STUDIES IN THE LOWER BAY OF NEW YORK HARBOR ASSOCIATED WITH THE BURIAL OF DREDGED SEDIMENT IN SUBAQUEOUS BORROW PITS

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Abstract

Subaqueous burial is a viable disposal alternative for isolating and containing dredged sediment. Although no large-scale project of this type has been done, studies in New York Harbor and elsewhere show that such an operation is technically feasible and that the concept is environmentally safe. A successful burial operation would require the accurate and deliberate deposition of dredged sediment in a subaqueous pit and burial of the deposit under a sediment cap probably composed of sand. The cap should be thick enough to isolate the underlying deposit from burrowing organisms, protect the underlying deposit from disturbance by storm-generated waves and currents, and serve as a reservoir for pore water that would be expelled from the underlying deposit during consolidation. The basic principles of all the essential features of a successful operation have been demonstrated.

Introduction

In 1979, the New York District of the U.S. Army Corps of Engineers began a multi-year study of alternatives to the open-water disposal of dredged sediment. The study was based on a preliminary survey of disposal alternatives that had been done for the Corps by the Mitre Corporation (Conner et al., 1979). In the Mitre Report the use of subaqueous borrow pits was recommended as one alternative that was "possible in special cases and feasible for large volumes of materials."

Our research was directed toward a more detailed assessment of the feasibility of using subaqueous borrow pits as disposal sites for dredged sediment. This objective evolved to include site-specific surveys and plans for the implementation and monitoring of a demonstration project. Our report contains the conclusions of a wide range of geological, biological, and geochemical investigations that were done between July 1980 and July 1983. We will first discuss the project's background and history. We will then summarize the conclusions of our studies. Almost all of the results from specific elements of this research have been reported in detail elsewhere.

Background

The floor of the Lower Bay of New York Harbor is composed predominantly of sand and gravel that were deposited as the last glaciers receded from this area about 18,000 years ago. It is estimated that the surficial sand deposits under the Lower Bay alone have a total volume of about 2,629 million cubic meters (Bokuniewicz and Fray, 1979). Over the past several decades sand and gravel have been mined from the floor of the Lower Bay for use as construction aggregate and fill. This resource has been used in the New York metropolitan area for both public and private construction projects including Battery Park City, Port Newark, Port Elizabeth, portions of the New Jersey Turnpike, and the Newark Airport extension. Between 1950 and 1973, the New York State Office of General Services estimates that 72.6 million cubic meters of sand and gravel have been dredged from the Lower Bay.

In 1966, the New York State Department of Environmental Conservation issued a recommendation to establish a preferred dredging area in the Lower Bay of New York Harbor (Fig. 1). This policy restricted sand mining to a area west of Ambrose Channel on the West Bank. In response to an increasing demand for sand and gravel and a desire to improve navigation channels, the Department approved additional dredging sites on the East Bank of Ambrose Channel in 1968. Three principal concerns were taken into account in designating these sites. First, Romer Shoal and areas of the West Bank that were perceived to be fish-spawning areas were to be protected. Second, the sites were chosen to reduce the effect of beach erosion which was thought to be caused, in part, by previous mining activity on the West Bank. Third, there was a desire to reduce the pressure for mining in Long Island's bays which had been the historic site of many sand-mining operations. In 1973 a violation of the Department's policy occurred when it was discovered that one area had been mined to a depth deeper than the limit which had been set at 45 feet. This borrow pit was on the west side of the Chapel Hill Channel approximately one n. mile south of the West Bank Light. This pit will be called New York Harbor Borrow Pit No. 1, or just Pit No. 1, as it was later classified by Broughton (1977). [In other reports it has been called Borrow Pit Number 7 (Conner et al., 1979), the CAC Pit (e.g., Cerrato and Scheier, 1984) after the company that dredged it, and the West Bank Pit (e.g., U.S. Army Corps of Engineers, 1984). Broughton's designation, however, preceded the others and, in addition, Broughton's published report has been more widely circulated and is more readily available than other references. We will, therefore, use his name for this borrow pit except when citing one of these other reports specifically.] The company that dredged the pit was fined one million dollars until they had refilled the pit to the limiting depth. The Department began to revise their policy soon thereafter and in 1977 limited sand mining to a narrow strip of bay floor along the east side of the Ambrose Channel. Mining could not extend deeper than 45 feet below mean low water. Other

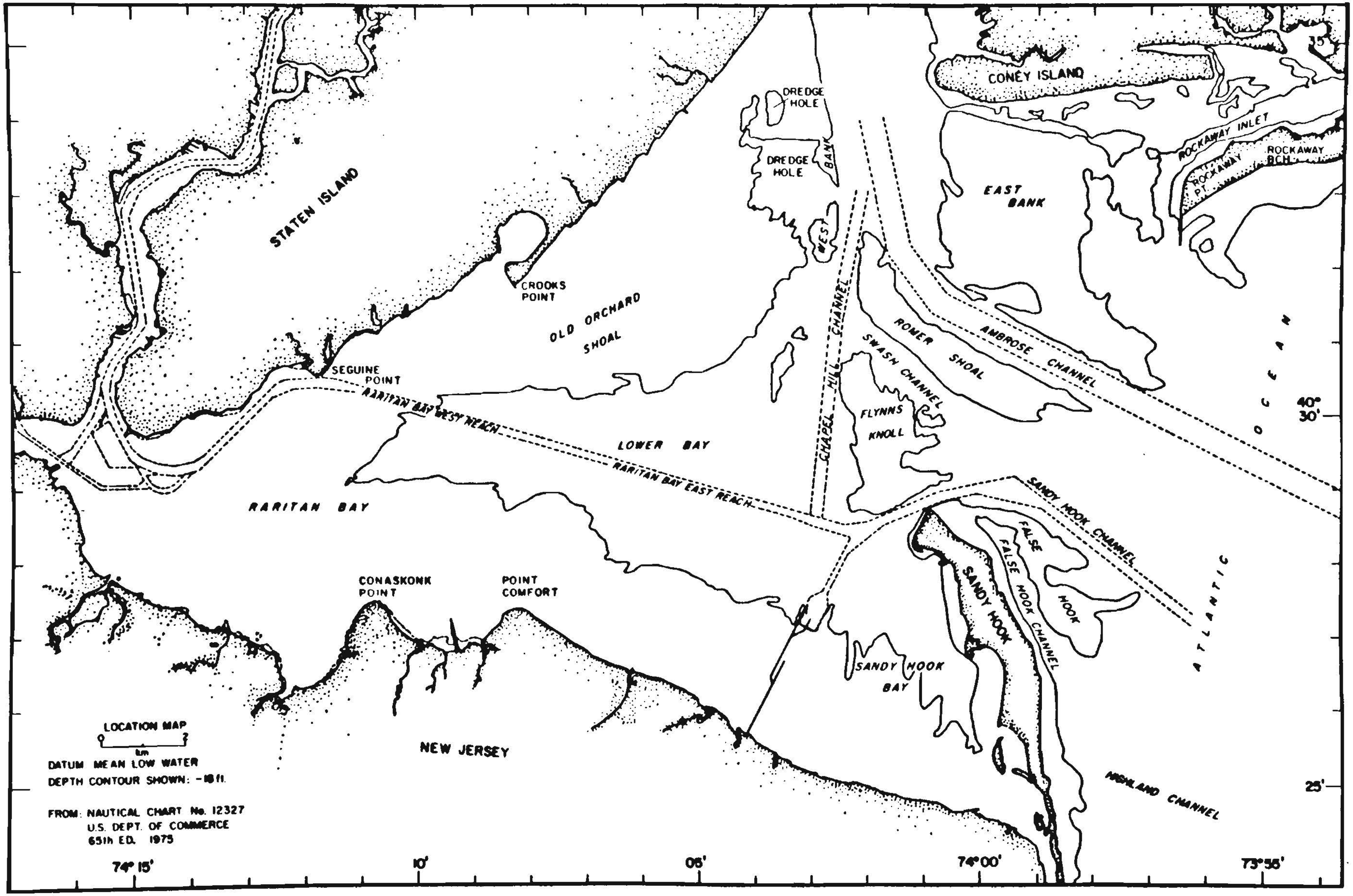

Fig. 1. Index map.

areas would not be considered until (1) the quantity, quality, and renewability of the bay's sand reserves were determined, (2) the biological impacts of mining were assessed, and (3) the effect of sand mining on shore erosion was investigated.

In 1976, scientists from the Marine Sciences Research Center began to study the environmental effects of subaqueous sand mining. The concern that pits may alter the waves and tides and possibly aggravate shore erosion was addressed with mathematical models (Kinsman et al., 1979; Wong and Wilson, 1979). Waves and currents can pass more easily over the pits than they can over the neighboring shoals and the course of currents and the paths of waves are altered slightly by the pits. Mathematical models of the waves and tides in the bay show that the pits are large enough to noticeably affect the waves and tides. Both the tidal range and the wave energy reaching the shore were slightly increased by the presence of the pits. Both of these changes would tend to aggravate shoreline erosion although for at least one scenario that of mining a large area of the East Bank to a depth of 90 feet, wave energy could be reduced in an area on Staten Island presently under severe attack. The changes, however, were usually small and the impact of these small changes in the waves and tides on shore erosion is difficult to assess. Erosion is likely to increase in some areas and to decrease in others as the shoreline adjusts to new conditions, but large adjustments were not expected.

Other concerns arose from the fact that the pits on the West Bank are natural traps for mud. Little or no mud is deposited on the sandy bay floor around the pits but in them mud was accumulating at rates between 4 cm/yr and 9 cm/yr (Bokuniewicz, 1979) or about 100 times faster than typical natural rates in other estuaries. The presence of the pits had changed about 1,053 acres of the sea floor from sand to mud and if mud continued to accumulate in the pits as rapidly as it has over the past 10 years, then the pits would be completely filled in 50 to 100 years. Because of the affinity of many contaminants for fine-grained sediments (e.g. Benninger et al., 1975), the pits are also likely sinks for contaminants in the Lower Bay.

The mud that is accumulating naturally in the pits on the West Bank also has a high organic content and there was concern that the natural degradation of this organic material would cause the water column to become anoxic during the summer. This had been known to occur in other areas, for example, in pits on the south shore of Long Island, NY (Turano, 1968 ms). In 1978, measurements showed that the pits on the West Bank did affect the oxygen demand. Lower oxygen concentrations were generally found over the pits there (Swartz and Brinkhuis, 1978). On at least one occasion the dissolved oxygen levels of the water in the New York Harbor Borrow Pit No. 1 fell below 3.5 ml/l which is the minimum level set by the New York State Department of Environmental Conservation (Swartz and Brinkhuis, 1978).

The muddy pit floors also appeared to support a different biological community than that found on neighboring shoals. Most of the studies of biological resources in the Lower Bay have covered only limited areas and relatively short time periods. The general state of knowledge concerning the biology here up to 1980 has been compiled from studies by Radosh and Reid (1980) and by Brinkhuis (1980). A study done in 1973 led to the conclusion that Pit No. 1 was "consistently low in macrofaunal density and diversity with species compositions typical of the mud fauna in Raritan Bay" (Radosh and Reid, 1980). Another survey of benthic populations in the pits was done between 1977 and 1978. The samples from pits on the West Bank were frequently azoic, and although "undredged sediments nearby did not appear to contain significantly more species or numbers" (Brinkhuis, 1980), "this is probably due to the generally low species diversity and abundance in the area."

Studies of fishes in the Lower Bay done before 1981 (e.g. Brinkhuis, 1980) cannot resolve the potential effects of the borrow pits on fish populations. At a hearing held by the New York Department of Environmental Conservation in 1975, however, sport and commercial fishermen testified that the borrow pits in the Lower Bay were devoid of fishes. (As we shall discuss later, this position was reversed in 1981 and two studies of fishes in the pits were done as part of the present research. The results of these studies were reported separately by Conover et al., 1985 Pacheco, 1983, and the National Marine Fisheries Service, 1984, but they will be summarized in the appropriate section of this report.)

To mitigate potentially adverse effects, the capability to fill these pits and to reclaim the sandy sea floor appeared to be a desirable goal. Even the smallest pit, however, had a volume of over 2 million cubic meters and the total volume of pits on the West Bank alone exceeded 25 million cubic meters. The cost of filling such a volume would be prohibitive unless a source of free material was available. Dredged material may provide that material and in addition, burying dredged sediment in submarine borrow pits has its own advantages. Much dredged mud is contaminated by agricultural, urban, or industrial products and whatever disposal technique is used, it is usually mandatory that the material be contained in the disposal site and isolated from the marine environment to the greatest possible extent. Subaqueous pits are attractive containment sites because mud is naturally accumulating in them at very rapid rates and the pit walls are sufficiently steep to limit the spread of dredged sediment during discharge (Bokuniewicz, 1979). If dredged material could be deposited in the pit and covered, or capped, with a blanket of clean sand, then not only could the bay floor be restored to its pre-mined condition but also the dredged mud could be buried beyond the reach of most burrowing animals and beyond the depth of disturbance by storm waves (Bokuniewicz et al., 1981). Burial keeps the mud in a reduced state so that particle-bound contaminants are unlikely to migrate. Burial at sea also eliminates the problems of groundwater contamination that may be a concern with landfill operations.

The idea that mined pits could be used as containment sites for contaminated sediment is not new. It was suggested at least as early as 1973 by J. H. Carpenter. There was a good discussion of this disposal alternative in a report to the Dredged Material Research Program by E. Johanson and others (1976). Research in this area had also been recommended by a panel at the NOAA workshop on ocean pollution that was held at Estes Park, Colorado in July 1978. In 1979 the New York District of the U.S. Army Corps of Engineers began the multi-year study of alternatives to the open-water disposal of dredged sediment that was based on a preliminary survey of disposal alternatives that had been done for the Corps by the Mitre Corporation. The use of subaqueous borrow pits was recommended as one alternative that was "possible in special cases and feasible for large volumes of materials" (Conner et al., 1979).

History of the Present Study

In July 1980, scientists at the Marine Sciences Research Center, State University of New York, began a site-specific study into the use of submarine borrow pits in the Lower Bay of New York Harbor as containment sites for dredged sediment. Ten questions concerning this disposal were posed at that time.

These were:

1. How much dredged sediment will escape from the pit during the disposal operation?
2. To what extent will the disposal operation affect the concentrations of nutrients, metals, chlorinated hydrocarbons, and dissolved oxygen in the water column?
3. What will be the form of the deposit of dredged sediment?
4. Will the dredged sediment remain in the pit until it can be capped or will substantial quantities be resuspended and dispersed by the tidal currents and storm waves?
5. What amount of dissolved contaminants will be released from the deposit of dredged mud prior to capping?
6. Can a sand layer be constructed over a deposit of dredged mud by conventional equipment?
7. After the cap is in place, what types of benthic organisms will recolonize the surface and at what rates will this happen?
8. How thick must the sand cap be in order to isolate the dredged mud from reworking by benthic organisms and resuspension by storm waves?

9. How effectively will the sand cap contain contaminants?

10. Once the sand cap is in place will it be mechanically stable?

The principal objective of the research project was to answer these questions as fully as possible from the available literature and field measurements. The answers that were generated by the research were to be made available to a committee called the Dredged Material Disposal Management Program's Joint Steering Committee. This committee is comprised of representatives from the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, the New York State Department of Environmental Conservation, the New Jersey Department of Environmental Protection, and the New York District of the Corps of Engineers. The committee met approximately every six weeks and, in addition to their other responsibilities, they would review the progress of the research as need arose.

In addition to studying the relevant literature and initiating theoretical studies we began a series of research cruises in the Lower Bay in order to collect site specific information.

On 3 November 1980, we readdressed the original 10 questions in light of our additional research and one new question was added. This was:

11. What will be the effects of gas generation on the stability of the deposit and the release of contaminants?

At that time a recommendation for a demonstration project was made. The research effort was expanded to include the most likely potential sites for the demonstration project.

We met with the Steering Committee on 26 February 1981 to discuss alternate demonstration projects and on 13 March 1981, a specific form for an alternate demonstration project was recommended. The demonstration project was proposed by the U.S. Army Corps of Engineers on 6 April 1981. The disposal operation was to be done in the southern tip of Borrow Pit No. 1. The demonstration project would be done in three stages (Bokuniewicz, 1982). In the first stage, dredged sand would be discharged to construct an underwater ridge of sand across the northern part of the disposal area to form a compartment in the southern tip of the pit. The ridge was constructed to provide a slope in the northern part of the compartment in order to limit the spread of material during discharge. After the deposit would be created it would be self-supporting; the ridge would not be required to hold it in place. During the second stage dredged mud would be deposited to partially fill the compartment. The third stage would be a sand cap to cover the mud.

On 17 July 1981 another question was added to the list. This was done partially in response to concern raised during the period for public comment on the permit application for the demonstration project. The new question was:

12. How do the borrow pits affect the abundance and distribution of fishes?

Following the permitting process, the demonstration project was begun and the first of three stages was completed in December 1981. The demonstration project was then halted pending litigation concerning one of the certificates needed to conduct the disposal of the dredged sediment for the second stage. An environmental impact statement was being prepared in 1984 to complete the project. By this time, however, all of the principal objectives of the demonstration project had been verified in the field at other locations. In 1985, the Steering Committee decided to begin preparation of an environmental impact statement to implement this disposal option. This is expected to be completed in 1986.

During the course of the research project not only did the work focus on many different objectives simultaneously but also the objectives changed as the project evolved. In the next section of this report we will first present answers to the 12 questions.

Question 1

How much dredged material will escape from the pit during the disposal operation?

If a clamshell dredge is used, we might expect 1 or 2% of the volume dredged to be resuspended or we might expect overflows from the barge at the dredging site. Gordon (1973) made measurements of the turbidity around a clamshell dredging operation in New Haven Harbor and estimated that about 2.5% of the material lifted by the clamshell was lost to the surrounding water. From measurements made around clamshell dredging operations in New York Harbor Tavolaro (1984) estimated that about 2% of the volume dredged becomes suspended in the water column at the dredging site. About two-fifths of this 2% resettles to the sea floor at the site presumably to be dredged again and the remaining three-fifths, or 1.2% of the total, probably settles to the bottom within 500 m (Barnard, 1978) from the dredging site. Martin and Yentsch (1973) found that the turbidity returned to normal about 400 m downstream of a dredging operation in the Annesquan Waterway, MA. Around operations in the Connecticut River, Bohlen et al. (1979) found that there were no measurable effects of the dredging on the suspended sediment concentrations beyond 300 m downstream of the dredge. Cronin et al. (1976) reported that background levels were reached within 90 m of a dredge in the Patapsco River, MD and Yagi et al. (1977) found that turbidity levels decreased by 50% within 23 m of the clamshell dredge.

During the disposal operation from a scow or hopper dredge, we should expect less than 5% of the released sediment to remain in suspension and to be dispersed from the disposal site. This conclusion was first reached by Gordon (1974). He made measurements during disposal operations in Long Island Sound and showed that less than 1% of the dredged silt released at the disposal site remained in suspension long enough to be dispersed by the tides. A similar conclusion was reached by Sustar and Wakeman (1977) as a result of operations they made in San Francisco Bay. They found that only between 1 and 5% of the mud that was discharged remained in suspension above 2 m of the bottom. They also conducted laboratory experiments that reenforced their conclusion that the disposal operation causes very little disturbance in the upper part of the water column. A similar conclusion was reached by Bokuniewicz et al. (1978) from observations they made for the Dredged Material Research Program during disposal operations in Puget Sound, Long Island Sound, Lake Erie, and Lake Ontario.

At the Mud Dump Site on the Atlantic continental shelf outside of New York Harbor, a detailed accounting of the dry mass removed in barges from dredging sites and the dry mass in the subsequently formed deposit at the disposal site, showed that an average of about 4% was lost during transport and discharge (Tavolaro, 1984).

A similar calculation was done for three disposal mounds in Long Island Sound (Morton, 1983). The volume of dredged material on disposal sites was measured by careful bathymetric surveys and compared to the volume dredged, although the volume dredged was estimated by the volume in the scows and the uncertainty is relatively large (Morton, 1983). In each of two mounds 95% of the amount discharged was found on the disposal site (Morton, 1983) indicating a loss of 5%. At the third site 90% was found at the site but additional material was present beyond the immediate mound and "it was possible for significant amounts of dredged material to be undetected by acoustic measurements" (Morton, 1983).

The limitations to the use of bathymetric surveys to estimate the volume of sediment deposited on a disposal site were demonstrated during the monitoring of another disposal operation in the Sound. During the U.S. Army Corps of Engineers Field Verification Program sediment was dredged from Black Rock Harbor, CT, and discharged at a disposal site in central Long Island Sound. The dredged sediment contained a significant amount of low density slurry and the resulting sediment deposit had low relief (Scott et al., 1984). Because of the low relief, estimates of the volume of the deposit based on bathymetric surveys alone underestimated the volume by about 70% (Marine Surveys, Inc., 1983). With the addition of underwater photography (Rhoads and Germano, 1982), however, about 75% of the dredged material was detected at the site (Marine Surveys, Inc., 1983). Allowing for losses during discharge and compaction almost all of the dredged sediment was deposited at the site.

The Mitre Report (Conner et al., 1979) also comes to the conclusion that almost all of the released sand and silt will be deposited quickly based on exploratory calculations for the New York Bight using the Tetra Tech model (Holiday et al., 1978; Brandsma and Divoky, 1976). In the model calculations, all of the sand and silt were deposited within about 20 minutes and within 200 yards of the point of discharge. For a clay slurry the time may be considerably longer; some of the model calculations showed that three hours would be needed to deposit 90% of the clay particles that were released as a slurry from the scow or hopper.

Of course, blocks of clay that were dredged would reach their terminal fall velocity quickly after discharge and reach the bottom presumably with little or no dispersion during descent. Blocks of cohesive sediment may either disintegrate or deposit intact upon impact with the bottom. The size of the block as well as its strength and the hardness of the sea floor all play a role in its fate (Bokuniewicz and Gordon, 1980a). Blocks of silt and clay smaller than 0.85 m in diameter are unlikely to fragment upon impact with a hard sea floor (Bokuniewicz and Gordon, 1980a). Clods about 0.2 m in diameter were found on the surface of one disposal mound in Long Island Sound (Bokuniewicz and Gordon, 1980a) and clods of cohesive sediment with diameters of about 0.4 m were found on another (Morton and Miller, 1980).

If the blocks do disintegrate upon impact, it is likely that the residue will join a slurry of dredged material and be incorporated into a thin, dense bottom surge (e.g. Proni, 1982) that contains almost all of the dredged sediment released except for that contained in the surviving blocks. Over a flat bottom, the sediment is deposited within a few hundred yards of the point of release. This has been documented under a wide range of conditions (Bokuniewicz et al., 1978). Discharges of muddy sediment from a hopper dredge in water 18 m deep in Lake Erie were monitored to show that the surge did not carry material farther than about 200 m from the impact point over a flat disposal area (Bokuniewicz et al., 1978). At this same site later, more than 70% of the dredged sediment was found within about 250 m of the designated discharge point (Danek et al., 1977); some of the missing material (an unspecified amount) was not found on the site because it had been released at another location. During a disposal operation in Long Island Sound 80% of the 1.2 million cubic meters of muddy dredged sediment that was discharged from scows in about 20 m of water was deposited within 30 m of the center of the discharge location and 90% within 120 m (Gordon, 1974). At each of three sites in Long Island Sound studied by Morton (1983), 90%, 95%, and 95% of the material discharged was found within 200 m of each discharge point. Discharges of sandy silt in Borrow Pit No. 1 showed comparable behavior; the surge was not detected farther than about 180 m from the point of impact (Bokuniewicz, 1985).

The previously cited studies show that during a normal point-dumping operation with good navigation, almost all of the dredged sediment can be sent to the shallow sea floor and that the spread of the surge is limited to a few hundred meters even over a flat sea floor. In a pit, however, the sloping wall of the pit will further limit the spread of the bottom surge. Little is known about the dynamics of the spreading bottom surge but we can get some idea of its ability to climb a slope from energy considerations. The spread of surges should be significantly restricted by even, gentle slopes; a slope of 3 degrees might reduce the run of a surge to 30% of that over a flat sea floor (Bokuniewicz, 1985). Both empirical calculations and observations of spreading surges in Borrow Pit No. 1 indicate that a pit wall 4 or 5 meters high is a very effective barrier to spreading surges and that lower walls can be effective if the discharge point is set back an appropriate distance from the rim (Bokuniewicz, 1985). This prediction has been supported by observations of a disposal operation near the Duwamish Waterway in Seattle, Washington (Sumeri, 1984). During this operation, cohesive silt was dredged with a clamshell dredge and discharged in 20 m of water over a depression in the river floor that measured about 30 m wide, 140 m long and up to 2.4 m deep below the ambient sea floor. The side slopes of this depression were as steep as 11 to 20 degrees. Even though the depression was relatively shallow, the side slopes significantly reduced the outward surge of the discharged material so that nearly all of the released sediment was deposited in the depression (Sumeri, 1984). These empirical results suggest that under comparable conditions, a borrow pit could be filled to within about 1.5 m of the ambient sea floor with discharges as close as 80 m from the rim.

Question 2

To what extent will the disposal operation affect the concentration of nutrients, metals, and dissolved oxygen in the water column?

These effects will be negligible. Many field and laboratory studies have tried and failed to detect significant releases of trace metals to solution during dredged material disposal. These negative results are in agreement with current geochemical theory about the mechanisms of sediment-metal interactions which predict the general immobility of trace metals in reducing sediment. Metals become bound to fine-grained sediment particles by three mechanisms. They may become bound to organic matter associated with the particles. They may co-precipitate with those common sedimentary metals (manganese and iron) that are insoluble under oxidizing conditions or they may precipitate as insoluble sulfide compounds under reducing conditions. It appears that the extremely low dissolved metal concentrations in nearshore waters are the results of these effects (Turekian, 1977).

Both field and experimental evidence confirms that the mechanisms for binding metals to sediment particles are numerous and operate under a wide range of chemical conditions (e.g.

Gambrell et al., 1976, 1980; Jenne, 1977; Patrick et al, 1977). In addition, no significant release of metals has ever been observed during the aquatic disposal of dredged material in the United States (Wright et al., 1978). This indicates that the common methods of open-water dredged material disposal do not significantly alter the chemical conditions of the particles probably because of the rapidity of descent.

Persistent ecological effects from nutrient releases during disposal operations are also unlikely to occur. Detailed monitoring of disposal operations around the country (Wright et al., 1978) has failed to detect significant elevations of nutrient levels in receiving waters even from very large disposal operations. Dilution is rapid and effective, and any elevated nutrient concentrations transitory. Observations at the New London Disposal Site in Long Island Sound, for example, showed that dissolved oxygen, total suspended solids, pH, eH, turbidity, and dissolved organic carbon all returned to background, predisposal levels within two hours of a scow discharge (National Marine Fisheries Service, 1977). Similar results were obtained in the Chesapeake Bay during dredging and pipeline disposals (Flemer, 1970) and at an open-water disposal operation offshore of Pearl Harbor, Hawaii (Chave and Miller, 1983).

Question 3

What will be the form of the deposit of dredged sediment?

The most effective form would be that of a truncated cone or pyramid. Its top surface should be relatively flat and below the elevation of the ambient bay floor. At its margin the surface of the deposit will slope downward toward the pit walls so that a shallow trough will be formed inside of the edge of the pit to hinder the escape of the bottom surge during the disposal operations.

The shape of deposits formed during open-water disposal operations can be forecast in light of available observations. As we discussed earlier, the diameter of potential deposits is limited by the range of the bottom surge that is formed during the disposal operation and very compact deposits can be created by point-dumping (e.g. Bokuniewicz and Gordon, 1980a; Morton, 1983). The side slopes of the deposit depend primarily on the character of the material. In principle, clods and coarse sediment could accumulate on the disposal site in a pile with side slope reaching the angle of repose for coarse material, about 35 degrees. Clods were found on the surface of a disposal mound in Long Island Sound which had been formed by the open-water disposal of about 1.2 million cubic meters of muddy sediment (Bokuniewicz and Gordon, 1980a). The deposit had an average slope of 6 degrees near its peak although locally steeper slopes were seen (Bokuniewicz and Gordon, 1980a). Two other deposits have also been created near this same site (Morton, 1983). The larger contains 118,000 cubic meters of mud. It has a radius of about

100 m and side slopes as steep as 7 degrees; clods of cohesive sediment were also found on its surface (Morton and Miller, 1980). The smaller deposit consisted of a mound of mud, which contained 26,000 cubic meters and had a radius of 100 m and side slopes as steep as 6 degrees, covered with a layer of sand. The combined deposit contained 60,000 cubic meters. Its radius was about 200 m and the side slopes reached angles as high as 8 degrees. During a discharge operation in Puget Sound, clods were detected leaving the scow and the resulting deposit here had slopes as steep as 2 or 3 degrees (Bokuniewicz et al., 1978). At a disposal site on the Atlantic shelf off the mouth of Chesapeake Bay about 650,000 cubic meters of loose silt and very fine sand was discharged to create mounds 3.3 m high with average side-slopes of about 2 degrees (Hands and DeLoach, 1984).

Deposition of fine-grained sediment from a bottom surge produces a dredged sediment deposit with low side slope. Observations of surges in Lake Erie have been used to calculate the maximum slopes for deposits formed in this way (Bokuniewicz and Gordon, 1980a). The maximum slope is the slope at which the rate of gain of energy as the surge flows down the slope is just equal to the rate of energy dissipation calculated from observations of spreading surges (Bokuniewicz et al., 1978). At the maximum slope, the surge should travel indefinitely without losing energy and, presumably, without depositing its sediment. The maximum slope has been calculated to be about 3 degrees (Bokuniewicz and Gordon, 1980a; Bokuniewicz, 1983). Such low slopes were found on the flanks of a deposit of dredged mud in Long Island Sound (Bokuniewicz and Gordon, 1980a). After a disposal operation involving dredged material that contained a significant amount of low density sediment slurry, the mound at the disposal site had side slopes less than 0.3 degrees (Scott et al., 1984). A dredged sediment deposit in Chesapeake Bay was found to have a maximum surface slope of about 0.59 degrees and an average slope of 0.12 degrees (Biggs, 1970). After a disposal operation in Lake Erie, the maximum slope of the deposit's surface was 0.3 degrees (Alther and Wyeth, 1980). During laboratory tank tests to simulate open-water disposals of dredged mud, mounds were formed with slopes on the order of 0.3 degrees (Chase, undated ms). In all of these cases, it appeared that the sediment had been deposited from a slurry.

The number of studies is relatively small and there is not yet a generalized model that is widely accepted and available to describe all the relevant processes and predicting the form of the deposit. Nevertheless, the available studies may be used as a basis for forecasting the form of deposits of dredged sediment if we assume that point-dumping will be done in relatively shallow (<20 m) water. Enough information is at hand to consider four classes of material--cohesive mud, fluid mud, sand, and a mixture of sand and fluid mud. The cohesive mud is likely to have been dredged with a clamshell-bucket dredge and the deposit formed primarily of clods of material. In this case we expect to find a deposit with slopes of less than 30 degrees; but experience has shown that the slopes will probably be 2 to 8 degrees.

The central mound of clods will be surrounded by a blanket composed of fine-grained material that had been deposited from a bottom surge formed by ablation of clods, entrainment of water during descent, and the disintegration of some clods upon impact. The surface slopes of the apron should be less than 3 degrees and experience has shown that they will probably be less than 1 degree. An example of such a deposit was formed in Long Island Sound (Bokuniewicz and Gordon, 1980a).

Fine-grained sediment dredged hydraulically will most likely be a very weak and fluid sediment in the hoppers or a very dense slurry. The expected bulk density of such material would be between 1.1 and 1.3 g/cubic centimeter (Bokuniewicz, 1979). This material will produce a deposit with a minimum radius of about 200 m and side slopes of less than 3 degrees. Experience has shown that actual side slopes will probably be less than 1 degree. An example of such a deposit was created in Lake Erie (Alther and Wyeth, 1980).

There is less experience to draw on to make a forecast for the form of a sandy deposit. If we assume that the sand is sufficiently coarse not to be carried out of the impact area by a bottom surge then a deposit with side slopes less than about 30 degrees and probably less than about 8 degrees will be created. An example of such a deposit was described by Morton (1983). A mixture of dredged sand and mud is likely to segregate during the disposal operation. In this case we might expect to find a deposit with a central mound of coarse-grained material having side slopes of about 8 degrees surrounded by an apron of fine-grained sediment with side slopes of about 1 degree, similar in shape to that formed by the discharge of cohesive mud.

This information was used to predict the form of the first stage of the demonstration project--the implacement of the submerged sand ridge (Bokuniewicz, 1982). The ridge was constructed in December 1981 by the hopper dredge Goethals using sand from Ambrose Channel. The deposit that was created by the Goethals was in a form that was very close to the predicted form (Bokuniewicz, 1982). The average water depth over the ridge crest was 39 ft; the predicted value was 37 ft. The 50-ft contour was displaced about 270 yds to the north as predicted and the location of the lowest points along the ridge crest were to the east and west of the center as predicted. The predicted side slopes were about 1.6 degrees and the actual slopes were later found to average 1.0 degree. To our knowledge this is the first time that the form of a deposit of dredged sediment had been successfully predicted in advance and intentionally constructed.

Question 4

Will the dredged material remain in the pit until it can be capped?

The arguments presented here are in support of the idea that the sediment will be contained in the pits. The pits on the West

Bank have at least one important characteristic that makes them very effective containment sites for fine-grained dredged sediment. They are very efficient natural traps for fine-grained sediment, and mud is accumulating on the pit floors at very rapid rates (Bokuniewicz, 1983; Bokuniewicz and Hirschberg, 1982a,b; Olsen et al., 1984). Fathometer records suggest that over the last decade mud has accumulated in parts of the borrow pit that are only 2 m below the ambient, sandy bay floor and 5.5 m below the water surface. The deposition of mud has been widespread where the pit floor is more than 6 m below the water surface, although in the middle pit there are occasional peaks on the pit floor in water depths of 9 m that are apparently free of mud.

Sedimentation rates of several centimeters per year are not unusual in features like borrow pits or dredged channels that are not in equilibrium with the environment. In channels in New York Harbor, Olsen (1979) measured sedimentation rates ranging in excess of 0.15 m/yr using geochemical techniques. Based on dredging records, the sedimentation rates in channels in the Harbor have been calculated to be from 0.01 to 1.01 m/yr with an average value for 27 projects of 0.27 m/yr, and similar values are calculated for the channels of harbors in Connecticut (Bokuniewicz et al., 1979). Cores taken from the floors of the pits penetrate a layer of mud overlying sand. In the northernmost pit on the West Bank measurements of the thickness of the mud layer show that mud has been accumulating here at an average rate of 0.05 m/yr (or 15 mg/square centimeter/day) over the past 15 years (Bokuniewicz and Hirschberg, 1982a). Measurement of the activity of radionuclides with depth in cores from this same pit supports this conclusion (K. Cochran and S. Sneed, 1983, Mar. Sci. Res. Center, SUNY, pers. comm.). Cores from the large dredged area south of Hoffman and Swinburne islands contain mud layers that suggest a sedimentation rate of 0.09 m/yr (Bokuniewicz, 1983). In June 1981, three cores were also taken in Borrow Pit No. 1 at the place where dredged sediment had been disposed in July 1980. These were x-rayed and two of the radiographs clearly showed the dredged sediment as irregularly laminated sediment interlayered by bands of coarse-grained sediment. At the tops of these cores a layer of less dense, homogeneous sediment was seen which had a thickness of about 3 cm in the one core and 8 cm in the other. The consistency of the surface material was similar to that of the sediment we had found in the pits farther to the north. If this surface layer has accumulated over the past year since the disposal operation was completed, the sedimentation rate would be 0.03 m/yr and 0.08 m/yr. This is the same value found in the more northern pits. In addition, cores in other areas of Borrow Pit No. 1 show layers of mud up to 0.78 m thick as would be expected if the sediment accumulation was occurring everywhere in the pit.

Sediment traps and hydrographic measurements were used to investigate the physical characteristics of the pit environments that make them traps for fine-grained sediments (Bokuniewicz and Hirschberg, 1982a,b). On the average, fine-grained sediment particles settle naturally into the pit at a rate of about 23 mg/square centimeter/day. Since the long-term accumulation rate is 15 mg/square centimeter/day, about 65% of the material that naturally settles to the pit floor stays there. Even though about 16 mg/square centimeter/day settles to the sandy floor of the Lower Bay near the pits, none of it stays there but is continually resuspended by tidal currents. For comparison, Long Island Sound essentially traps all of the fine-grained sediment that enters it (Bokuniewicz, Gebert, and Gordon, 1976), but only about 0.6% of the total amount of material that settles to the Sound floor remains there (Bokuniewicz and Paige, 1985). This means that the amount of sediment that is resuspended by the tides from the pit floor is very low. The amount of sediment that is resuspended by the tides can be estimated by monitoring changes in the vertically-integrated suspended sediment load at one place over a tidal cycle. This has been done in Long Island Sound where the tidal currents were found sufficient to resuspend a layer of mud up to 3 mm thick (Bokuniewicz and Gordon, 1980b). The depth of resuspension was found to be between about 1 and 3 mm also in the Inner Harbor (Olsen, 1979). During the observations made in our study of the pits, changes in the vertically integrated suspended sediment load over the pits was found to be 7 mg/square centimeter over six hours on the ebb tide. If all of this change in the suspended load was resuspended from the pit floor, then a layer of mud about 0.14 mm thick had been resuspended. Some of the measured change in the suspended sediment load, however, could be due to the advection of more turbid or less turbid water under the stationary observing vessel. The horizontal gradient in the suspended sediment concentrations is about 0.1 mg/l/km, and half of a tidal excursion is about 7 km. The change in the integrated suspended load over the pit due to advection alone should be about 1 mg/square centimeter or only 15% of the measured total value. As a result, we believe that the currents resuspend, at most, a few tenths of a millimeter of mud from the pit floor every tidal cycle. The long-term accumulation rate is 5 cm/yr or 0.14 mm/day so sediment on the pit floor is only subject to resuspension for about a day before it is buried by the natural deposition.

The pits are so effective at trapping sediment because the circulation is restricted inside them. This was studied at both the northernmost pit and within the compartment that was created in the first stage of the demonstration project within Borrow Pit No. 1 (Bokuniewicz and Hirschberg, 1982b). In both cases, the salinity of the water in the pit that is below the depth of the ambient sea floor barely changes over a tidal cycle while the surface water shows the usual tidal variation. This salinity stratification over the pits greatly restricts the circulation in them. There is essentially no ebb tide in the northernmost pit near the pit floor and within the compartment of Borrow Pit No. 1 the current speeds remain less than 6 cm/sec throughout the tidal period. Such conditions can account for the high trapping efficiency of the pits. Furthermore, since the hydrographic conditions are seen to change dramatically at a water depth over the pit equal to that of the ambient sea floor, it seems likely that the pits will remain traps for fine-grained material even as they are being filled.

Some additional evidence for the limited degree of sediment transport within the pits can be had from diver observations of the ridge of fine sand that was created in December of 1981 in Borrow Pit No. 1 as the first stage of the demonstration project. This type of sediment is very susceptible to erosion. In June and July 1981, the ridge was visited by divers. The divers found a smooth sand surface with no evidence of ripples or other indications of sand transport. This is consistent with current meter observations which showed very low current in this pit below the sill depth (Bokuniewicz and Hirschberg, 1982b). A survey rod fitted with a weighted slider was inserted in the ridge in June 1982. Changes in the absolute elevation of the sand surface can be measured on the rod and in addition, the thickness of disturbance of the sand surface that occurred without net erosion or accretion is marked by the slider which is expected to sink into the disturbed layer at the time of the disturbance (Clifton, 1969). The survey rod was examined in July after 34 days and no significant erosion or deposition was observed. The slider had moved 1 cm into the sand. Although this is near the limit of resolution of the device, the observation suggests to us that a thin layer may have been disturbed by waves or currents without net erosion. In addition, a bathymetric survey of the ridge was made in March 1983 over 14 months after it had been created. A comparison of this survey to one done in January 1982 showed a slight reduction in the elevation of the ridge. The changes, however, had a magnitude of about 30 cm; this is at the limit of accuracy of the survey and such small changes may have been due to current-induced smoothing of the surface, compaction, or consolidation of underlying deposits.

Question 5

What amounts of dissolved contaminants will be released from the deposit of dredged mud prior to capping?

Before the sand cap is in place, the deposit of dredged mud will consolidate under its own weight; we will refer to this process as self-consolidation. During consolidation, the surface of the deposit will settle, the deposit will become more dense, and pore water will be expelled carrying with it dissolved contaminants. A detailed and reliable theory is available to predict consolidation from the results of standard laboratory consolidation tests on the material (Been and Sills, 1981).

The settlement of the surface of the deposit, that is the increase in water depth, is comprised of two parts. Part of the settlement is due to the consolidation of the layer of natural marine sediment at the site. To a first approximation, this may be calculated as

$$W = a\ (\rho g)\ H\ h$$

where (pg) is the submerged unit weight of the dredged sediment deposit, H is the thickness of the dredged sediment deposit, h is the thickness of the layer of marine sediment at the site and "a" is an empirical coefficient for the marine sediment called the final compressibility (Biot, 1956) which can be determined by a standard consolidation test in the laboratory. The second part of the consolidation is due to the consolidation of the dredged sediment deposit under its own weight. This may be calculated as:

$$w = b\ (pg)\ H^2/2$$

where b is the empirical final compressibility for the dredged sediment. The amount of pore water expelled in the process is the product of the settlement and the plane area covered by the deposit; or, alternatively, the product of the percentage change in thickness of the deposit and its original volume.

Predictions of the consolidation of dredged sediment in contained, subaerial sites are common (e.g. Bartos, 1977) and consolidation has also been tried at a subaqueous site in Long Island Sound (Bokuniewicz and Gordon, 1979, and Demars et al., 1984). For one deposit at this location the observed settlement compared favorably with the theoretical estimate although the measured settlement contained large uncertainties (Bokuniewicz and Gordon, 1979). The ratio of the final settlement to the deposit thickness was measured to be 0.33 ± 0.13 while the calculated ratio was 0.24. At another deposit in the Sound a volume change of about 4% was observed between precision bathymetric surveys three months apart (Morton, 1983). Changes in this mound and others at this location (Morton, 1983) have been attributed to consolidation (Demars et al., 1984).

Tests were done on mud from North Shooters Island Channel as a representative of dredged mud in the harbor and the results used to predict the consolidation of a hypothetical mud deposit (Bokuniewicz and Liu, 1981; Liu, 1982). If the mud deposit was about 2 m thick as expected, then we expect a settlement of about 6 cm or 3% of the original thickness. The second stage of the proposed demonstration project was to have had a volume of 385,000 cubic yards of mud, so the maximum volume of pore water that might be expelled is about 11,550 cubic yards. This is the maximum volume because the actual amount expelled before the cap is in place depends on the length of time the deposit remains uncapped. Consolidation theory can also supply a form for calculating the rate of consolidation but we hesitate to recommend its use for subaqueous dredged-material deposits. The reason for this is that the theory requires the assumption that the deposit is homogeneous and the rate of consolidation depends upon the rate at which water can percolate through the deposit. An actual deposit, however, is more likely to be composed of blocks of material separated by waterfilled interstices. The interstices would provide escape routes for the water and, as a result, consolidation would proceed more rapidly than predicted. Subaqueous mounds in Long Island Sound have been found to consolidate at rates about 1.5 times faster than those predicted theoretically from laboratory studies (Demars et al., 1984). Field observations of a capped deposit of dredged silt in the Duwamish Waterway, Seattle, Washington, suggest to the investigator there that initial consolidation is quickly effected (Sumeri, 1984) and experience at the New Haven disposal site in Long Island Sound suggests that the initial self-consolidation of a deposit of the expected size may be substantially complete in several months.

To estimate the release of contaminants due to the expulsion of pore water we need to know the dissolved concentrations. The concentrations of dissolved metals in pore waters are extremely difficult to measure, but we have determined values for dissolved iron, manganese, and copper in the pore waters of mud from the northernmost pit on the West Bank. Concentrations of iron, manganese, and copper in the pore water near the surface of the mud were 4.7, 4.6, and 20.0 ug/ml respectively. If 11,550 cubic yards of this water were expelled, the total amount of iron, manganese, and copper added would be 41.5, 40.6, and 176.3 kg. This is probably an overestimate, however, since most of the pore water should contain lower levels of contaminants than are found at the surface.

Consolidation will continue when the sand cap is in place and the chemical consequences of any consolidation will be discussed further in our answer to Question No. 9.

Question 6

Can a sand layer be constructed over a deposit of dredged mud by conventional equipment?

Yes. This has been done at the Central Long Island Sound Site (Morton, 1983), at the Mud Dump Site on the Atlantic shelf outside of New York Harbor (O'Connor, 1982), and in the Duwamish Waterway, Seattle, Washington (Sumeri, 1984). At the Mud Dump Site, vibracores through the completed deposit showed a layer of sand with an average thickness of 1.1 m overlying the dredged mud; there was a very sharp interface between the sand and the mud (Bokuniewicz, 1986). Even though there were no special precautions taken to spread the sand over the surface, the coverage was good and there was very little inmixing between the two layers. During an experimental disposal operation in Borrow Pit No. 1 in July 1980, we looked at a discharge of sand onto a muddy deposit. Water samples were pumped from within the bottom surge to examine the sizes of material it carried. The surge was found to carry as much as 69% sand but most of the material was fine-grained sediment particles. These had apparently been resuspended from the deposit by the impact of the sand but the resuspension was probably limited to a layer only a few millimeters thick. We might expect, therefore, that the transition from sand to mud will be gradual, extending over at least a few centimeters.

The grain-size distribution across the interface in vibracores at the Mud Dump showed that the transition from sand to mud occurred over a distance of less than five centimeters (Bokuniewicz, 1986).

Question 7

After the cap is in place, what types of benthic organisms will recolonize the surface and at what rate will this happen?

During the past 20 years, the recovery of seafloor communities after a physical disturbance such as dredging and dredge spoil disposal has been intensively studied (e.g. Dean and Haskins, 1964; Harrison and Wass, 1965; Cronin et al., 1976; Sykes and Hale, 1970; Leppakoski, 1971; Jenkinson, 1972; Rounsefell, 1972; Saila et al., 1972; Pratt et al., 1973; Maurer et al., 1974; Scheibel, 1974; Kaplan et al., 1975; Boesch et al., 1976a,b; Oliver and Slattery, 1976; Rosenberg, 1976; McCall, 1977; and Wolff et al., 1977). At present, our knowledge of benthic recolonization is far from complete. For example, the mechanisms controlling community development have not yet been identified. Nevertheless, research has shown that community development after a physical disturbance follows an orderly pattern of succession involving changes in species structure and community processes with time (McCall, 1977; Rhoads et al., 1978; Rhoads and Boyer, 1982).

A seasonal benthic survey has been conducted in the Lower Bay of New York Harbor between July 1980 and June 1983. A total of 313 benthic samples were collected during this period. Each sample consisted of three pooled 0.04 square meter Shipek grabs. The data set represents stations located in the following areas: (a) within the northern pit on the West Bank near Hoffman and Swinburne islands, (b) on the shoals adjacent to that pit, (c) within Borrow Pit No. 1, (d) on the sea floor neighboring Borrow Pit No. 1, (e) at a control site near Old Orchard Shoal (Cerrato and Scheier, 1984).

The benthic data for each area have been analyzed in terms of species composition, abundance, number of species, Shannon-Wiener diversity, equitability, and rarefaction diversity. In comparing the various geographic areas, the following principal conclusions were made:

a. The two pits have the same dominant fauna and very similar seasonal patterns in abundance, number of species, diversity, and equitability.

b. The pit stations showed a distinct annual pattern in abundance. The major period of recruitment within the pits appears to be in the fall. Abundances decline during the winter and generally remain low throughout the spring and summer months. A similar annual pattern is also found for the number of species per sample. The numerically dominant fauna in the pits were species which have been characterized as opportunists in other studies.

c. Borrow pits were found to be distinctly different than the control site in terms of species composition. In addition, the absolute magnitude and the amplitude of the temporal variations in abundance, number of species, diversity, and equitability were dissimilar when comparing these habitats. The benthic fauna at the control site was in general more stable and diverse through time than that found at the pit sites.

d. The temporally variable, opportunistic assemblage found at the pit stations but not at the control site suggests that the borrow pits are the more highly stressed of the two habitats.

e. There is evidence that the borrow pits have an effect on the benthos in adjacent areas. Samples collected at stations close to the pits tended to have a mixed fauna, with dominant species which were characteristic of both the borrow pits and the control site. In addition, the absolute magnitude and the amplitude of temporal variations in abundance, number of species per sample, diversity, and equitability for this transitional region tended to be intermediate between the patterns found at Borrow Pit No. 1 and the control site.

The data gathered by the present study permit several predictions about the fauna that would ultimately develop on a capped deposit. In the following, it is assumed that the physical environment of the capped deposit resembles that found at the control site. This assumption includes no effects of dredged sediment composition, that the cap material is stable and similar in composition to the well sorted sands on the West Bank, that the disposal operation has restored the area to ambient depth, and that there are no borrow pits or navigation channels adjacent to the deposit.

In the long term, several years after capping, the fauna which would ultimately characterize the deposit would differ from the observed borrow pit assemblage. The borrow pit fauna are numerically dominated by a few species. Two of these dominants, Streblospio benedicti and Mulinia lateralis have been identified as opportunists by McCall (1977) and Rhoads et al (1978). Opportunistic species, however, are not numerically dominant at the control site. Using the control site assemblage as a basis and given enough time for recovery after disposal, opportunistic species on the capped deposit would likely be found in moderate abundances and each would represent a numerically small percentage of the total fauna. Less opportunistic species such as Nepthys spp. and Tellina agilis were often found in comparable abundances at the control site and within borrow pits. Because of the predicted decrease in opportunists over that observed in the borrow pits, such species would probably constitute a larger numerical fraction of the total fauna on the capped deposit. On the whole, the community on the capped deposit would probably be more stable and diverse through time than the current pit fauna.

Some question remains as to whether the fauna on the capped deposit would more closely resemble that found at the control site or whether it would be an intermediate assemblage such as that observed in the transitional region adjacent to Borrow Pit No. 1. The control site is not in close proximity to existing borrow pits or navigation channels. Results in Cerrato and Scheier (1984) suggest that the fauna in areas surrounding borrow pits are to some extent affected by the presence of the pits. Also, the possibility that navigation channels have an effect on adjacent areas in a manner similar to borrow pits can not be excluded. Were Borrow Pit No. 1 partially filled, it is likely that an intermediate fauna resembling the transitional region would develop since a pit area would remain. In this specific case, even if the pit were filled entirely, the benthic assemblage may never fully resemble the control site because of the proximity of this area to Chapel Hill Channel.

Based on prior studies and the results in Cerrato and Scheier (1984), an estimate of the rate of recovery following capping can be made. Dredging and dredge spoil disposal operations are not the only sources of physical disturbances in shallow water. The sea floor may also be disturbed naturally by, for example, storm waves, strong longshore and rip currents, and tidal scour. The probability of natural environmental perturbations is high nearshore (Johnson, 1970, 1971, 1972; Oliver et al., 1977; Rhoads et al., 1978; Rhoads and Boyer, 1982). Communities in shallow areas are, therefore, maintained at lower order pioneering stages and should recover from dredge spoil disposal faster than those in deeper areas. As a specific example, Rhoads et al. (1978) estimated recovery at two sites in Long Island Sound. One site, located in 14 m of water and in an area frequently disturbed by storms, recovered from an experimental disturbance in less than one year. The second site, a disposal site in 20 m of water and rarely perturbed by storm turbulence, was estimated to require several years for recovery.

Estimates of the time to recovery after dredging or dredge spoil disposal in shallow water areas range from less than one year to greater than ten years (e.g. Drobeck, 1970; Harper, 1973; Rogers and Darnell, 1973; Saila, 1976; Oliver et al., 1977; Rhoads et al., 1978; Saloman et al., 1982, Culter and Mahadevan, 1982; Turbeville and Marsh, 1982). The borrow areas in New York Harbor all lie within a shallow, fairly high energy environment. The distinct fall increases in abundance observed in the borrow pits demonstrate that once conditions are favorable, recruitment can proceed rapidly in this area. Colonization of the capped deposit should be rapid, and the time to recovery should be at the lower end of the above range.

Question 8

How thick must the sand cap be in order to isolate the dredged mud from reworking by benthic organisms and resuspension by storm waves?

The proposed demonstration project would have required a cap more than a meter thick in order to bring the level of the deposit just below the level of the ambient sea floor (Bokuniewicz, 1982). The pit would not be completely filled with dredged mud; at the pit wall the surface of the mud layer must be several meters below the rim of the pit. A cap over a meter thick is sufficient to isolate the mud deposit by the criteria discussed next (Bokuniewicz et al., 1981).

The cap must be thick enough to prevent resuspension of the underlying mud. In the Lower Bay, the natural sand bottom appears to be relatively stable. A study of bathymetric surveys that were conducted over a period in excess of 100 years shows minor shifting of the depth contours but no major changes in water depth with the exception of dredged areas (Fray, 1969). There does not appear to be any net erosion of the harbor floor in this area. In addition, there are no large bed forms on the undisturbed surfaces of the West Bank which might indicate that large amounts of sand are not moved regularly by the tides. Divers placed survey rods in the sea floor near Old Orchard Shoal, about 0.8 n miles from Borrow Pit No. 1. These rods were described earlier in the answer to question 4. There were two deployments on the sandy bay floor near Old Orchard Shoal in water 7.5 m deep. One covered a period of 27 days beginning in June 1981 and the other covered a period of 60 days beginning in September 1981. Measurements on both of these rods suggested slight erosion, but the measured change was only about 1 cm. This must be considered to be at the limit of resolution of these devices, however, and the data are inconclusive. Sand ripples had been observed at this site by divers, and migration ripples past the devices could account for such a change. The level of the sliding carriage on each rod had lowered by 2 cm or 1 cm below the sand surface. This may indicate that the sand had been disturbed to a depth of 2 cm but this interpretation is subject to the same uncertainties and can not be conclusive. If any erosion occurred during these periods it must have been less than 1 cm and the maximum depth of disturbance of the sand layer must have been less than 2 cm. There are no other data available to suggest how deep into the sediment a storm disturbance might extend. On the submerged shoreface off the exposed coast of Long Island the depth of disturbance may be as deep as 1 m (Sanders and Komar, 1975). On the Atlantic shelf off the mouth of Chesapeake Bay disturbance by currents (as well as by organisms and fishing activity) is limited to about the upper 30 cm of the sediment layer (Hands and DeLoach, 1984). In the protected Lower Bay, however, the depth of disturbance should be much less than it is at these exposed locations.

Another way to estimate the depth of disturbance of surficial sand by waves may be based on correlations that have been observed between the suspended sediment concentrations and the wave-induced water velocity at the sea floor (Lesht et al., 1980). During an experiment off the south shore of Long Island, a relationship was found between the wave velocity at the sea floor and the suspended sediment concentration in the water column. At one location, for example, wave-induced current velocities of 18 cm/sec caused a change in the suspended sediment load of 45 mg/l. These were the largest values of the wave-induced velocities and the suspended sediment concentration that were measured in this study. The water depth at the location where the measurements were made was 10 m. The bottom sediments here were sand containing 5% fine-grained sediment. If we assume that the suspended sediment concentration increases because fine-grained particles are washed from the sand by the wave-induced water motions and that the suspended sediment concentration in the water column is always uniform, then the depth of disturbance of the sand is only a few centimeters.

Cores taken in silts in Long Island Sound showed that after a hurricane the estuarine muds in 14 m of water had been disturbed to a depth of 2 cm (Aller and Cochran, 1976). The changes in the suspended sediment load in the water column over a tidal cycle there could be accounted for by the resuspension of less than 1 mm of the silty sea floor; the greatest suspended sediment concentrations here were observed during a gale and could be accounted for by the resuspension of about 3 mm of the Sound floor (Bokuniewicz and Gordon, 1980b). Similar measurements of the changes in the suspended sediment load over a tidal cycle in New York Harbor coresponded to the resuspension of a layer of silt between 0.6 and 3.2 mm thick which was comparable to the thickness of observed sedimentary laminations and the liquified (oxidized) layer at the sediment-water interface here (Olsen, 1979).

The cap should also be sufficiently thick so that burrowing animals will not reach the mud. The burrowing capabilities of the infaunal species will determine the depth to which sediment reworking will occur. It has been reported in many studies that the majority (50-85%) of the macrofauna is in the upper 10-15 cm of the substrate with some species burrowing to depths of 30-60 cm (Myers, 1979; Pratt and O'Connor, 1973; Guinasso and Schink, 1975; Arrhenuis, 1963; MacGintie, 1939; Molander, 1928). These studies range from intertidal to abyssal communities; however, their results on depth of burrowing are all very similar. Pratt and O'Connor (1973), for example, found that in nearby Long Island Sound, most benthic species occurred at depths of less than 10 cm but two species penetrated to depths of 30 cm. Also in Long Island Sound, Germano (1983) examined the vertical distribution of infauna collected with 30 cm-long cores. Core segments 1 cm thick and 17.71 square centimeters in area were sieved through a 250 micron screen. Germano (1983) found on the average less than one animal per segment below depths of 10 cm.

Some information on depth of burrowing is available for specific taxonomic groups. Stanley (1970) studied the life habits of 95 species of western Atlantic bivalves. These included 8 of 12 species found in the recent study of the Lower Bay (Cerrato and Scheier, 1984). Depth of burrowing was measured as the distance from the sediment surface to the shallowest point on the shell. Of the 95 bivalve species, none burrowed below 22 cm (Stanley, 1970). For polychaetes common to the West Bank of the Lower Bay, data in Cerrato and Scheier (1984) indicate that at least two genera are deep burrowers. These are Glycera and Nereis. Both groups are probably restricted for the most part to the upper 30 cm. Maximum burrowing depths, however, should be restricted to burrows in cohesive sediments in which long vertical burrow walls can be supported; in a non-cohesive sand cap the range of deep burrowers will be limited by the inability of the substrate to support the burrows (L. Stewart, Univ. of Conn., 1984, pers. comm.). The northern lobster, Homarus americanus, is reported to build U-shaped burrows extending 20 cm below the surface of the sediment. These burrows can only be constructed in a mud substrate which is firm enough to support the tunnel (Berrill and Stewart, 1973; Cobb, 1976). On smooth sands such as those of the West Bank, the lobster will dig a shallow saucer-shaped depression about 10-15 cm deep (Richards, 1981, Univ. of Rhode Island, pers. comm.). No other deep burrowing crustaceans such as mud shrimp have been reported in this area (Brinkhuis, 1980).

Nichols et al. (1978) conducted in situ experiments to investigate the response of natural assemblages of benthic invertebrates to anisotrophic burial. All work was carried out in Buzzards Bay, MA. Small areas of the bottom were isolated in open boxes or tubes and covered with various thicknesses of macrofauna-free, native sediment. At 30 cm thick, they determined that no animals even attempted to crawl up through the burying sediment. Nichols et al. (1978) suggest that animals fail to initiate upward movement when the "overburden stress," a measure for quantifying the pressure exerted on an organism by burial, exceeds a critically high level.

Kranz (1974) examined the escape response of bivalves to anistrophic burial. The escape potential, the maximum depth of burial that an organism can successfully escape and reestablish itself, was determined in the laboratory for 25 species. For all cases reported, the escape potential exceeded normal living depth.

While not confirmed for the majority benthic taxa, it is reasonable to suppose that for most animals, the escape potential would be comparable to or exceed natural living depth. Otherwise, benthic organisms would not be capable of escaping sedimentation events caused by severe storms or current, wave, and tidal erosion. Given this assumption, the findings in Nichols et al. (1978) suggest that macrofauna in Buzzards Bay are restricted to the top 30 cm under normal conditions.

Question 9

How effectively will the sand cap contain contaminants?

Here we are concerned with the release of dissolved contaminants and with the uptake of dissolved contaminants by organisms. The sand cap is expected to reduce the migration of metals and organic contaminants from the underlying mud deposit. Studies both here and in Japan have shown that sand caps decrease the release of both nutrients and contaminants from the capped deposits (O'Connor, 1982 and Brannon et al., 1984a,b).

The most rapid fluxes of dissolved chemicals will be associated with dewatering due to consolidation. After the expulsion of pore water, dissolved chemicals could diffuse upward but diffusive fluxes are usually very small. As pore water is expelled from the contaminated mud it will displace the existing pore water in the uncontaminated cap. The cap may have sufficient pore space to contain all the water expelled from the capped layer and prevent its release into the overlying water. If the porosity of the cap is equal to the porosity of the mud and if the thickness of the cap is at least as great as the expected settlement then the cap should be a sufficient reservoir to contain all the pore water expelled by the consolidation of the mud.

In laboratory tests using contaminated sediments over a 40-day period, a cap 22 cm thick prevented the transfer of dissolved oxygen, ammonium and nitrogen across the cap and a cap 50 cm thick is effective in preventing the transfer of PCBs, PAHs, and heavy metals across the cap even in the presence of severe bioturbation although unusually deepburrowing polychaetes (e.g. Nereis) can penetrate caps 50-cm thick (Brannon et al., 1984a,b). The flushing of ground water through the deposit is another mechanism by which dissolved constituents may be released into the bay water. Fresh water probably does percolate across the bay floor. This phenomenon has not been studied in the bay, but other research indicated that the seepage of ground water across the sea floor should be concentrated in a band within a few hundred meters of the shoreline (Bokuniewicz, 1980). Borrow pits are unlikely to be found within this zone of rapid ground-water seepage; the pits on the West Bank are not. Far from shore the advection of pore water should be very small or nonexistent. In addition, the mud deposit will have a low permeability and, as a result, any ambient advection of pore water will be retarded through the deposit or restricted to channels between blocks of dredged mud. After consolidation, therefore, the release of dissolved contaminants through the pore water should not occur at exceptionally great rates.

In the bottom, most of the metals of environmental concern are bound to sediment as reduced compounds. In fine-grained estuarine sediments, typical of the dredged materials considered here, sediment pore waters develop a chemical microenvironment determined largely by the interaction of various sediment-associated constituents, principally organic compounds, and sulfur. The bacterial oxidation of organic matter in sediments quickly utilizes any free oxygen in the sediment upper layers and the pore water environment approaches an oxygen-free state. Below this depth sea water sulfate is utilized to oxidize organic matter by sulfate reducing bacteria and abundant free sulfur is released. Thomson et al. (1975) pointed out that the dissolved levels of trace metals that form insoluble sulfide compounds in equilibrium with these conditions must be extremely low, indicating a small chemical mobility for trace metals in reducing sediment. Included in this group are all the major pollutant metals--copper, zinc, cadmium, mercury and lead. Under the same conditions iron and manganese, which are naturally abundant and form soluble sulfide compounds, migrate to the sediment surface where they become oxidized and partially precipitate insoluble oxides and partially diffuse into near bottom waters (Matisoff et al., 1975). These continually forming ferro-manganese oxides are effective at co-precipitating other dissolved metals at the sediment-water interface (Khalid et al., 1978). Organic compounds in the sediment, present as intermediate products of bacterial decay, are also effective at binding metals (Nriagu and Coker, 1980). According to Turekian (1974) "The best informed conclusion must be that as far as metals are concerned, what has been deposited with the dredge spoil has little chance of leaching out of the sediment. The problems of polluted dredge spoil dumping are thus more concerned with mobilized toxic organic compounds and changes in the physical character of the substrate than with the potentially toxic heavy metals."

The mud that is naturally accumulating in the pits is geochemically very similar to muds dredged from the harbor. Table 1 compares the concentration of metals found in the north pit with those in the Upper Bay (Williams et al., 1978), in dredged sediment at the Mud Dump Site (Carmody et al., 1973; Dayal et al., 1981), in mud from Shooter's Island Channel, Newark Bay (Suszkowski, 1978), New York Harbor and dredged sediments (Williams et al., 1978; and Connor et al., 1979, as reported in Dayal et al., 1981) suspended sediments in the water of Lower Bay, and the highest values from Raritan Bay (Grieg and McGrath, 1977), muds in the Passaic River (Multer, 1978 as reported in Olsen et al., 1984) and from the Hudson Estuary within 11 miles of the Battery (Olsen et al., 1984). The mud deposits in the pit may therefore be examined to learn how the deposit of dredged mud in the second stage of the demonstration project might behave geochemically if we remember that the natural pit deposits are not capped while the muds in the demonstration project will be capped with sand. Detailed geochemical studies have been done on muds that are accumulating in the pits. There is no significant variation in the vertical distribution of most trace metals in the mud layers on the pit floors. This indicates that the natural supply of trace metals on sediment to the pits has not changed significantly over the last 13 years and that the sediment currently accumulating in the pits is general resuspension of harbor bottom sediments. The concentrations of all trace metals, except for manganese, on the suspended sediment in the overlying waters are

Table 1. Concentrations of selected metals in the sediments of New York Harbor and vicinity.

Location	Ag	Cd	Cr	Cu	Co	Mn	Pb	Ti	Zn	Ni	Fe
	µg/gm										%
N. Borrow Pit[1]	6.9±0.5	5.2±0.2	207±17	203±2	26.2±0.4	680±17	319±3	355±20	359±8	52±2	3.15±0.004
Shooters Island[1]	12.2±0.6	12.2±0.2	480±10	550±9	28.4±0.8	415± 5	446±6	257±51	680±23	47±1	3.40±0.1
Mud Dump[2a,b]	NA	1.6[a]	106[b]	76[a], 141[b]	NA	261[a]	68[a], 144[b]	NA	NA	24[b]	1.99
NY Harbor & Hoppers[3]	NA	3.6	NA	180	NA	420	134	NA	NA	NA	3.5
Upper Bay[4]	NA	NA	NA	248	NA	550	202	NA	337	NA	3.3
Raritan Bay[5]	NA	12.8	227	812	NA	667	565	NA	617	44.3	NA
Newark Bay[6]	NA	10.6	247	318	NA	NA	315	NA	497	43.5	NA
Suspended Sediment in Lower Bay*	8.4	8.0	258	322	376	568	376	NA	NA	69	4.15
Inner Harbor[7]	NA	NA	NA	220	NA	NA	390	NA	315	NA	NA
Passaic River mud[8]	NA	22.3	913	NA	29	NA	1784	NA	991	216	0.23

NA - Not Available

* Material in near-surface sediment traps

1. D. Hirschberg, pers. comm. in letter to John Tavolaro of 24 March 1982

2a. Dayal et al., 1981

2b. Carmody et al., 1973

3. Williams et al., 1978 and Conner et al., 1979 as reported by Dayal et al., 1981

4. Williams et al., 1978; top 5 cm of one core.

5. Average of the three highest values of Grieg and McGrath, 1977, from a copy of the data set supplied by R. Reid, National Fisheries Service, 1984.

6. Suszkowski, 1978

7. Olsen et al., 1984, The "Inner Harbor is defined as the Hudson Estuary downstream of mile point 11"

8. Multer, 1978 as reported by Olsen et al., 1984

generally higher than the values found in the bottom sediments. This may be due to size or density fractionation of the suspended material because of the association of metals with low density organic matter. As a result, it is unlikely that the pits are acting as sources of metals to the overlying water by the resuspension of pit muds. In contrast to the other metals, however, the concentration of manganese was found to decrease away from the sediment-water interface in the pit both above the bottom in the water column and below the bottom in the sediment. This indicates that manganese, which is soluble in its reduced state, is diffusing out of the bottom sediments and adding to the suspended particulates in the water column. We believe that the restricted circulation in the pit causes the oxidation-reduction interface that would normally be found in the bottom sediment to be displaced upwards into the water column. As a result the sediment in the pit could be contributing excess manganese to the overlying water. Filling the pit and capping would reduce the residence time of the near-bottom water, displace the oxidation-reduction interface down into the sediment, and prevent the escape of most manganese to the water.

The amounts of iron, manganese, and copper dissolved in the pore waters of the pit's mud deposits were also examined. The concentration of chemical species in the pore water is very low. The distribution of iron and manganese was irregular with depth ranging from 1.2 to 20.3 ug/ml for iron and from 3.6 to 7.9 ug/ml for manganese. Copper concentrations, however, decreased rapidly with depth from 20 ug/ml at the surface of the core to about 2 ug/ml at a depth of 10 cm. This seems to indicate rapid removal of dissolved copper onto the sediment particles.

Releases of nutrients from dredged material during and subsequent to disposal occur as the result of dilution of sediment pore waters with receiving water, and subsequent expulsion of this water during consolidation of the disposal pile. Nitrogen compounds are of greatest concern, being at already high levels in the proposed receiving waters. The principal nitrogen species in fine-grained, reducing sediment is ammonium.

Subsequent to disposal, as the pile consolidates, expulsion of pore waters will cause a local source of excess nutrients until consolidation is complete. The potential impact of this on overlying waters can be assessed by comparison with the natural rates of nutrient regeneration from the bottom. As an example of such a comparison, let us assume that we have constructed a deposit of dredged sediment consisting of a layer of mud 2 m thick overlain by a 1 m thick sand cap. The surface should settle about 10% based on the laboratory consolidation tests discussed earlier. We might also assume that the consolidation will be mostly complete after 100 days. During this time an average of approximately 200 l of pore waters per square meter of the pile will be expelled. For a disposal mound of area 126,000 square meters (radius = 200 m) this will result in the eventual release of about 25 million liters of pore water. All the water originating from the underlying mud deposit would be contained in the pores of the sand cap and some of the water previously in the cap would be released to the bay. If these waters contain 6,000 um/l ammonium, a very high estimate (values of less than 1,000 or 2,000 um/l are more likely), then a total release of 150 billion um of ammonium will result. The present contribution of ammonium by the Hudson and Raritan rivers has been crudely estimated at 90 billion um/hr (Rowe et al., 1975) and just the Hudson River at 5 billion um/hr (O'Connors and Duedall, 1975). The total release of ammonium from the pilot disposal mound over a 100-day period is approximately equal to the contribution of ammonium by the Hudson River in one day. It would seem that such a project could not have a regional effect but potential, local effects should not be ignored.

For all the reasons discussed above the releases of dissolved contaminants through an adequate capping layer should be very slight. Nevertheless, benthic organisms that recolonize the cap will be exposed to those dissolved chemical species that do percolate or diffuse to the surface layer of the cap. Initially, most of the colonizing organisms will be small polychaete worms and isopods/amphipods, depending on the time of year of the operation. These organisms will burrow into the sediment, aerating and irrigating it during the construction and maintenance of their burrows. In effect, this might further introduce dissolved and sediment-associated contaminants by changing equilibrium concentrations beyond that caused by consolidation. These organisms will be exposed to these contaminants, and may concentrate them in their tissues. Since these organisms are food for other bottom dwelling invertebrates and fishes, the potential of further concentration exists.

At the New London dredged sediment disposal site in Long Island Sound, the blue mussel Mytilus edulis and the hard clam Mercenaria mercenaria were used as monitors of biological uptake of metals (Brown, 1979). In the same study, the oyster Crassostrea virginica was used for the same purpose near the dredging site. The study areas were stocked with groups of monitor organisms in polypropylene mesh bags that were suspended from a PVC rack one meter above the sea floor. The study began before dredging in March 1977 and continued until March 1979, nine months after the disposal operation was complete. The populations were subsampled monthly (or bimonthly depending upon the dredging activity) and analyzed for cadmium, chromium, copper, nickel, lead, zinc, and mercury. Of these six heavy metals, zinc was the most concentrated by the bivalve molluscs. The concentration of zinc in the oyster tissue was nearly two orders of magnitude higher than that in the other species. The strongest effect, however, was the concentration of nickel by mussels. Temporal variations in nickel concentration correlated with both the disposal activity and the seasonal runoff. These variations were seen at all stations including the reference stations. Increases in the metal levels could be associated either with the disposal operation or the natural increase in runoff or both. Concentration of heavy metals in the monitor organisms returned to normal levels quickly after the disposal operation was completed and after runoff decreased. The investigators in this study concluded that little or no adverse effects were due to the disposal operations. In addition, because the concentrations of metals in the test animals returned to normal, it would seem that there was no transfer of metals from the mound of dredged sediment at the disposal site to the monitor organisms subsequent to the disposal operation.

Two other studies have recently been completed which compare the contamination of organisms at the Mud Dump Site, at a site in Gravesend Bay, and at a control site (Pequegat et al., 1980; Tifft et al., 1979). Both of them looked at the concentration of heavy metals and chlorinated hydrocarbons in organisms from each of the study areas. One study (Pequegat et al., 1980) examined fishes, bivalve molluscs, a shrimp, and a worm, and the other (Tifft et al., 1979) studied lobsters. The investigators in both of these studies concluded that biological contamination is not localized at the disposal site. Organisms in Gravesend Bay were at least as contaminated as those at the Mud Dump Site. As a result, we may not expect to see significant contamination of organisms that might recolonize a particular deposit of dredged sediment above the ambient levels unless the deposit was exceptionally highly contaminated with some chemical species.

The population that recolonizes the cap of the demonstration project will be likely to include polychaetes that are common in the Lower Bay (Fitzpatrick, 1983). In anticipation of monitoring contaminants in the recolonizing organisms, the body-burdens of cadmium, copper, iron, manganese, nickle, lead, and zinc were monitored seasonally over a year in polychaete worms from a sandy control area near Old Orchard Shoal about 1 n. mile to the WSW of Borrow Pit No. 1. Cadmium values ranged between 2.5 and 13 ug/gm dry wt, copper between 150 and 460, iron between 1200 and about 3300, manganese between 17 and about 880, nickle between 21 and 114, lead between about 8.6 and 92 and zinc between 340 and 2250 ug/gm dry wt. Seasonal patterns were seen with concentrations of cadmium, copper, nickle and zinc reaching maximum values in the late winter and early spring and minimum values in the midsummer. Iron and manganese reach maximum values in the fall and minimum values in the winter. The composition of the body-burdens found here are comparable to those found in benthic organisms in other stressed environments.

Question 10

Once the sand layer is in place will it be mechanically stable?

It is technically feasible to construct a stable deposit of mud, of the type that is typically dredged in clamshell dredging operations, capped with sand as long as the heights of irregularities on the sand-mud interface are less than some critical value (Bokuniewicz and Liu, 1981). The critical value is determined by the shear strength and the difference in density between the layers. Such a stable deposit has apparently been constructed in Long Island Sound (Bokuniewicz and Liu, 1981).

From tests on mud from North Shooters Island Channel and sand from Ambrose Channel we estimate that the critical height should be 60 cm. That is to say, that if irregularities on the sand-mud interface of the capped deposit are less than 60 cm high, then the deposit will be strong enough to support them, no deformation should occur, and the cap will be stable against internal deformations indefinitely. For mounds of dredged sediment that have been created by conventional techniques a surface relief of 60 cm is small but not impossible. If the irregularities in our layered deposit are greater than 60 cm high, then we should expect the deposit to deform internally and subsequent work has been directed at predicting the type of deformation that might occur and its rate (Liu, 1982).

The instability of some layered fluids is well known. When a more dense fluid overlies a less dense one, convection cells will form. The less dense fluid flows upward and the more dense fluid flows downward in a series of convection cells that are typically hexagonal in plan and have diameters approximately equal to the thickness of the layer with the lower viscosity. This phenomenon is called Rayleigh-Taylor instability. Mathematical models are available to describe the instability of layered viscous fluids where the upper layer is more dense than the lower layer (Ramberg, 1968; Biot and Ode, 1965) and these have been applied to at least one other geological phenomenon--the formulation of salt domes. Under certain conditions, sediments behave like viscous fluids and these models can be used to describe the deformation of layered sediments. Viscosity is merely an empirical property that describes the behavior of some materials under stress. A viscous material will undergo strain under an applied load at a rate that is proportional to the applied stress. The proportionality constant between the stress and the strain rate is called the viscosity. It has been shown (e.g. Sherif et al., 1980; Ode, 1966) that many soft sediments behave viscously. They are, however, non-newtonian which means that their effective viscosity depends upon the magnitude of the applied stress. From our tests on the North Shooters Island Channel mud we estimate that it has an effective viscosity of 0.1 megapoise under the stress levels that are likely to be encountered in the capped deposit. The sand has an effective viscosity of at least between 0.1 and 10 megapoise under the same conditions. There is more uncertainty surrounding a reasonable value for an equivalent viscosity of sand because deformation of the sand in the laboratory tests was slight. The effective equivalent viscosity of the sand was difficult to measure and, as a result, it may have been underestimated.

Sediments differ from typical viscous fluids in at least two important respects. Sediments have a shear strength and fluids do not; sediments are compressible and fluids are often assumed to be incompressible. Because the sediments have strength they are able to support irregularities up to a certain size without deforming, as we discussed before. As a result, the fluid models can only be applicable if the irregularities on the sand-mud interface are larger than the critical size, preferably much larger. In our case they must be greater than 60 cm high. In addition, to apply the models the sediments should be incompressible. The sand has a very low compressibility and is effectively incompressible. The mud has a higher compressibility but, for our situation, it may be considered to be incompressible for two reasons. First, the consolidation in the deposit that is intended to be built should be less than about 10%. This value is based on laboratory consolidation tests of mud from the North Shooters Island Channel. The second reason is that our subsequent calculations show us that the consolidation proceeds at rates that are greater than the deformation rates predicted by the fluid models. The consolidation is about 75% complete in six months while the internal deformation should occur at much slower rates. This means that the mud is quickly consolidated or fully compressed before the other deformation has proceeded very far; after it has been consolidated, if it continues to deform it will do so as an incompressible material.

Once the strength of the sediment is exceeded, therefore, the assumption that it behaves like a viscous, incompressible fluid is probably not unreasonable. The mathematical models were used to investigate the rates of internal deformation for a hypothetical deposit in which the irregularities on the sand-mud interface were greater than the critical value. Based on our predictions of the deposit's geometry, we chose the irregularities to be 150 cm high and to have a peak-to-peak spacing of about 200 m. The deformation rate does depend on the wavelength of the irregularities, but for our case, the rates of deformation are not sensitive to changes in the wavelength. Based on our laboratory tests, the mud was assumed to have a density of 1.2 gm/cubic centimeter and a viscosity of 0.1 megapoise. The sand was assumed to have a density of 2.2 gm/cubic centimeter and a viscosity of 10 megapoise. The mud layer was assumed to be 2 m thick and overlain with a layer of sand 1 m thick. We believe this is a reasonable approximation of the proposed deposit and may be conservative because the effective viscosity value for sand may have been underestimated.

The results show that the irregularities tend to decrease in height as the deposit ages. The irregularities on the sand-water interface, however, tend to flatten out more quickly than the ones on the sand-mud interface. As a result, if the mean elevation of the sand-water interface is above the maximum elevation on the sand-mud interface, the cap cannot be disrupted by internal deformations. In our example, this was not the case. In time the distances between the peaks in the sand-water interface and those in the sand-mud interface decreased. The peaks converged and, in our example, the peaks in the sand-mud interface reached the sand surface before the height of the irregularities had been reduced to 60 cm and the deposit consequently immobilized. In the model calculations, it took 40 to 50 years for the cap to be penetrated. If such a deformation occurs, it may be necessary, therefore, to schedule periodic maintenance for the sand cap. The deposit, however, should be monitored because, as we said earlier, the use of an equivalent viscosity for sand is uncertain and appears to be underestimated. If the sand's effective equivalent viscosity is an order of magnitude higher than we assumed, the lifetime of the cap would be about 400 or 500 years instead of 40 to 50 years.

The cap should also be monitored for erosion. The surface stability of the sand cap at the Mud Dump Site has been investigated by Freeland et al. (1983). Models of the response of the sand cap under normal conditions on the open shelf there showed that potential erosion rates were slow and that a cap 0.3 m thick could be expected to have a lifetime of between 18 and 46 years. Severe storms, however, could cause erosion and possible breaching of the cap. Maintenance or armoring of the cap with coarser material may be needed to insure its integrity. For the intended demonstration project in the Lower Bay, however, the surface of the cap is intended to be below the level of the ambient sea floor and of similar material. As a result, we should not expect mass erosion to strip the cap off the underlying mud. Some erosion, however, may tend to smooth the cap surface by eroding peaks in the irregularities of the sand-water interface and depositing that material in the depressions. In other studies, this has been shown to increase the rate of internal deformation and may accelerate instabilities if they exist (Biot and Ode, 1965). The surface stability of the cap deserves careful monitoring.

Question 11

What will be the effects of gas generation on the stability of the deposit and the release of contaminants?

Gas (probably methane) may be generated within the deposit at a rate sufficient to produce bubbles. We have completed one experiment to measure the rate at which muddy sediment from Borrow Pit No. 1 produces gas. Half of a liter of mud was incubated in a closed, sea-water system. The incubation was done in the dark at room temperature and gas was generated at a constant rate of about 2.5 ml of gas/liter of sediment/day. This gas was analyzed on a gas chromatograph and found to consist of 60% methane, 8% carbon dioxide, 6% oxygen, 4% nitrogen, and 0.5% hydrogen. The rate of gas generation varies with changing temperature. We measured the rate of gas generation at 0, 12, 16, 20, and 26 degrees Centigrade to be 0, 0.4, 1.3, 2.5, and 5.7 ml of gas/liter of sediment, respectively. Rates at other temperatures can be predicted from the Arrhenuis relationship using an average value for the activation energy of 31.3 Kcal/mole that we determined from our experiment.

If the cap is sand, the gas pressure should not reach levels sufficient to mechanically disrupt the cap. There are two reasons for this. First, the cap should be permeable enough to allow any bubbles that form to migrate and to escape (Nelson et al., 1979). The second reason is that we expect the bubbles to dissolve in the undersaturated pore water of the sand cap (C. Martens, Univ. of South Carolina, 1981, pers. comm.). The migration of bubbles in the deposit will enhance the transport of dissolved chemical species in the pore water, but we do not anticipate that the increased transport rates will present a serious problem.

The presence of bubbles in the mud may increase the pore pressure and reduce the strength of the deposit (e.g. Whelan and Lester, 1979). This phenomenon deserves attention, but we do not expect it to be a serious problem. As far as we know, the generation of gas has not caused any mechanical failures at any other deposit of dredged sediment nor has it been perceived to be a problem at the capped deposits in Long Island Sound or at the Mud Dump Site. Radiographs of vibracores taken through the capped deposit at the Mud Dump Site do not show gas bubbles or evidence of gas turbation in the mud deposit. Furthermore, we believe that the mud deposit in the proposed demonstration project will be composed of clods or blocks of mud (Bokuniewicz and Gordon, 1980a). Although the permeability of the individual blocks should be low, the interstices among the blocks should provide escape routes through which gas bubbles could migrate more rapidly to the cap. As a result, we would not expect unusually high gas pressures to pervade the deposit.

Question 12

How do borrow pits affect the abundance and distribution of fishes?

In general, fish species composition in the Lower Bay and patterns of abundance of the major species are typical of mid-Atlantic estuaries (Berg and Levinton, 1985). However, the Lower Bay complex has lower overall fish densities and fewer species than nearby estuaries, and benthic-feeding species are relatively underrepresented (Berg and Levinton, 1985).

Three fishery studies were specifically done to assess the resource at West Bank borrow pits and to compare these to other locations within the Lower Bay (Conover et al., 1985, Pacheco, 1983; National Marine Fisheries Service, 1984). Since the studies differed in methods and sampling locations, a brief description of each one is necessary prior to discussing the catch data.

Conover, et al. (1985) collected fish using a 30-foot by 37-foot semi-balloon otter trawl constructed with 2-inch mesh wings and a 1/4-inch cod-end liner. Three five-minute trawls were taken approximately monthly between February 1982 and January 1983. Three locations were studied in the Lower Bay (Fig. 2):

<u>Control</u> <u>site</u> - This locality is approximately 2 km (1.1 nm) southwest of the West Bank pit (i.e. Borrow Pit No. 1). The sediments are predominately medium- to fine-grained

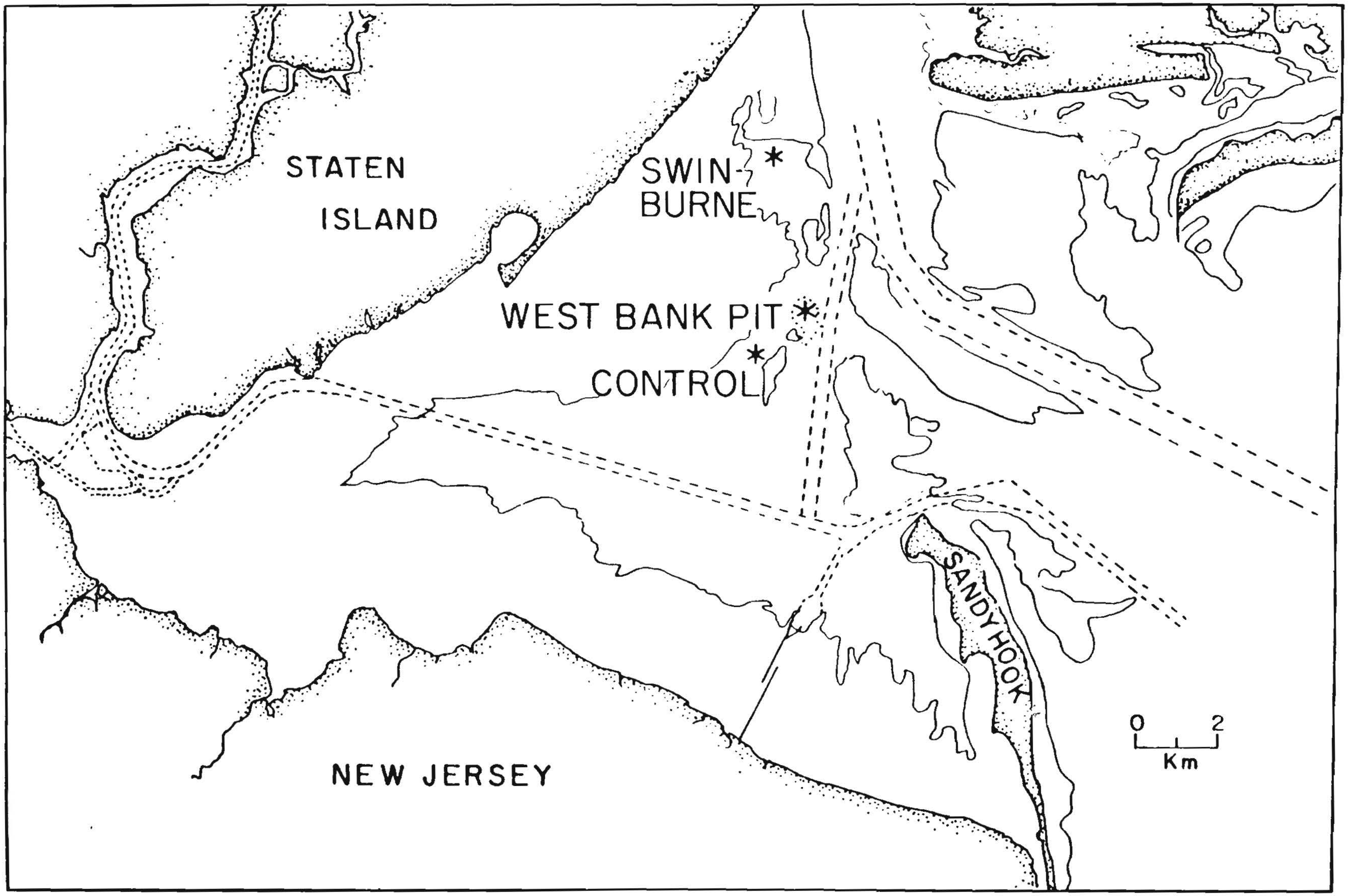

Fig. 2. Fishing sites of Conover et al. (1985).

sands (Gandarillas and Brinkhuis, 1981), and the water depth is approximately 6 m (20 ft).

Swinburne site - This is a large borrow pit on the West Bank south of Swinburne Island. The bottom is muddy, and the water depth is approximately 8 m (26 ft).

West Bank pit - Depth ranges from 10 to 16 m (33 to 53 ft) along the transect, and the bottom sediments consist of fine-grained, organic-rich material (Swartz and Brinkhuis, 1978). This location is identified as Borrow Pit No. 1 in other sections of this report.

Pacheco (1983) sampled the fish populations using a 10 m (33 ft) otter trawl constructed of 1.5-inch stretched mesh throughout. One twelve-minute tow was collected approximately bi-weekly at each sampling locality. This survey, conducted by the National Marine Fisheries Service (NMFS), was carried out between September 1981 and October 1982 at the following stations (Fig. 3):

C11 site (Station 1) - This location is immediately south of the West Bank pit and west of the Chapel Hill Channel buoy C"11". The bottom is undredged, approximately 7 m (23 ft) deep, and consists of fine sand.

Swinburne site (Station 2)

West Bank pit (Station 3)

Beginning in November 1982, the National Marine Fisheries Service survey was extended and expanded to include five additional stations (National Marine Fisheries Service, 1984). Methods were identical to the earlier study. Trawls were bi-weekly between November 1982 and October 1983 at the following locations (Fig. 3):

C11 site (Station 1)

Swinburne site (Station 2)

West Bank pit (Station 3)

Sandy Hook Bay (Station 4) - This location has a soft, muddy bottom and is about 7 m (23 ft) deep.

East Reach (Station 5) - This transect is within the Raritan Bay East Reach Channel between buoys R"6" and N"8". The controlling depth is 11.6 m (38 ft) and the bottom is silty mud.

Great Kills (Station 6) - This site is on Old Orchard Shoal in about 5 m (16 ft) of water, and it has a hard sand and shell bottom.

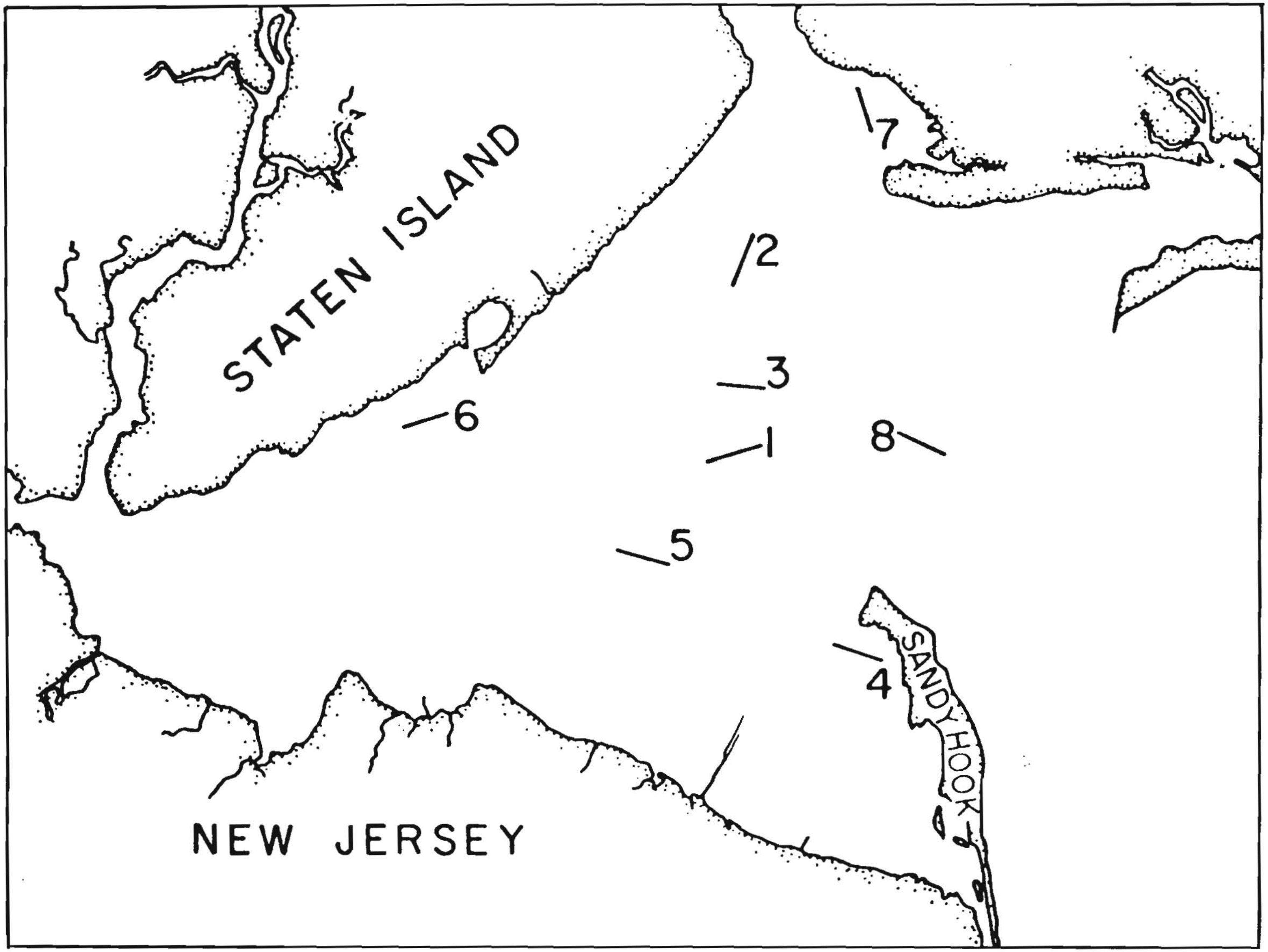

Fig. 3. Fishing sites of Pacheco (1983). Line indicates trawl length and orientation.

Gravesend Bay (Station 7) - Trawls were taken at a depth of about 9 m (30 ft), over a sticky, mud bottom.

Romer Shoal (Station 8) - Water depth ranges from 5 to 6 m (16-20 ft), and the bottom is hard sand and shell.

Two sampling stations, the West Bank pit and the Swinburne site, were common to all three studies. The data collected by Conover, et al. (1985) and the National Marine Fisheries Service are, however, not directly comparable because of differences in trawl duration and mesh size. The trawl used by Conover, et al. (1985), with 2-inch wings and a 1/4-inch cod-end liner, was probably more efficient at catching small fish and juveniles of larger species than the 1.5-inch mesh trawl used by Pacheco (1983) and National Marine Fisheries Service (1984).

A composite species list for the study by National Marine Fisheries Service (1984) is given in Table 2. A total of 54 fish species were collected. This table represents a fairly complete list of fish taxa caught in all three studies. Including the data in Conover, et al. (1985) and Pacheco (1983) results in the addition of four more species of fish. These are the lookdown, American sand lance, inshore lizard fish, and sea horse.

Catch per tow data were tested using statistical analyses based on Friedman rank sums. See Appendix I for a description of the test procedures. For each of the three fish surveys, sampling stations were found to differ at a 0.05 level of significance. The West Bank pit had the highest average rank in all studies (Table 3). The Swinburne site ranked second in the studies by Conover, et al. (1985) and Pacheco (1983), and it had the fourth highest average rank in the study by National Marine Fisheries Service (1984). A multiple comparisons test, using an experimentwise error rate of 0.10, was also carried out on each survey (Table 3). The West Bank pit and the Swinburne site were not significantly different. The West Bank pit and the Swinburne site were generally found to be significantly different from the Control site, C11, Great Kills, and Romer Shoal. However, they did not differ significantly from Sandy Hook Bay, East Reach, and Gravesend Bay in terms of overall mean catch per tow.

Based on Friedman rank sums tests, sampling stations for each of the three studies were found to differ in overall mean number of species per tow at a 0.05 level of significance. The West Bank pit had the highest average rank in all studies (Table 4). The Swinburne site ranked second in the studies by Conover, et al. (1985) and Pacheco (1983), and it had the fourth highest average rank in the study by National Marine Fisheries Service (1984). A multiple comparisons test with an experimentwise error rate of 0.10 was also carried out on each data set. The West Bank pit and the Swinburne site differed significantly from the Control site, C11, Great Kills, and Romer Shoal. The Swinburne site and the West Bank pit did not differ in two of the three studies. In addition, no differences were found either between the West Bank pit or the Swinburne site and Sandy Hook Bay, East

Table 2

Station Totals from NMFS (1984)

	1	2	3	4	5	6	7	8	TOTAL
Fish									
Smooth dogfish		16			1		7	1	25
Clearnose skate					1				1
Atlantic sturgeon		1			9		9		19
Atlantic herring	1		1		1		7		10
Alewife	32	349	83	54	94		31	3	646
Blueback herring	19	12	1	7	4	2	41	4	90
American shad	97	14	6	18	4	27	4	2	172
Atlantic menhaden					2		1		3
Hickory shad			1		3				4
Gizzard shad			1		6				7
Bay anchovy	58	342	90	313	3040	18	143	1	4005
Striped anchovy		1		8			2		11
Silver hake	4	131	325	17	355		9	20	861
Pollock							1		1
Atlantic tomcod	1	5			2		66		74
White hake		1	9		24				34
Red hake	31	78	2259	68	978		65		3479
Spotted hake		13	62	4	11			1	91
Fourbeard rockling			1						1
Summer flounder	9	7	8	84	26	1	14	4	153
Fourspot flounder	4	7	23	2	7	63	11	5	122
Winter flounder	222	359	782	756	1203	322	1532	150	5326
Windowpane	48	198	151	85	149	45	58	64	798
Atlantic silverside	1	1				2	8	1	13
Lined seahorse				2					2
Northern pipefish		1		2	1	1			5
Smallmouth flounder	2		1	1		33	2		39
Hogchoker			2						2
Atlantic mackerel	1								1
Butterfish	16	804	73	48	191	3	182	22	1339
Atlantic moonfish		6							6
Crevalle jack					1				1
Bluefish	1	8		7	8		2	3	29
Striped bass	1						2		3
Black sea bass			1		5			3	9
White perch							1		1
Scup	28	6	41	28	2	41	211	81	438
Weakfish	5	50	296	11	442	3	3	5	815
Spot					14		2	1	17
Longhorn sculpin	2	1	9	3	16	3		2	36
Sea raven	1		2	1	2		4		10
Grubby	5	13	10	11	164	15	37	14	269
Northern searobin			3				2	2	7
Striped searobin	2	1	5	10	12		2	2	34
Cunner	7	5	3	5	3	2	5	28	58
Tautog	18	2	15	22	5	14	6	43	125
Rock gunnel						2			2
Striped cusk eel		1	1	1					3
Fawn cusk eel			1						1
Northern puffer			1						1
American eel		2	2	4	9				17
Conger eel				4					4
Ocean pout			1					1	2
Oyster toadfish	1			3					4
Total # Individuals	617	2435	4270	1579	6795	597	2470	463	19226
Total # Species	27	30	34	29	35	18	32	25	54
Invertebrates									
American lobster	2	83	102	16	102	5	716	1	1027
Rock crab	59	349	845	1220	234	627	382	175	3891
Blue crab	7	11	15	45	5	7	15	3	108
Jonah crab					2				2
Spider crab	1		18	7	1	4	2	1	34
Horseshoe crab	8	9	38	22	14	6	26	3	126
Lady crab	521	1072	623	158	53	553	1181	318	4479
Total # Individuals	598	1524	1641	1468	411	1202	2322	501	9667
Total # Species	6	5	6	6	7	6	6	6	7

Table 3

Statistical analyses of catch per tow data using nonparametric tests based on Friedman rank sums. Ranks assigned from lowest to highest values.

1) Data from study by Conover, et al. (1985)

	West Bank pit	Control site	Swinburne
West Bank pit	--		
Control site	**	--	
Swinburne	ns	ns	--
Average Ranks	2.50	1.30	2.20

2) Data from study by Pacheco (1983)

	C11	Swinburne	West Bank pit
C11	--		
Swinburne	**	--	
West Bank pit	**	ns	--
Average Ranks	1.08	2.25	2.67

3) Data from study by NMFS (1984)

	C11	Swinburne	West Bank pit	Sandy Hook Bay	East Reach	Great Kills	Gravesend Bay	Romer Shoal
C11	--							
Swinburne	**	--						
West Bank pit	**	ns	--					
Sandy Hook Bay	ns	ns	ns	--				
East Reach	**	ns	ns	ns	--			
Great Kills	ns	**	**	ns	**	--		
Gravesend Bay	**	ns	ns	ns	ns	**	--	
Romer Shoal	ns	**	**	**	**	ns	**	--
Average Ranks	2.86	5.19	6.76	4.88	5.62	2.98	5.74	1.98

** = Tested and found to be significant at a 0.10 experimentwise error rate.

ns = Tested and found to be not significant at a 0.10 experimentwise error rate.

Table 4

Statistical analyses of species per tow data using nonparametric tests based on Friedman rank sums. Ranks assigned from lowest to highest values.

1) Data from study by Conover, et al. (1985)

	West Bank pit	Control site	Swinburne
West Bank pit	--		
Control site	**	--	
Swinburne	ns	**	--
Average Ranks	2.55	1.20	2.25

2) Data from study by Pacheco (1983)

	Cll	Swinburne	West Bank pit
Cll	--		
Swinburne	**	--	
West Bank pit	**	**	--
Average Ranks	1.21	2.04	2.75

3) Data from study by NMFS (1984)

	Cll	Swinburne	West Bank pit	Sandy Hook Bay	East Reach	Great Kills	Gravesend Bay	Romer Shoal
Cll	--							
Swinburne	**	--						
West Bank pit	**	ns	--					
Sandy Hook Bay	**	ns	ns	--				
East Reach	**	ns	ns	ns	--			
Great Kills	ns	**	**	**	**	--		
Gravesend Bay	**	ns	ns	ns	ns	**	--	
Romer Shoal	ns	**	**	**	**	ns	**	--
Average Ranks	2.60	5.43	6.64	5.48	6.26	2.38	4.91	2.31

** = Tested and found to be significant at a 0.10 experimentwise error rate.

ns = Tested and found to be not significant at a 0.10 experimentwise error rate.

Reach, and Gravesend Bay in terms of overall number of species per tow.

The weight data in Pacheco (1983) and National Marine Fisheries Service (1984) were analyzed separately using Friedman rank sums tests. Sampling stations differed in overall mean weight per tow at a 0.05 level of significance. Using the data from the Pacheco (1983) study, the West Bank pit had the highest average rank and differed significantly from the C11 site (Table 5). The Swinburne site had the second highest average rank and also differed from the C11 site. In this analysis, the West Bank pit and the Swinburne site were not found to differ. Based on the data collected by the National Marine Fisheries Service (1984) survey, Gravesend Bay had the highest average rank. The West Bank pit was second highest in average rank, and the Swinburne site was fifth highest. In the analysis of the eight stations, the West Bank pit differed significantly from C11, Great Kills, and Romer Shoal. No differences were found between the West Bank pit and either the Swinburne site, Sandy Hook Bay, East Reach, or Gravesend Bay in terms of overall weight per tow. The Swinburne site differed significantly only from Gravesend Bay.

The multiple comparisons tests for catch (Table 3), number of species (Table 4), and weight (Table 5) when analyzed together indicate some consistent similarities and differences between sampling stations. When the National Marine Fisheries Service (1984) data were analyzed, the C11 site, Great Kills, and Romer Shoal were never found to differ among themselves. For the purpose of discussion, this set of stations will be referred to as Group I stations. The remaining stations (i.e., Swinburne, West Bank pit, Sandy Hook Bay, East Reach, and Gravesend Bay) rarely differed when compared to one another. This set will be referred to as Group II stations. In addition, when individual stations between groups were compared, they were almost always found to be significantly different.

Considering the results for the Pacheco (1983) survey, the same grouping pattern emerges for relating the Swinburne site, C11, and West Bank pit. Analysis of the Conover, et al. (1985) data indicate that the West Bank pit and the Swinbure site were again similar, and that both borrow pits were often different than the Control site. Because of this, the Control site will be included in the Group I stations.

The three fish surveys also collected information on a number of environmental parameters (temperature, salinity, and dissolved oxygen). These data were analyzed using the statistical tests based on Friedman rank sums. In almost all cases, sampling stations were found to differ at a 0.05 level of significance. Multiple comparisons tests, using an experimentwise error rate of 0.10, were also carried out on the environmental data. The results are shown in Tables 6 to 8. None of the environmental parameters, when considered separately, group the stations in the same pattern as found in the fish analyses.

Table 5

Statistical analyses of weight per tow data using nonparametric tests based on Friedman rank sums. Ranks assigned from lowest to highest values.

1) Data from study by Pacheco (1983)

	Cll	Swin-burne	West Bank pit
Cll	--		
Swinburne	**	--	
West Bank pit	**	ns	--
Average Ranks	1.33	2.21	2.46

2) Data from study by NMFS (1984)

	Cll	Swin-burne	West Bank pit	Sandy Hook Bay	East Reach	Great Kills	Grave-send Bay	Romer Shoal
Cll	--							
Swinburne	ns	--						
West Bank pit	**	ns	--					
Sandy Hook Bay	**	ns	ns	--				
East Reach	**	ns	ns	ns	--			
Great Kills	ns	ns	**	**	**	--		
Gravesend Bay	**	**	ns	ns	ns	**	--	
Romer Shoal	ns	ns	**	**	**	ns	**	--
Average Ranks	2.83	4.36	6.05	5.38	5.33	2.79	6.48	2.79

** = Tested and found to be significant at a 0.10 experimentwise error rate.

ns = Tested and found to be not significant at a 0.10 experimentwise error rate.

Table 6

Statistical analyses of dissolved oxygen data using nonparametric tests based on Friedman rank sums. Ranks assigned from lowest to highest values.

1) Data from study by Pacheco (1983)

	C11	Swinburne	West Bank pit
C11	--		
Swinburne	ns	--	
West Bank pit	**	**	--
Average Ranks	2.22	2.26	1.52

2) Data from study by NMFS (1984)

	C11	Swinburne	West Bank pit	Sandy Hook Bay	East Reach	Great Kills	Gravesend Bay	Romer Shoal
C11	--							
Swinburne	ns	--						
West Bank pit	ns	ns	--					
Sandy Hook Bay	ns	ns	ns	--				
East Reach	ns	ns	ns	ns	--			
Great Kills	ns	ns	ns	ns	ns	--		
Gravesend Bay	ns	ns	ns	ns	ns	ns	--	
Romer Shoal	ns	ns	**	ns	ns	ns	ns	--
Average Ranks	4.26	5.03	3.11	5.18	3.53	4.58	4.68	5.63

** = Tested and found to be significant at a 0.10 experimentwise error rate.

ns = Tested and found to be not significant at a 0.10 experimentwise error rate.

Table 7

Statistical analyses of salinity data using nonparametric tests based on Friedman rank sums. Ranks assigned from lowest to highest values.

1) Data from study by Conover, et al. (1985)

	West Bank pit	Control site	Swinburne
West Bank pit	--		
Control site	**	--	
Swinburne	ns	**	--
Average Ranks	2.40	1.00	2.60

2) Data from study by Pacheco (1983)

	C11	Swinburne	West Bank pit
C11	--		
Swinburne	**	--	
West Bank pit	**	ns	--
Average Ranks	1.27	2.14	2.59

3) Data from study by NMFS (1984)

	C11	Swinburne	West Bank pit	Sandy Hook Bay	East Reach	Great Kills	Gravesend Bay	Romer Shoal
C11	--							
Swinburne	**	--						
West Bank pit	**	ns	--					
Sandy Hook Bay	ns	**	**	--				
East Reach	ns	ns	ns	ns	--			
Great Kills	ns	**	**	**	**	--		
Gravesend Bay	**	ns	ns	ns	ns	**	--	
Romer Shoal	**	ns	ns	**	ns	**	ns	--
Average Ranks	3.00	5.86	6.31	3.71	4.45	1.24	5.43	6

** = Tested and found to be significant at a 0.10 experimentwise error rate.

ns = Tested and found to be not significant at a 0.10 experimentwise error rate.

Table 8

Statistical analyses of temperature data using nonparametric tests based on Friedman rank sums. Ranks assigned from lowest to highest values.

1) Data from study by Conover, et al. (1985)

	West Bank pit	Control site	Swinburne
West Bank pit	--		
Control site	ns	--	
Swinburne	ns	ns	--
Average Ranks	1.70	2.30	2.00

2) Data from study by Pacheco (1983)

	C11	Swinburne	West Bank pit
C11	--		
Swinburne	ns	--	
West Bank pit	**	**	--
Average Ranks	2.24	2.24	1.52

3) Data from study by NMFS (1984)

	C11	Swinburne	West Bank pit	Sandy Hook Bay	East Reach	Great Kills	Gravesend Bay	Romer Shoal
C11	--							
Swinburne	ns	--						
West Bank pit	ns	ns	--					
Sandy Hook Bay	ns	ns	**	--				
East Reach	ns	ns	ns	ns	--			
Great Kills	ns	**	**	ns	**	--		
Gravesend Bay	ns	ns	**	ns	ns	ns	--	
Romer Shoal	ns	ns	ns	ns	ns	**	ns	--
Average Ranks	4.79	3.45	2.79	5.45	3.98	6.62	5.31	3.62

** = Tested and found to be significant at a 0.10 experimentwise error rate.

ns = Tested and found to be not significant at a 0.10 experimentwise error rate.

Other environmental factors, especially substrate type and water depth, can also regulate the distribution of fish in estuaries. Interestingly, all Group I stations were shallow (5-7 m) and were characterized by sandy bottoms. The Group II stations were all muddy and ranged in depth from 7 m to 16 m.

To summarize, from statistical analyses of catch, number of species, and weight per trawl data obtained from these surveys, two station groups were identified. Group I stations corresponded to shallow, sandy locations and included the C11 site, Great Kills, Romer Shoal, and the Control site. Group II stations were those which had deeper, muddy bottoms. These were the West Bank pit (i.e., Borrow Pit No. 1), Swinburne, Sandy Hook Bay, East Reach, and Gravesend Bay. Group I stations were generally lower than Group II stations in terms of catch, number of species, and weight per trawl. Aside from sediment type and water depth, no other environmental parameters (e.g., temperature, salinity, and dissolved oxygen) when considered separately grouped the stations in the same pattern as found in the analysis of the fisheries data.

Based on these results, the fish populations that would ultimately characterize a capped deposit will depend primarily on the water depth and the sediment type at the project site. A range of outcomes depending on the nature of the disposal operation is possible. At one end of this range, it is assumed that the disposal operation leaves the area below the depth of the ambient sea floor, and that the project site will accumulate fine-grained, organic-rich material at a rate comparable to that now found in borrow pits on the West Bank. Fish populations at the project site in this instance would probably continue to resemble those observed in West Bank borrow pits as well as those found at the other Group II stations. Reducing the water depth at the project site may cause small reductions in the fish populations, but abundances will most likely be higher than that observed at the Group I stations.

At the opposite end of the range of possible outcomes, it is assumed that the disposal operation has restored the area to ambient depth, that the project site will not accumulate fine-grained, organic-rich material, and that the surficial sediments correspond to the original sand can and/or to the well sorted sands on the West Bank. The environment would, therefore, resemble that found at the Group I stations. In this instance a significant decline in fish abundance, number of species, and biomass would probably occur at the project site.

Conclusions

The burial of dredged sediment in subaqueous pits is technically feasible and, at least in concept, environmentally acceptable. The basic principles of all the essential elements of such a disposal operation have been accomplished in the field and a small-scale demonstration project has been completed in the Duwamish Waterway, Seattle, Washington (Sumeri, 1984). Cohesive mud should be dredged with a clamshell dredge in order to reduce dispersion during discharge and to create a compact deposit of sufficient strength to support the cap. Steep pit walls are effective barriers to the spread of dredged sediment during discharge even in relatively shallow pits. The shape of the deposit can be empirically forecast and the requisite deposit can be constructed by point dumping to contain more than 95% of the dredged material.

Capping with sand can be done using conventional equipment and can be effective in isolating and containing the underlying dredged material. Subsequent settlement of the deposit may be predicted. The total settlement, however, will be slightly greater, and consolidation will occur at a rate faster than that predicted theoretically from laboratory experiments on homogeneous samples.

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Appendix I

Description of Statistical Analyses Used in this Report

The traditional approach in testing for differences in means among two or more sampling stations is to carry out an analysis of variance (ANOVA). ANOVA techniques assume that the error terms are independent, normally distributed, random variables with equal (homogeneous) variances. These criteria are rarely met when considering either fish or benthic survey data (e.g., Barnes and Bagena, 1951; Oviatt and Nixon, 1973; Downing, 1979; Elliot, 1977). As a result, a log, square root, or fourth root transformation is generally applied to the survey data in such a manner that the transformed variates meet the assumptions of the analysis. The effectiveness of the transformation may be checked by applying, for example, a Kolmogorov-Smirnov test (Sokal and Rohlf, 1969). However, in the present case, the data in the fishing studies by Conover, et al. (1983), Pacheco (1983), and NMFS (1984) and the benthic survey by Cerrato and Scheier (1983) consist of from one to three samples per station. With few replicates or none at all, it is difficult to impossible to test whether a transformation has normalized the survey data and eliminated inhomogeneities in the error variances.

Because of this problem, all statistical tests in this report are based on analyses of Friedman rank sums (Noether, 1967; Conover, 1971; Hollander and Wolfe, 1973). Friedman tests are nonparametric. Both fisheries and benthic survey data as well as physical parameters such as temperature, salinity, and dissolved oxygen values can be tested without transforming the data or assuming the form of the underlying distributions. The Friedman method outlined below is the nonparametric equivalent to a two-way analysis of variance and is sometimes referred to as a "two-way analysis of variance by ranks" (Conover, 1971).

1. A Distribution-Free Test for Differences in Means Based on Friedman Rank Sums (Noether, 1967; Conover, 1971; Hollander and Wolfe, 1973)

The data are assumed to consist of nk observations, with one observation from each of k stations during each of n sampling dates (Table). The statistical model is taken to be:

$$X_{ij} = u + b_i + c_j + e_{ij}, \qquad i = 1,\ldots,n, \quad j = 1,\ldots,k,$$

where u is the unknown overall mean, b_i is the effect of sampling data i (the b's are unknown nuisance parameters), c_j is the unknown station j effect, e_{ij} are mutually independent random variables, and

$$\sum_{i=1}^{n} b_i = 0 \qquad \sum_{j=1}^{n} c_j = 0.$$

It is desired to test the null hypothesis

$$H_0: c_1 = c_2 = \ldots. = c_k$$

against the alternative hypothesis (H_1) that the c's are not all equal.

To carry out this test, the k observations within each sampling date are ranked from least to greatest. Define r_{ij} as the rank assigned to X_{ij} in the joint ranking of $X_{i1},\ldots\ldots,X_{ij}$. Let

$$R_j = \sum_{i=1}^{n} r_{ij}.$$

Then the Friedman test statistic is defined as

$$S = \frac{12}{nk(k+1)} \sum_{j=1}^{k} (R_j - n(k+1)/2)^2.$$

The null hypothesis is rejected at the α level of significance if

$$S \geq s(\alpha,k,n),$$

where the constant $s(\alpha,k,n)$ satifies the equation $P_0 \{S \geq s(\alpha,k,n)\} = \alpha$. Some exact values of $s(\alpha,k,n)$ can be found in Hollander and Wolfe (1973). For other cases, when H_0 is true, S has an approximate x^2 distribution with k-1 degrees of freedom. The approximate α level test is then

$$\text{reject } H_0 \quad \text{if} \quad S \geq x^2_{(k-1,\alpha)}$$

$$\text{accept } H_0 \quad \text{if} \quad S < x^2_{(k-1,\alpha)}.$$

The x^2 approximation has been found to be reasonably close and improves as n gets larger (Conover, 1971).

When ties occur, average ranks are used and S is replaced by

$$S' = \frac{12 \sum_{j=1}^{n} (R_j - n(k+1)/2)^2}{nk(k+1) - [1/(k-1)] \sum_{i=1}^{n} \left\{ (\sum_{j=1}^{g_i} t_{ij}^3) - k \right\}}$$

where g_i is the number of tied groups during date i, t_{ij} is the size of the jth tied group during date i, and untied values are counted as ties of size 1.

In this test, ranking occurs only within each sampling date. No comparison is made between dates. Differences among sampling dates are assumed to be large enough to invalidate a comparison of station effects from one date to another. Hence the b_i are treated as nuisance parameters. In this report α has been set at 0.05 for all tests.

2. Distribution-Free Multiple Comparisons Based on Friedman Rank Sums (Hollander and Wolfe, 1973)

The S or S' statistic described above can be used to test whether station means differ. It does not, however, specify which of the c's are unequal. To determine this, a multiple comparisons test based on Friedman rank sums was used.

For this test the k(k-1)/2 absolute differences $|R_v - R_w|$, v<w are computed. At an experimentwise error rate of α, $c_v \neq c_w$ if

$$|R_v - R_w| \geq r(\alpha,k,n)$$

where the constant $r(\alpha,k,n)$ satisfies the equation

$$P_0\left\{|R_v - R_w| < r(\alpha,k,n),\ v=1,\ldots k-1,\ w=v+1,\ldots,k\right\} = 1 - \alpha.$$

Values of $r(\alpha,k,n)$ for $k \leq 15$ and $n \leq 15$ can be found in Hollander and Wolfe (1973). In other cases, an approximate procedure is used. For large n and at an experimentwise error rate of α, $c_v \neq c_w$ if

$$|R_v - R_w| \geq q(\alpha,k,\infty)[nk(k+1)/12]^{1/2}.$$

Values of $q(\alpha,k,\infty)$ can be found in Hollander and Wolfe (1973). The value of α is the overall significance level for the entire set of comparisons. It is, therefore, generally referred to as an experimentwise error rate. In this report, α has been set at 0.10 for all tests.

3. Asymtotic Relative Efficiency of the Friedman Tests (Noether, 1967; Hollander and Wolfe, 1973)

The standard method for determining the effectiveness of a nonparametric test is to estimate its asymtotic relative efficiency (ARE). The ARE is a measure comparing the nonparametric test to its nearest parametric counterpart under identical conditions. An exact definition of ARE may be found in Noether (1967). Values of the ARE less than 1 indicate that the nonparametric test is the less efficient estimator. When the ARE is greater than one, the the nonparametric test is more efficient. The ARE of the Friedman rank sums test relative to the traditional ANOVA has been shown by Noether (1967) to be

$$\text{ARE(normal)} = 0.955\ k/(k+1),$$

when the underlying distribution is normal and where k is the number of treatments or stations. For several nonnormal distributions, Noether (1967) found

$$\text{ARE(uniform)} = 1.0\ k/(k+1)$$

$$\text{ARE(double exponential)} = 1.5\ k/(k+1).$$

Furthermore, for other nonnormal distributions, Hodges and Lehman (1956) have determined that the ARE can never fall below 0.864 k/(k+1) but can be considerably greater than 1.

Data arrangement for Friedman rank sums test.

	Stations			
Dates	1	2		k
1	X_{11}	X_{12}	...	X_{1k}
2	X_{21}	X_{22}	...	X_{2k}
.	.	.	...	.
.	.	.	...	.
.	.	.	...	.
.	.	.	...	.
.	.	.	...	.
n	X_{n1}	X_{n2}	...	X_{nk}