in shear					
5	PVSC	5	1/1000	1.15	1.29
6	PVSC	10	1/1000	1.30	1.53
7	PVSC	15	1/1000	0.68	0.74
8	PVSC	20	1/1000	0.11	0.09
Series 3. Variation in dilution					
9	NYCDEP	10	1/500	1.59	1.84
10	NYCDEP	10	1/1000	1.62	1.93
11	NYCDEP	10	1/2000	1.63	1.94
12	NYCDEP	10	1/5000	1.45	1.72

mechanisms (fluid shear and differential settling), resuspension and floc breakup terms. The flocculation terms were added to the advection-dispersion equation to increase the mass loss rate. Flocculation can involve three collision mechanisms. However, perikinetic flocculation was not included because it is dominant for particles less than 1 μm diameter. All of the sewage sludge suspensions had an insignificant mass fraction below 1 μm. So, only velocity gradient (fluid shear) and differential settling were considered for the transport of aggregated particles. These two mechanisms were included in the collision frequency function in which only binary collisions were assumed to make effective contacts (Ernest *et al.*, 1991c). The volume of the new particle equalled the sum of volumes of the primary particles. The density from the primary particles remained the same for the newly formed particle. The collision efficiency, defined as the number of effective particle contacts divided by the total number of contacts, was a free parameter that ranged from 0.02 to 0.31. Similar particle experiments conducted in our facilities by Sanders (1990) and Ernest *et al.* (1991c) using New Bedford Harbor sediments, indicated that the model collision efficiency values ranged from 0.05 to 0.35. During these settling studies, resuspension and floc breakup were observed in the column at high shear, so resuspension and floc breakup processes were included in the model. The calibrated model predicted the volume fraction in each size category over time and space. Figure 8 represents a sensitivity analysis for this model. The advection-dispersion model predicted a mass removal of 40% over a 50 hr period. Differential settling alone increased the settling rate with a mass removal of 80%. Fluid shear alone had an improved settling pattern compared to that observed with some slight underestimation, but a better fit with the observed data points. However, when all the terms, differential settling, fluid shear, resuspension, and floc breakup were added, the optimum predicted fit was achieved. This sensitivity analysis indicates that fluid shear was the dominant transport mechanism.

Figure 9 compares the differences between the observed particle-size distributions and the predicted distributions. Ports 2, 4, 6, and 8 from experiment 4 were used for this illustration. Both initial particle-size distributions had similar peaks. However, the predicted particle-size distribution slightly over-estimated the volume fraction in

Downloaded At: 14:24 15 January 2011

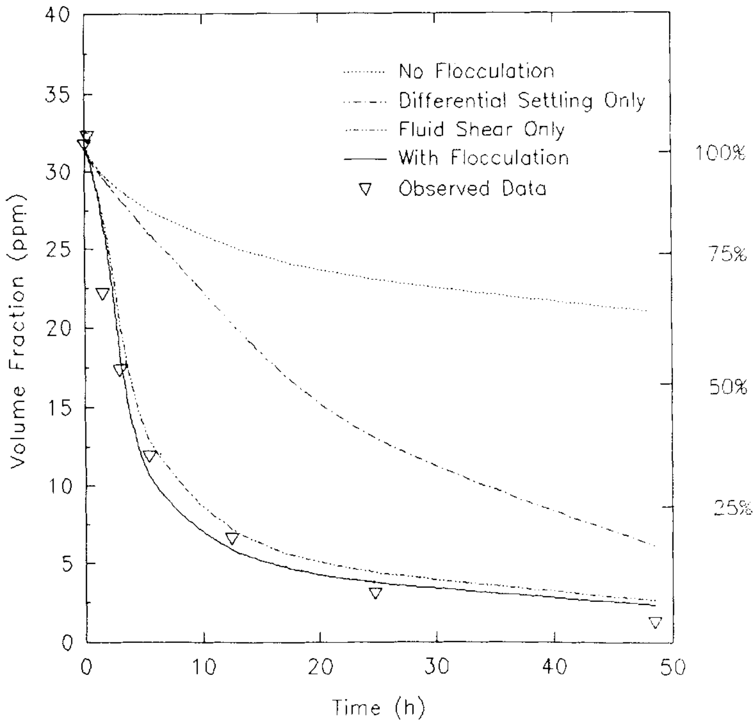


Figure 8 Predicted temporal variation of NYCDEP sludge concentration versus time with gravitational settling only, fluid shear driven flocculation only, differential settling only and a combination of fluid shear flocculation and differential settling ($G=10\ s^{-1}$, Dilution = 1/1000).

the 60 μm range. In comparing mass removal over the 50-hr period, the observed concentration showed almost no trace of a particle mass. However, the predicted distributions indicated a small fraction of particles above and below the 50 μm particle diameter range.

Application

This model can be scaled to predict the fate of sludge after release from a barge at the 106-Mile Site. This required that the segment geometry for the Site be implemented by adding a length segment in three dimensions (X, Y, Z). The X (east to west) and Y (north to south) dimensions were used as length segments to enclose the perimeter

Downloaded At: 14:24 15 January 2011

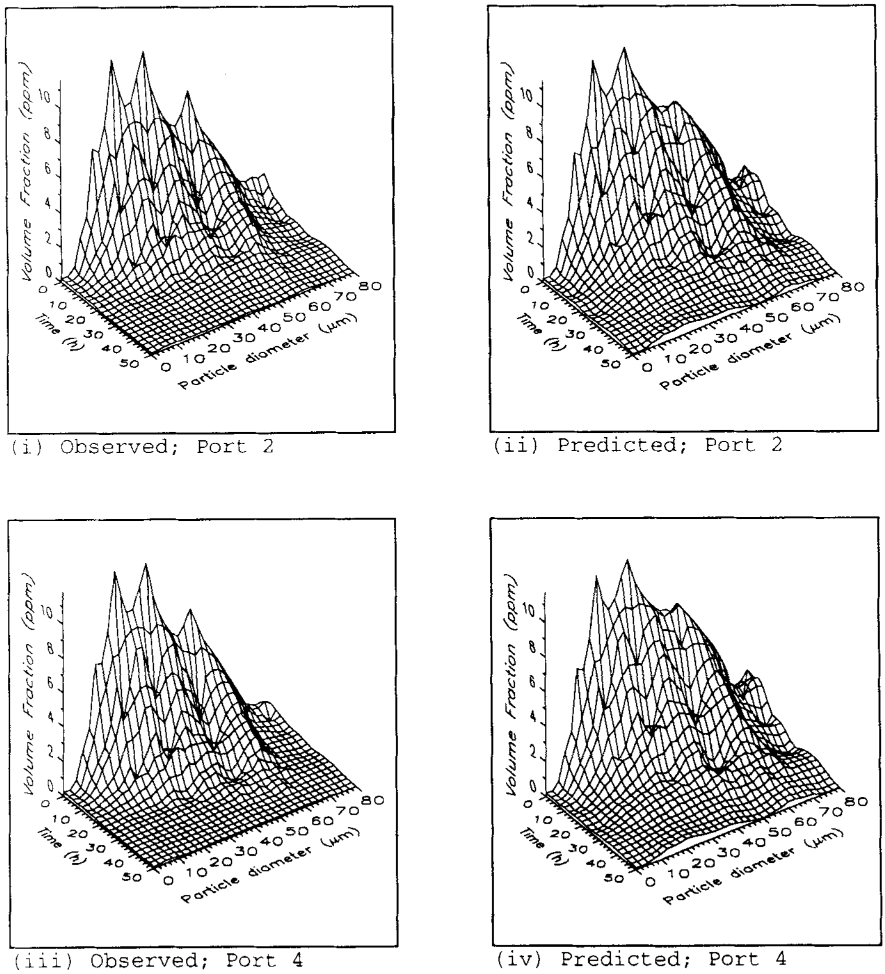


Figure 9 Observed and predicted particle-size distribution from Experiment no. 4.

of 106-Mile Site, while the Z dimension was used to represent the depth of the Site. The boundary conditions remained the same, reflective at the top boundary and advective/resuspension at the ocean floor. Current velocity was added in only one direction because of the existing current heading due west from 106-Mile Site. Dispersion coefficients were assumed and added in three dimensions, 20,000, 5,000 and 5 $cm^2 s^{-1}$ for X, Y and Z, respectively.

The model coefficients used to predict the fate of the waste plume were taken from the parameterized results of sludge settling experiments. The model was used to predict the mass fraction of the initial load impacting the benthos. This was accomplished by integrating the particle volumes at the bottom boundary over their corresponding particle sizes and numbers relative to the initial sludge mass for the 3×3 km dump site. The flocculation mechanism was based on the binary particle collision, collision frequency function and the ambient particle concentration. Figure 10 shows the results of four different scenarios over a range of dilutions designed to encompass possible extremes. The initial sludge dilution was 1/500 corresponding to the highest expected sludge concentration during discharge from the barge. This

Downloaded At: 14:24 15 January 2011

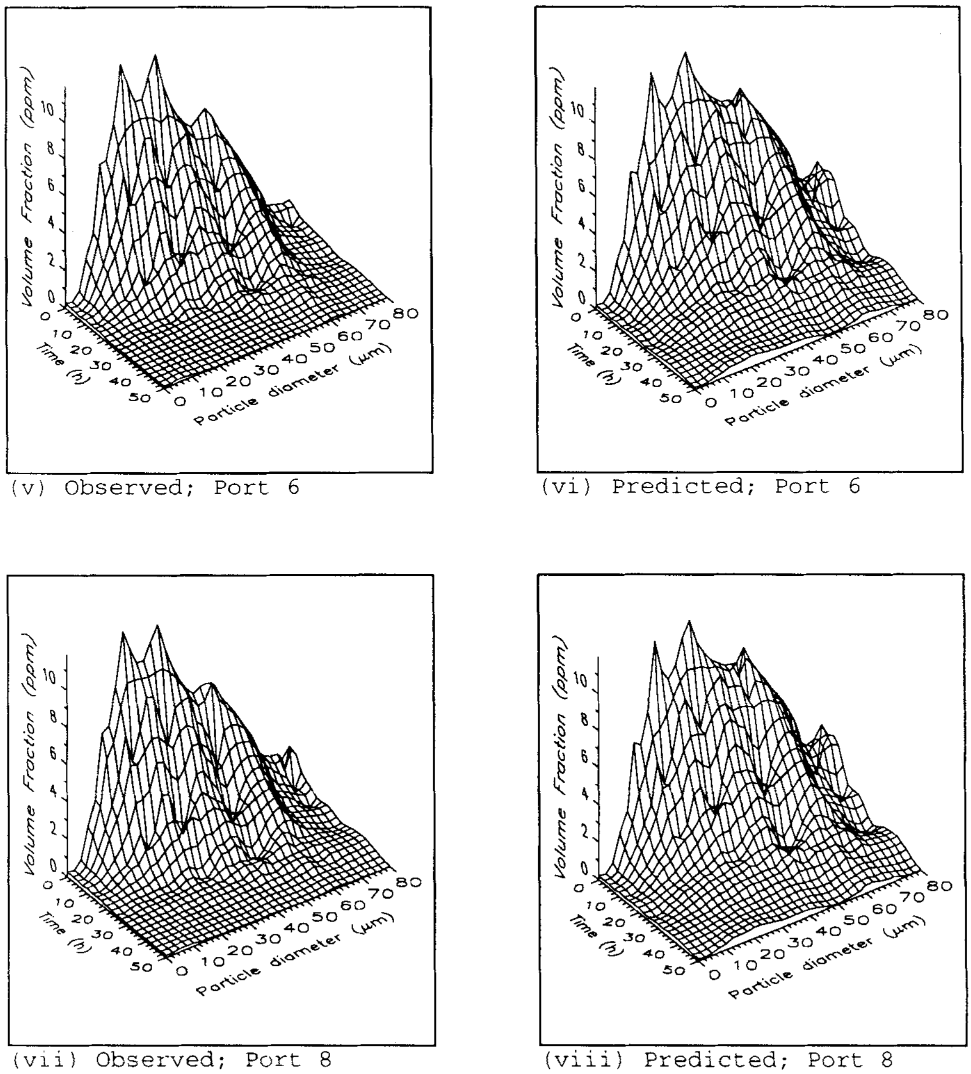


Figure 9 Continued.

concentration was used as a first case to evaluate extreme conditions. The vertical removal trend indicates that the particles reached an equilibrium particle size during flocculation with subsequent rapid removal of the mass from the water column. Under this scenario, over 85% of the mass fraction was removed in 160 days (5.3 months). Two other dilution scenarios were evaluated: 1/500,000 and 1/5,000,000. In both cases a distinct two stage accumulation of sludge at the bottom was noticed. At a dilution of 1/500,000, more than 200 days (6.7 months) passed before any mass reached the benthos. For the next 400 days (13.3 months) larger, faster settling sludge aggregates, comprising 35% of the original mass fraction reached the bottom. A slight inflection in accumulation rates was noticed at this point before the smaller particles arrived, with 95% of the sludge reaching the bottom in 1100 days (3 years).

Downloaded At: 14:24 15 January 2011

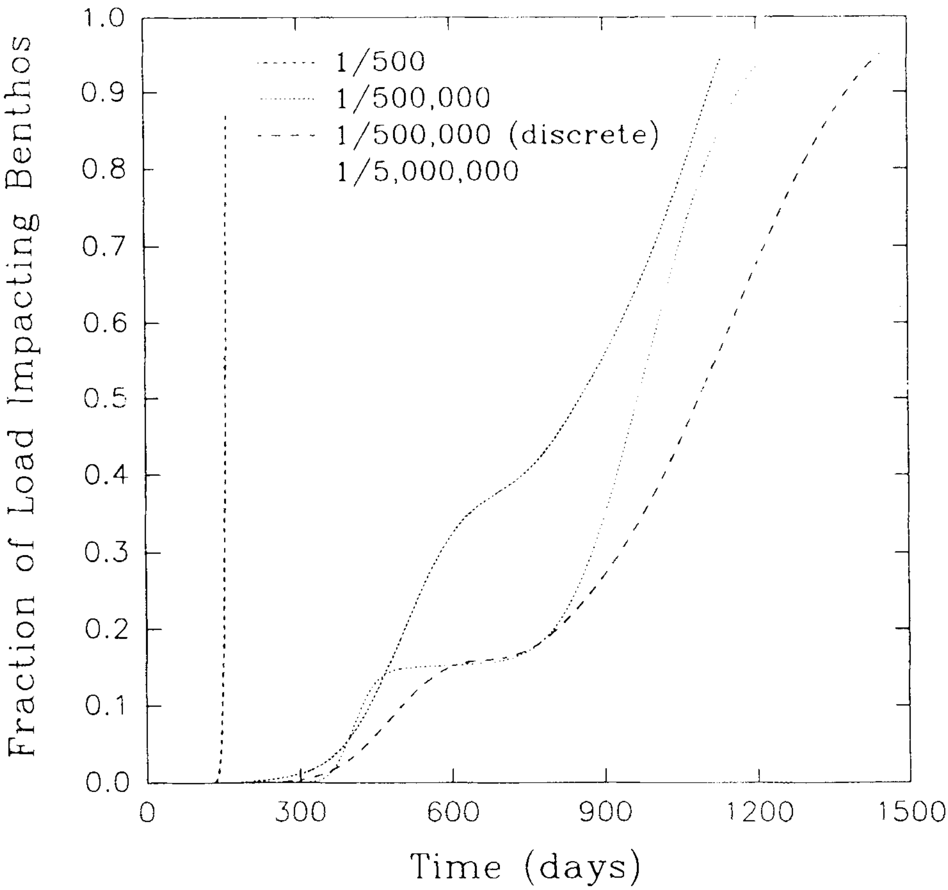


Figure 10 Fraction of dumped sludge impacting benthos as a function of time under various sludge dilution scenarios.

Downloaded At: 14:24 15 January 2011

The same dilution scenario (1/500,000) was modelled under a discrete settling assumption. In this case, enhanced settling rates due to flocculation was neglected. Discrete settling was observed to have the longest retention time of 1,400 days for a 95% mass removal. Rate of accumulation at bottom was slower than with flocculation, while a hiatus between the arrival of the larger and smaller particles was noticed (200 days or 6.7 months). For the final dilution scenario (1/5,000,000), Figure 9 indicates that the mass remained in suspension for 300 days (10 months) before any mass impacted the benthos. After 300 days, a rapid mass fraction removal occurred for 150 days (5 months) until 15% of the mass fraction settled. There was no appreciable increase in sludge particles reaching the bottom for the next 450 days, after which another 80% arrived at the bottom over 400 days (13.3 months), representing the smaller, slower settling particles. The model predicted 95% mass removal in a total of 1200 days (3.3 years). It is conceivable that at very low concentrations, the polydisperse discrete settling rates of the sludge particles may overwhelm the tendency of the flocculation process to enhance bulk settling rates.

The settling velocities based on model prediction ranged from 3.2×10^{-3} cm s^{-1} for a particle size of 3.5 μm, and 1.3 cm s^{-1} for a particle size of 70 μm.

CONCLUSIONS

The following conclusions may be drawn from the study.

1. The sludge with the highest total volume fraction and large mean particle size (JMEUC) showed the largest bulk settling velocity and exhibited a settling range of $0.77–4.05\times10^{-3}$ cm s^{-1}.
2. The sludge with the highest density, total number concentration and the lowest mean particle size (PVSC) showed the lowest bulk settling velocity with a settling velocity range of $0.55–2.38\times10^{-3}$ cm s^{-1}.
3. Shear levels above 15 s^{-1} in the experimental apparatus inhibit settling of PVSC sludge due to floc breakup.
4. No significant variability in the settling velocities has been found over the sludge volume fraction range of 2.9 to 27.9×10^{3} ppm for the sludge NYCDEP.
5. Shear dominates the transport mechanism because as shear is increased flocculation increases, but at above 15 s^{-1} settling rates are decreased due to floc breakup.
6. The average settling rates increased for shear levels between 5 to 10 s^{-1} and decreased for shear levels above 10 s^{-1}.
7. The average settling rates increased at a shear level of 10 s^{-1} and did not vary with sludge dilution over a range of 1/500 to 1/5000.

Downloaded At: 14:24 15 January 2011

REFERENCES

Battelle (1989) Nearfield Monitoring of Sludge Plumes at 106-Mile Site: Results of a Survey Conducted August 31–September 5, 1987. US EPA: Office of Water, 503/4-91/004, Washington, D.C.

Battelle (1988b) Final Report for the 106-Mile Deepwater Dumpsite: Winter 1988 Oceanographic Survey. US EPA: Office of Water, 503/4-91/009, Washington D.C.

Battelle (1990) Work/Quality Assurance Project Plan for Determination of Settling Rates. Report to the US under Contract 68-C8-0105. Work Assignment 1-108. pp. 1–22.

Bonner, J.S., Autenrieth, R.L., and DePinto, J.V. (in preparation, 1991) Measurement of phytoplankton cell density using a calibrated density gradient.

Camp, T.R. and Stein, P.C. (1943) Velocity gradients and internal work in fluid motion. *Journal of the Boston Society of Civil Engineers,* Boston, MA, **30**: 219–237.

Ducharme, S.L. (1989) Design and validation of a settling column for particle transport studies. pp. 22–108. M.S. thesis. Texas A&M University at College Station, TX.

Ernest, A.N., Bonner, J.S., and Autenrieth, R.L. (1991a) Model parameter estimation for particle transport. *Journal of Environmental Engineering,* in press.

Ernest, A.N., Bonner, J.S., Autenrieth, R.L., and Ducharme, S.L. (1991b) Particle transport studies under controlled turbulent hydrodynamic conditions. *Journal of Environmental Engineering,* submitted.

Ernest, A.N., Bonner, J.S., Sanders, S.C., and Autenrieth, R.L. (1991c) Vertical transport of cohesive sediments in estuarine environments. *Journal of Environmental Engineering,* submitted.

Faisst, W.K. (1978) Characterization of particles in digested sewage sludge. pp. 259–282 in Kavanaugh, M.C., and Leckie, J.O., eds., *Particles in Water: Characterization, Fate, Effects and Removal,* Vol 69, American Chemical Society, Washington, DC.

Farley, K.J. and Morel, F.M.M. (1986) Role of coagulation in the kinetics of sedimentation. *Environmental Science and Technology,* **20:** 187–195.

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

Friedlander, S. (1960) Similarity considerations for the particle-size spectrum of a coagulating sedimenting aerosol. *J. Meteorology.* **17,** 479–483.

Friedlander, S. (1977) *Smoke, Dust, and Haze.* pp. 175–207. John Wiley & Sons, New York.

Gibbs, R., and Hopkins, M. (1984) Effects of solids concentration and turbulence upon the coagulation rate of sewage sludge in seawater. Technical report, Center for Colloidal Sciences, College of Marine Studies, University of Delaware, Newark, Delaware.

Hunt, J.R. and Pandya, J.D. (1984) Sewage sludge coagulation and settling in seawater. *Environmental Science and Technology,* **18:** 119–121.

Hernandez, D.S., Bonner, J.S., and Ernest, A.N. (1991) Determination of sludge settling rates. pp. 23–33. A report submitted to US Environmental Protection Agency under Contract No. 68-C8-0105. Work Assignment 1–105.

Ingham, M.C., Bisagni, J.J., and Mizendo, D. (1977) The general physical oceanography of deepwater dumpsite 106. NOAA Dumpsite Evaluation Report 77-1. Baseline report of environmental conditions in deepwater dumpsite 106. Vol. 1: Physical characteristics. pp. 29–54. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, DC.

Ives, K.J. (1978) Rate theories. pp 243–258 in Ives, K.J., *The Scientific Basis of Flocculation,* Nordhoff-Leyden, The Netherlands.

John, J.A., and Quenouille, M.H. (1977). *Experiments: Design and Analysis.* Charles Griffin & Company, London, England, UK, 296 pp.

Kranck, K. (1980) Experiments on the significance of flocculation in the settling of fine-grained sediments in still water. *Canadian Journal of Earth Science,* **17:** 1517–1526.

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.

Lawler, D.F. (1979) A particle approach to the thickening process. PhD. dissertation, University of North Carolina, Chapel Hill, NC, 220 pp.

Lawler, D.F., Singer, P.C. and O'Melia, C.R. (1983) Particles in thickening: mathematical model. *Journal of Environmental Engineering,* **109:** 332–349.

Lick, W. (1982) Entrainment, deposition and transport of fine grain sediments in lakes. *Hydrobiologia,* **91:** 31–40.

Li, D.H., and Ganczarcyk, J.J. (1987) Stroboscopic determination of settling velocity, size, porosity of activated sludge flocs. *Water Research.* **21:** 257–262.

Morel, F.M.M. and Schiff, S.L. (1980) Geochemistry of municipal waste in coastal water. Report No. 259, pp. 33–51, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Sanders, S.C. (1990) Vertical transport and dynamic size distribution of New Bedford Harbor sediments. pp. 44–112. M.S. thesis. Texas A&M University at College Station, TX.

Smoluchowski, M. (1917) Versuch einer Mathematischer Theorie der Koagulation-Kinetik Kolloides Losungen. *Z. Physic. Chem.,* **92:** 129–168.

Swift, D.L. and Friedlander, S.K. (1964) Coagulation of hydrosols by Brownian motion and laminar shear laws. *Journal of Colloidal Science,* **19:** 621–647.

Zanevel, R.V., Spinrad, R.W., and Bartz, R. (1982) An optical settling tube for the determination of particle-size distributions. *Marine Geology,* **49:** 357–376.

Downloaded At: 14:24 15 January 2011