DREDGE SPOIL DISPOSAL IN RHODE ISLAND SOUND

S. B. Saila
S. D. Pratt
T. T. Polgar

Marine Experiment Station
Sea Grant

MARINE TECHNICAL REPORT NUMBER 2
UNIVERSITY OF RHODE ISLAND

DREDGE SPOIL DISPOSAL IN RHODE ISLAND SOUND

S. B. Saila
professor of oceanography and zoology

S. D. Pratt
research associate

T. T. Polgar
research assistant

Based on a report to the Bureau of Sport Fisheries and Wildlife, U.S. Department of the Interior, under University of Rhode Island contract 98-20-6012. Publication funds for Marine Technical Report Number 2 are from the University's sea grant program.

1972 University of Rhode Island, Kingston

This publication is based on a report submitted to the Bureau of Sport Fisheries and Wildlife, May 26, 1971. The report has been shortened by deletion of data tables, several graphs and a description of trend surface analysis. Some references have been added to update the review of possible effects of spoil dumping.

In December, 1971, a new, one-year study of the spoil dump site was initiated under a contract with the New England Division, U.S. Army Corps of Engineers. This study consists of (1) a new field survey of the dump site area to determine the present distribution of spoil, the levels of pollutants in sediment and animals, and the progress of animal colonization; (2) laboratory experiments on the effects of burial and turbidity on marine animals; (3) examination of fisheries records for the study area before and after dumping; and (4) turbidity measurements in the study area under normal conditions and after storms.

Additional copies may be obtained from the Marine Advisory Service, University of Rhode Island, Narragansett Bay Campus, Narragansett, Rhode Island 02882.

TABLE OF CONTENTS

List of Figures

Introduction

Between December, 1967, and September, 1970, a total of 8.2 million cubic yards of dredge spoil from the Providence River was deposited on an offshore site in Rhode Island Sound.

The spoil was taken from the navigation channel to Providence, which was deepened from 35 to 40 feet with a bucket dredge. This was done as part of the Army Corps of Engineers Providence River Improvement Project. The areas dredged include Providence Harbor, a series of reaches extending about 5 miles down the Providence River, and a 2-mile-long approach channel in upper Narragansett Bay (figs. 1 and 12).

Although much of the spoil removed from the harbor consisted of recently deposited silts of the type handled by maintenance dredging, a large volume of it consisted of compact sands and silts deposited before the estuary was significantly affected by man's activities. This relatively dense and cohesive material contrasts strongly with the fluid silt-clays deposited by suction dredges in Chesapeake Bay and described by Harrison (1967) and Briggs (1970). It also contrasts with the fluid sewage sludge and highly polluted harbor spoil studied by Pearce (1970) in New York Bight.

The spoil was carried to sea in scows of 2,000- and 3,000-cubic-yard capacity and discharged within a 1-square-mile dumping area, approximately 4 miles south of Newport, Rhode Island. The depths in this area were between 96 and 106 feet before dumping began.

This was the first time that dredge spoil from Narragansett Bay had been dumped offshore rather than within the estuary. The reasons for this included (1) the large volume of spoil — approximately 10 million cubic yards for the completed project; (2) the knowledge that spoil dumped within estuaries is often transported back to the dredged channels, and (3) the concept — growing more popular — that estuaries are valuable recreational and fisheries resources, and these uses are incompatible with their use as spoil dumps.

Background about the site choice appears in an initial study of dredge spoil dumping in Rhode Island Sound (Saila, Polgar and Rogers, 1968). That study provides limited predisposal information on the dump site, some short-term tolerance studies of locally important marine organisms, a calculation of spoil volume on the site, and turbidity measurements made during those dumping operations. In general, the outcome of the early work suggests that minimum damage to natural resources had occurred up to the end of the project period; at that time a total of 1.96 million cubic yards had been dumped.

The present study, which was carried out between March and September, 1970, was designed to update physical observations, to examine aspects of dredge spoil dumping not explored in the first study, and to reach general conclusions about the response of benthic invertebrates to environmental disturbances.

The contracted objectives were (1) to reassess by bathymetry the observed distribution of spoil material after 5.5 million cubic yards had been discharged on the dump site; (2) to relate observations of the speed and direction of bottom currents in the vicinity of the site to observed and potential spoil movements, and (3) to make observations on the species composition and abundance of benthic invertebrates on the dump site and surrounding areas, to assess the effects of the spoil dumping on these animals, and to predict the nature of recovery of the area after dumping ceases.

To these were added (1) a bathymetric survey after 8.2 million cubic yards had been dumped, (2) an examination of the sediments of the spoil and of the dump site area, and (3) a description of the fisheries in the dump site area.

Some information in this report was collected by University of Rhode Island personnel during 1969 as part of the University Marine Experiment Station's continuing program of studies on marine resource utilization.

Although the emphasis of this study is on aspects of spoil disposal which relate to the management of a specific offshore area, information of general ecological importance was obtained on the composition of the benthic assemblages of Rhode Island Sound and on the colonization of new sea bottom by benthic animals.

Moreover, future decisions on the use of the continental shelves for mining and dumping will require integrated studies dealing with benthic

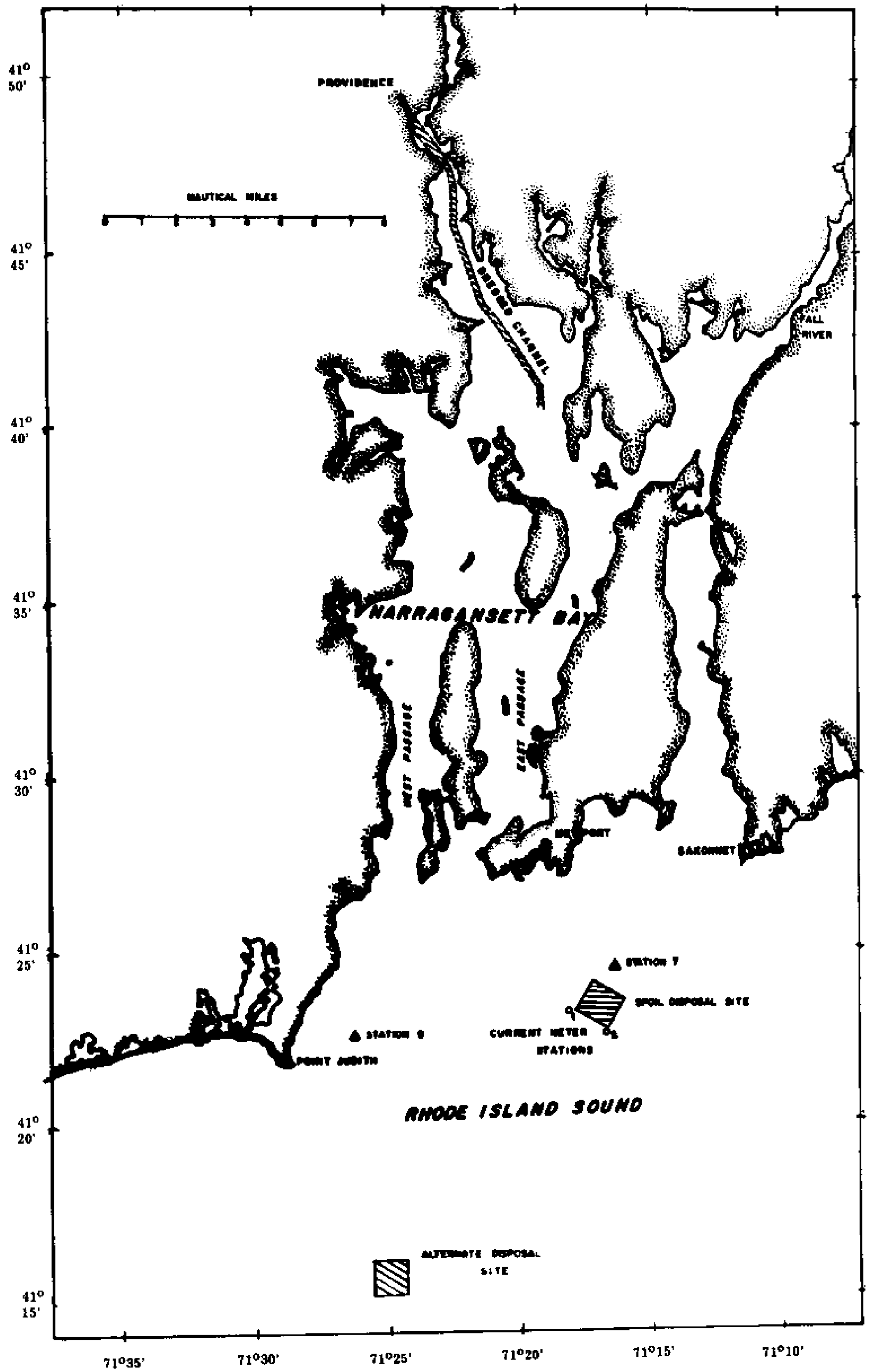


Fig. 1. General location map for Narragansett Bay and Rhode Island Sound.

ecology, sedimentary geology, and hydrography. This study, although on a limited scale, is an example of such a program.

SUMMARY

Disposition of Spoil on the Dump Site

The disposition of spoil was determined by two bathymetric surveys and two series of sediment samples, which were checked by sub-bottom profiles and by diver observations. The following results and conclusions were reported.

1. Within the limits of the precision of the bathymetric surveys, the volume of dredge spoil on the disposal area was the same as that reported dumped. No large-scale loss had taken place during or after the dumping operation.
2. A layer of incohesive silt-clay covered much of the dump during the summer of 1970. This indicated a non-erosive hydrographic regime during that period.
3. In July, 1968, the spoil formed a low cone centered in the middle of the disposal area.
4. In October, 1969, and September, 1970, the spoil formed a cone 16-18 feet high and about a mile in diameter centered near the west corner of the disposal area. The spoil extended from 1/4 mile to 1/2 mile outside the designated disposal area to the northwest and southwest.
5. Spoil from Providence Harbor containing a high percent organic matter was deposited during the early part of this project. This was covered by less organic spoil from the lower Providence River except in two places, outside the dumping area to the northwest and inside the dumping area along the northeast edge.
6. Patches of spoil were found as much as a mile outside the dump site toward the northwest and southwest.

Sediments of the Dredging and Disposal Areas

The sediment types found in the Providence River, Rhode Island Sound, and the dumped spoil were described on the basis of published information and the analysis of a small number of representative samples. The following results and conclusions were reported.

1. The sediments in the dump site area were well-sorted fine sands. They were yellow or olive in color and contained about 1 percent organic matter.
2. The dredge spoil included sediments which had been deposited in various environments within the present estuary and under various post-glacial environments. These sediments included polluted silts containing up to 12 percent organic matter, unpolluted estuarine silty sands with shells and pebbles, and varved sands and clays deposited in glacial outwash.
3. Although much of the spoil had a smaller median grain size and a higher percentage of organic matter than the natural sediments in the dumping area, these were not always distinguishing characteristics. Poor sorting and the presence of the shells of estuarine mollusks were more reliable indicators. Clay, pebbles, plant detritus, oil globules, and gray or black color were also used to identify spoil.
4. Soft silt/clay mantling the spoil surface appeared to be much less resistant to erosion than the sand outside the dumping area. Denser mixed sand/silt/clay appeared to be relatively erosion resistant. Coarse fractions were found in most of the spoil samples which could form protective lag deposits after some erosion has taken place.

Characteristics of the Physical Environment

The physical characteristics of the dump site environment were described on the basis of: (1) a review of recent studies on Rhode Island Sound circulation, (2) bottom current measurements near the dump site during periods of high tidal velocity, and (3) review of regional wave data and predicted wave-induced velocities at 100-foot depths. The probability of erosion and transportation of spoil was examined on the bases of experimental results in the literature and the sedimentary characteristics of the spoil. The following results and conclusion were reported.

1. Currents in the dump site region were dominated by the semidiurnal tide. Instantaneous bottom currents rarely exceeded 0.3 knots, whereas the net tidal transport velocity was no greater than 0.1 knots.
2. Currents alone were not effective in resuspending sediments.
3. Waves in the area could develop bottom velocities sufficient for the resuspension (erosion) of unconsolidated sediments for a significant fraction of the time.
4. The mode of deposition and mechanical characteristics of dredged materials apparently resulted in an erosion resistant disposition. The dumped material could not be considered unconsolidated, and theoretical predictions based on the behavior of unconsolidated sediments were not applicable.
5. It was concluded that beaches in the region should remain free of dredge spoil traces from the dump site.

Review of Some Direct Effects of Spoil Dumping on Marine Animals

Possible effects of spoil dumping were examined on the basis of published information and a single burial experiment. An attempt was made to identify those effects which would be significant in the Rhode Island Sound environment. The following conclusions were reported:

1. A few benthic species are able to reach the surface after deep burial (over 20 cm.). Although

some offshore mollusks may have limited mobility compared to analagous estuarine species, most benthic species around the dump site can probably reach the surface after shallow burial.

2. Many marine animals, including fish species and lobsters, can withstand very high concentrations of suspended sediment for short periods. It is doubtful that any mortality has resulted from turbidity in the dump site area, but the effect of turbidity on the feeding efficiency of filter feeders and on the behavior of fish is not known.

3. Although lack of oxygen in spoil sediments may restrict the colonization of infauna, the overlying water probably never becomes anoxic.

4. Hydrocarbons have been detected in some spoil samples and in some Providence River sediments. It is difficult to tell whether or not hydrocarbons are a problem on the dump site. Although the hydrocarbons at the site probably contain some toxic fractions, most of the exposed spoil appears to consist of sediments with low hydrocarbon content. It is possible, however, that some spoil has hydrocarbon levels high enough to affect the chemical senses of benthic animals.

5. Toxic metals are present in some Providence Harbor sediments. The levels of these metals in the surface sediments of the spoil dump are not known, although it is likely that most surface sediment has low metal concentrations. Detritus-feeding infauna and their predators would be most likely to concentrate such metals.

6. It is difficult to predict the effect of a change in grain size distribution on the makeup of the benthic community at this location. Hydrographic conditions, which will remain unchanged, may continue to determine the species found.

The Effects of Spoil Dumping on the Benthic Fauna of the Sound

Macrobenthic invertebrate assemblages were examined in the spoil source area and in undisturbed areas of Rhode Island Sound. Analysis was based on a limited number of quantitative 1/10 M^2 bottom samples. A similarity index was used to compare samples. Qualitative grab samples served as a check on the representativeness of the 1/10 M^2 samples. Faunal diversity index values were calculated and their usefulness as indicators of environmental disturbance, examined. The following results and conclusions were reported.

1. A small number of pollution-resistant benthic species were found in Providence Harbor. Although low oxygen seemed to be the major stress, toxic substances are probably also present in this area.

2. Over 30 benthic species were found in the lower Providence River. These indicated a relatively low level of pollution in that part of the spoil source area.

3. Several species, which had been transported from the dredge area, were found on the spoil dump. The only abundant transported species which seemed well adapted for Rhode Island Sound conditions was *Nephtys incisa*, a polychaete, which is found there naturally.

4. The natural faunal assemblage on sandy sediments in the spoil dump area was dominated by *Ampelisca agassizi*, a tube-building amphipod crustacean. Dense mats of *Ampelisca* tubes determined sediment quality and provided a habitat for subdominant species.

5. Much of the spoil was recently dumped and had few animals on it. However, some surfaces which had been exposed to colonization for 1-3 years yielded large numbers of species (up to 53 per 1/10 M^2 sample) indicating that these spoil surfaces lacked gross toxic or repellent properties.

6. Although the spoil was generally silty, only a few colonizing species were recognized as members of the offshore silt bottom assemblage. Lack of information on the presence of the larvae of these species in the overlying water makes it difficult to ascribe this absence to sediment properties, however.

7. Most of the species colonizing the spoil were members of the surrounding sand-bottom assemblage. Several species of deposit-feeding polychaetes and an amphipod crustacean, *Leptocheirus pinguis*, were found in greater abundance on the spoil than in their natural habitat.

8. *A. agassizi* was found on some spoil areas indicating that colonization was independent of the quality of underlying sediment where the hydrographic regime was suitable. It seemed likely that this species would eventually dominate the spoil as it did the surrounding area. It was not possible to estimate the time necessary to establish this dominance.

9. Although the faunal assemblages sampled in this study had characteristic diversity index values, these could not be simply interpreted. For example, some spoil samples had relatively high values indicating little disturbance, while the natural *A. agassizi* assemblage had extremely low values.

10. Several of the species which were abundant on the colonized spoil have been reported as food used by commercially important fish.

Fisheries Resources in the Dump Site Area

Commercial fishermen from Newport, Rhode Island, were interviewed to determine the types of fisheries in the dump site area and the extent to which each of these was affected by the spoil dumping. Summaries of information on the three major fisheries follow.

1. Trawling for fin fish is done east and southeast of the dump site during winter and

spring and north and northeast of the dump site during summer and fall. The winter fishery for cod and flounder was successful in 1970. The summer fishery for butterfish and scup has been relatively unsuccessful for several years, believed to be due to natural variations in abundance. The major concerns of trawl fishermen were that spoil might be dumped outside the designated area and that it might increase turbidity after storms, reducing fish catches.

2. Lobstering is carried on throughout Rhode Island Sound in the summer. Most lobstermen avoided trapping near the dump site, fearing low or polluted catches, burial of traps, and loss of buoys. One fisherman, however, made good catches on the perimeter of the dump site during 1970; these lobsters probably entered the spoil area during normal movements. Lobstering was the least affected fishery and will probably be carried out on the spoil after dumping ceases.

3. The dump site is located near the center of a discrete patch of ocean quahogs, which were not being harvested when dumping began. During 1970 these were dredged from areas on the perimeter of the dump site. Animals killed by burial were recovered from the inshore edge of the dump site and from a location on which spoil was dumped before the present dump was approved.

RECOMMENDATIONS

Dump Site Management

The following recommendations are made for future use of this site for disposal of spoil which is acceptable in terms of ecological and public health standards.

1. *Special attention should be paid to accurate placement of the spoil.* One way to monitor the accuracy of placement would be to require tow boats to carry recording fathometers. A record of each trip would prove that the dump site had been reached since the profile of the present spoil mound is easily recognizable.

2. Spoil should be dumped in the center as well as the north and east parts of the site in order to cover relatively organic spoil and to prevent further movement outside the site to the south and west.

3. Dredging projects which include a variety of sediment types should be planned so that either unpolluted or coarse materials are dumped in a pattern which buries polluted or very incohesive materials.

4. Dredging and dumping techniques — using large bucket dredges or large hopper scows — should be used which deliver spoil to the bottom with minimal suspension and loss of compaction.

5. Large volumes of incohesive fine-grained sediments should not be dumped at the site until the possibility of erosion and transport by wave-induced bottom currents has been investigated further.

6. Future surveys of the dump site should include an area at least 1/2 mile outside the designated area. Improved navigation and profiling systems should be utilized in volume measurements. Spoil should be identified on the basis of poor sorting, the presence of shells of estuarine mollusks, high percentage of volatile material, and high percentage of silt-clay.

7. A permanent record should be kept of the volume, sediment properties, and placement of all spoil dumped on this site.

Geological Research

Studies in the following areas would provide information of value in planning the use of the continental shelves for mining and cable laying as well as for disposal of various materials.

1. Laboratory and field studies should be carried out on the velocities necessary to erode spoil sediments with or without populations of tube-building animals.

2. Near-bottom wave-induced velocities should be monitored by rapid-response, solid-state velocity sensors on the present site and on proposed alternate sites.

3. The suspension of sediments from the bottom during storms should be studied. The maximum density and the settling time course should be described for various natural and spoil-covered bottoms.

4. Surface sediment parameters on the present dump site should be monitored for several years in order to detect loss of fine fractions and the development of a lag deposit.

5. The extent to which sediments deposited from suspension contribute to the spoil extending outside the designated area should be determined. The presence of horizontal structures and graded beds will reliably indicate this type of deposition.

Biological Considerations and Research

1. Dumping of spoil from unpolluted areas should be allowed on the present disposal site. With accurate dumping no areas outside the designated zone should be affected, and colonization of the spoil by benthic organisms should begin soon after dumping ceases.

2. No spoil from polluted areas should be dumped on this site until more information is available on the possibility that toxic substances and pathogenic microorganisms may be transferred from spoil to species eaten by man.

3. Any ocean sites should be closed to fishing while spoil from polluted source areas is being dumped, and they should not be reopened until a complete check has been made of possible health hazards.

4. A program should be initiated to consider the possibilities of toxic substances from spoil dumped at sea being transferred to human food. The present dump site could be used as an experimental

area and model for such a program. Areas of concern would include (a) toxic metals present in the sediments of the spoil source area and the disposal area; (b) toxic metals present in selected animals from the dump site, including detritus-feeding polychaetes, predators, and species eaten by man, and (c) concentration factors of metals from prey to predator.

This information should be considered in relation to the surface area of polluted spoil exposed on the dump site, the resistance of spoil to erosion, and the depth of reworking by burrowing animals. The longevity of important pathogens in seawater and the biochemical stability of organic pollutants are additional areas of concern.

5. The colonization of the spoil on the present site should be monitored for several years. When this study was conducted, the spoil surface was physically unstable and colonization had only begun on the edges of the site, but the characteristics of the sediment and the specific makeup and productive capacity of the fauna will continue to change for several years. Continuing studies should benefit from the taxonomic work of the present study.

6. Laboratory studies should be made on the effects of burial and high turbidity on selected offshore benthic species.

Alternate Disposal Sites

The present disposal site appears to be well chosen on the basis of minimal disturbances to regional fisheries and minimal erosion of spoil, and area is available within the site for a large volume of additional spoil. Continued use of this site for disposal of relatively cohesive and unpolluted material is preferable to the establishment of a new site in near-shore waters. Alternate sites should be considered, however, in the event that the present site is judged as unsuitable for the disposal of polluted spoil or large volumes of incohesive fine-grained spoil.

The area which appears most suitable for the location of a permanent disposal site for Rhode Island and southern Massachusetts is approximately 50 miles from the mouth of Narragansett Bay at a depth of 210 feet. This area is centered at 70°55'W and 40°40'N at the edge of an existing munitions disposal site.

The continental shelf within the 180-foot contour supports an intensive trawl fishery; however, outside this area fish abundance decreases markedly. During 1969 no catches of bottom fish were reported from within 10 miles of the suggested alternate dump site location by boats based in Point Judith, Rhode Island (National Marine Fisheries Service, 1970). The offshore lobster fishery is concentrated on the continental shelf edge which is about 45 miles from this location, and a developing ocean quahog fishery is located inshore of this area.

The presence of relict silty sediments in this area indicates that little erosion or transportation is taking place (Garrison and McMaster, 1966; McKinney and Friedman, 1970). McClennen (1971) calculated the expected velocities of wave-induced bottom currents on the New Jersey continental shelf using Airy wave theory and the wave records of Hogben and Lumb (1967). Velocities capable of eroding fine sand (15 cm./sec.) would be expected 17 percent of the time at 120-foot depths but only 3 percent of the time at 240-foot depths.

If it is considered technically or economically feasible to dump in this area in the future, a preliminary study of its hydrography, geology, benthic ecology, and fisheries potential could be carried out on the basis of available information. Such a study could allow an initial decision to be made on the suitability of the location and serve as a basis for future field surveys.

Disposition of Spoil on the Dump Site

BATHYMETRY

Bathymetric maps of the disposal area were prepared as a basis for determining the volume, distribution, and bulk properties of the spoil. It was considered desirable to map the area with a precision of ± 0.5 feet due to the small vertical dimensions of the spoil mound.

The original bottom in the general region of the dump site slopes toward the southwest (fig. 2). Within the disposal area a 4-foot-high ridge strikes southeast-northwest across this slope (fig. 3). A large fraction of the spoil was deposited on the southwest side of this ridge (figs. 7-3, 8-2). Low rises 1-2 feet high and approximately 1/8 mile wide are found throughout the area. Volume changes were calculated by subtracting the depths obtained after a period of dumping from those determined before dumping began. The precise registration of these maps was of considerable concern since large volume changes would seem to result if the maps represented different areas of the sloping bottom.

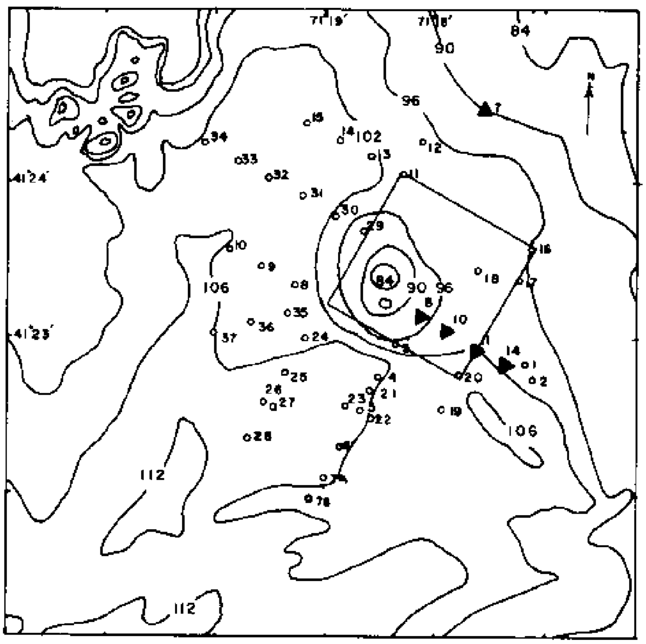


Fig. 2. Location map of the spoil dump area. The 1-square-mile designated dumping zone is outlined. Depth contours in feet are derived from Coast and Geodetic Survey Bathymetric Map 0808N-51 and from a survey of the dumping zone in September, 1970. Sample locations are shown for single grabs (circles) and for triplicate $1/10M^2$ Smith-McIntyre grabs (triangles).

Figures 3 and 4-1 (from Saila, Polgar and Rogers, 1968) show the depth contours from surveys made before dumping and in July, 1968, after 1.96 million cubic yards had been dumped. Figure 4-2 shows the contours of equal thickness of added material (isopachs) obtained by subtraction. The spoil was distributed in a cone centered in the middle of the dump site, a pattern which probably resulted from dumping near a central buoy in place at that time. Much of the material shown on this map came from Providence Harbor. It is believed that the negative values in the east corner of the dump site were due to mapping error and not to erosion.

Figure 5-1 shows the depth contours obtained on October 22, 1969, utilizing the Army Corps of Engineers 105-foot tug, the *Manomet*. The quality of the depth records from this survey was diminished by the recording of 4-foot-high waves superimposed on the bottom trace. The isopach map is shown in figure 5-2. Spoil volume calculated from this map gave an estimate of 5.46 million

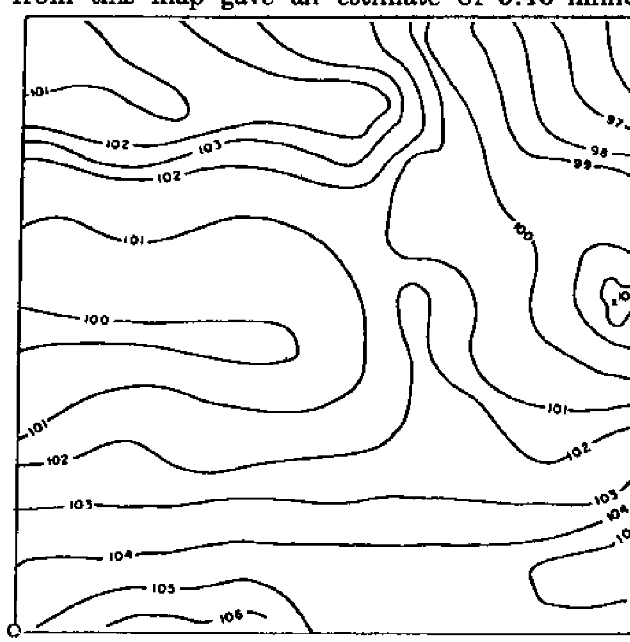


Fig. 3. Contoured bathymetry of the dump site previous to dumping. The contour interval is 1 foot. (From Saila, Polgar and Rogers, 1968.)

cubic yards. The volume reported dumped at that time was 5.5 million cubic yards.

Figure 6-1 shows the depth contours obtained on September 25, 1970, utilizing the *R/V La Nina*, a 50-foot trawler operated by the University of Rhode Island. Calm seas permitted unusually good resolution of bottom features. Figure 6-2 is the isopach map for this date. Calculated volume was 8.3 million cubic yards. An estimated 8.5 million cubic yards had been dumped at that time: 8.2 million from the Providence River Project and 320,000 from a project in Fall River, Massachusetts.

In the two surveys just discussed the spoil was found in a low cone centered ¼ mile from the west corner of the dump site and extending slightly outside the designated dumping area to the northwest and southwest. This pattern reflects the fact that barges were unloaded close to the west corner, and the dumping followed the placement of the bouys presently marking the south and west corners. Areas on the north, northeast, and east edges of the dump site had received little added material since the 1968 survey.

Estimates were made of the characteristic slopes of the spoil from examination of the September, 1970, depth records, three of which are shown in figures 7-1, 7-2, and 7-3. Small, relatively steep mounds with slopes of approximately 2° 30' are believed to represent single barge loads of dense spoil from recent dredging operations. They are about 100 feet wide and 3 feet high. A large-scale feature of the spoil "pile" is a central cone with a 1° slope, an "angle of repose" that results from the combined effects of dumping pattern, impact of the spoil with the bottom, gravity flow of fluid sediments, slumping of compact sediments, and erosion and transport by waves and tides. Slopes of less than 1° are found around the perimeter of the site. These may be composed of suspended sediments which flowed to the base of the cone. Cores in these areas would be expected to show nearly horizontal strata and graded beds.

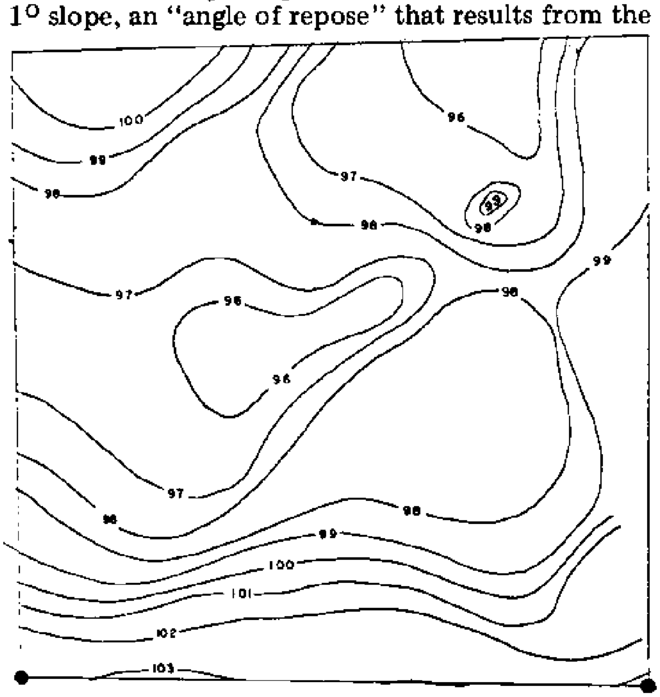


Fig. 4-1. Contoured bathymetry of the dump site from a survey made in July, 1968, after 1,960,000 cubic yards had been dumped. Contour interval is 1 foot. (From Saila, Polgar and Rogers, 1968.)

The technique used in mapping spoil thickness in this study required accurately positioned bathymetric surveys both before and after dumping. However, an alternate method would be necessary to map spoil in areas where no previous survey had been made. Thus, it was decided to examine the utility of high resolution, near sub-bottom profiling in obtaining simultaneous traces of the spoil surface and the original bottom.

Ocean Systems, a part of the Raytheon Submarine Signal Division, generously provided test runs over the study area using their recently developed CESP system. This system uses a wide bandwidth, long-duration signal which is stored as a reference replica and correlated with the returning echo from the sub-bottom layers.

Figures 8-1 and 8-2 show the tracings of reduced records, obtained with the CESP system, using a 1KH_Z narrow-beam and a 3.5 KH_Z wide-beam transducer. These sections duplicate the bottom profiles shown in figures 7-2 and 7-3. Although the trace of high waves somewhat obscured these records, they were useful in determining the exact position of the spoil on the slope of a ridge crossing through the dumping area. Although this system has a theoretical resolution of about 2 feet, the thinnest layers seen in the test records were between 3 and 4 feet thick. This resolution would not be sufficient to map spoil

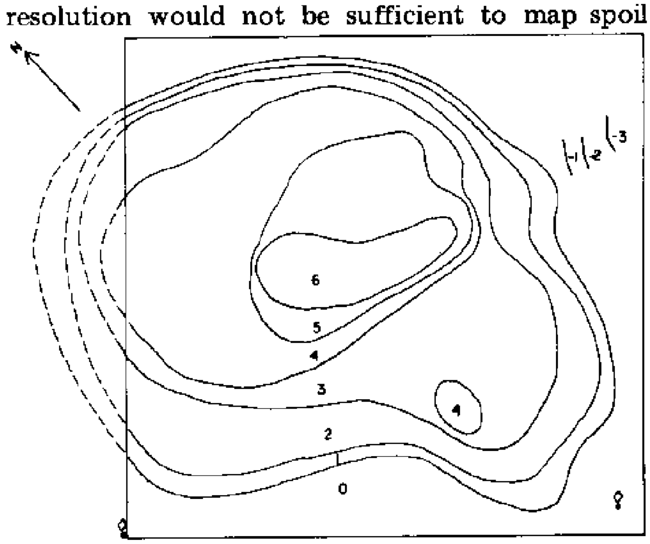


Fig. 4-2. Isopach map of dump site representing the difference between depths prior to dumping and after 1,960,000 cubic yards had been dumped. The contour interval is 1 foot. (Map redrawn from data of Saila, Polgar and Rogers, 1968.)

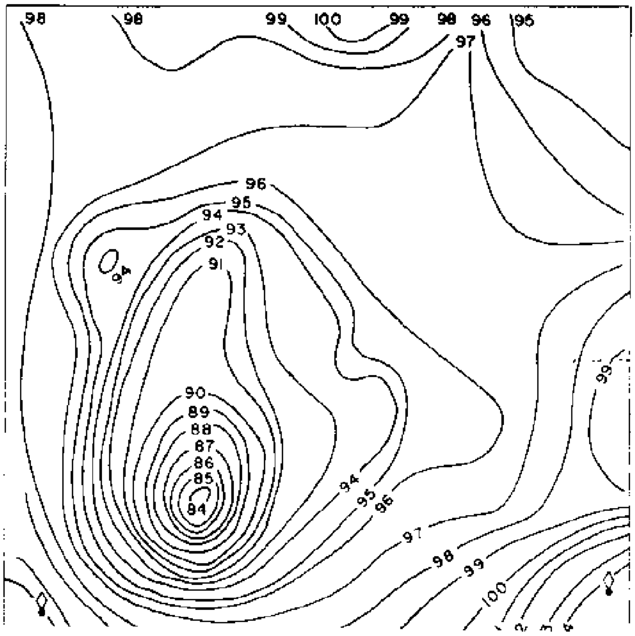


Fig. 5-1. Contoured bathymetry of the dump site from a survey made October 22, 1969, after 5,500,000 cubic yards had been dumped. The contour interval is 1 foot.

which had spread in very thin layers. Cores would be necessary in such an area, but it was concluded that near sub-bottom profiling could be a valuable addition to the present techniques for mapping sediment thickness.

SURFACE DISTRIBUTION OF SPOIL

The surface distribution of spoil was mapped from bottom samples collected during the summers of 1969 and 1970.

In August, 1969, a total of 41 short cores was collected by University of Rhode Island personnel. The sampling array is shown in figure 9. Symbols on the map identify the sample locations that yielded visually recognizable spoil materials. These were found mainly within the designated disposal area.

Although the spoil was composed of a variety of materials, nearly all spoil samples contained higher percentages of fine particles and organic matter than did the sandy sediments in the disposal area. A computer technique, described in detail by O'Leary *et al* (1966) was used to contour the percentage of silt-clay and the percentage of carbon from these samples. Least-square surfaces were fitted to the data points. These became increasingly complex as the degree of the trend surface equations was increased from 1 to 6. The higher-degree surfaces were not useful in this application because they fit each variation within the spoil deposit, obscuring the general pattern of spoil distribution. The third-degree surfaces (figs. 10-1 and 10-2) illustrate this pattern more clearly. Spoil sediments with a relatively high percentage of silt/clay and carbon were found within the

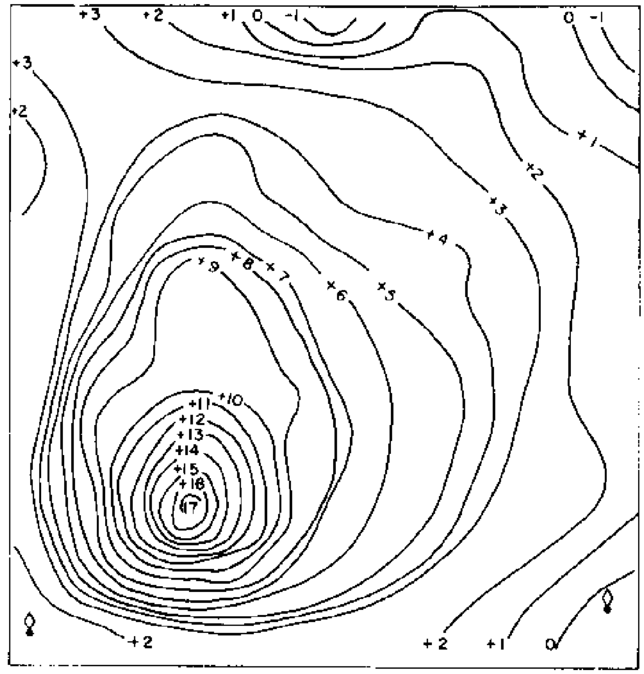


Fig. 5-2. Isopach map of dump site, representing the difference between the depths prior to dumping and after 5,500,000 cubic yards had been dumped. Calculated spoil volume is 5,460,000 cubic yards. The contour interval is 1 foot.

dumping area with the silt/clay spreading outside to the southwest and carbon, to the west.

During June-October, 1970, a series of Petersen grab samples was taken from the *R/V La Nina;* most samples were taken outside the designated dumping area (fig. 11). Considerable small-scale heterogeneity in sediment types was found. Inside the dumping area the spoil materials varied, while outside patches of spoil were found on the original sandy bottom sediments. Some samples which yielded spoil material (fig. 11, Sta. 7A) were within a dumping area used for a short period before the present area was established (fig. 22). The perimeter of the area affected by the presence of gross quantities of spoil included 3 to 4 square miles, although some clean bottom was found within this area.

The characteristic sediment type in the center of the dumping activity was dense gray sand/silt/clay. This sediment contrasted strongly with the soft black organic materials, described by Saila, Polgar and Rogers (1968), indicating the progress of the dredging operation from Providence Harbor to upper Narragansett Bay. Samples taken in the late summer of 1970 showed a distinct gray silt/clay layer, 1-2 cm. thick, mantling both the spoil "pile" and the original bottom south and west of the disposal area. A very large number of samples would be required to complete a map of the spoil deposit since the basic sedimentary units were patches not more than a few hundred feet in diameter.

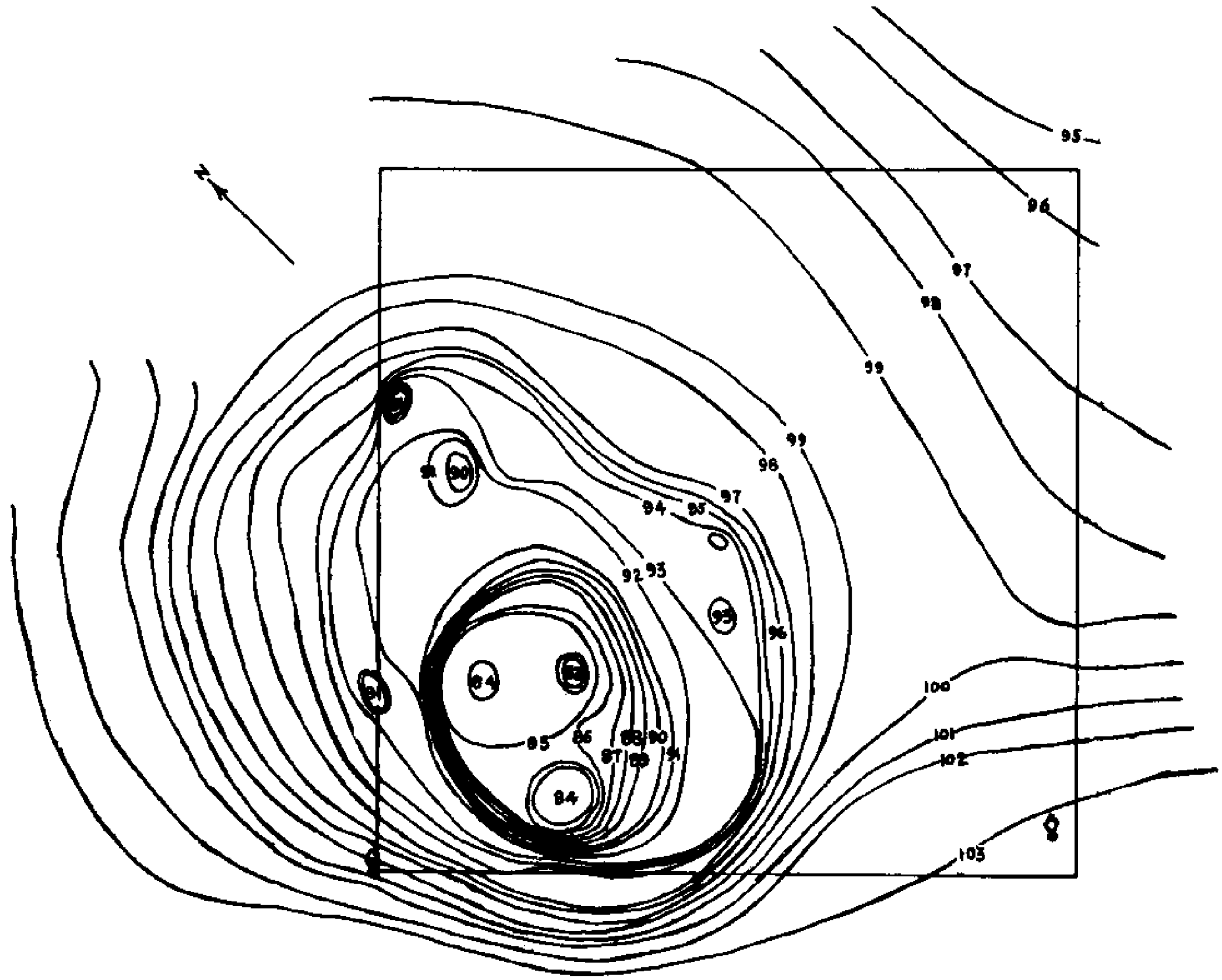


Fig. 6-1. Contoured bathymetry of the dump site from a survey made September 25, 1970, after 8,500,000 cubic yards had been dumped. The contour interval is 1 foot.

DIVER EXAMINATION OF THE DUMP SITE

In October, 1970, divers made direct observations of topographic features, animal life, and sediment variability in the area of active dumping in order to obtain information to properly interpret bathymetric records and grab samples from the area. An attempt to make such observations by submarine photography during 1968 had failed, probably due to turbidity caused by contact of the equipment with the bottom.

The dive was made during calm weather at a time when current velocity was barely perceptible at the surface. The surface water had the expected high clarity of Rhode Island Sound water in autumn. The water a few feet from the bottom contained some suspended material but still appeared less turbid than Narragansett Bay water at any time of the year. Enough green light penetrated the water to enable the divers to see the general topography.

The bottom was covered with a smooth layer of homogeneous gray silt. Contact with this sediment generated dense clouds several feet high; the silt was soft and incohesive enough to allow a hand to be passed through it without meeting appreciable resistance. More consolidated sediment with coarse sand in it was detected beneath this layer. A short core indicated that the surface layer was about 2 cm. thick. Lumps of clay, marsh peat, and clinker ash 10-20 cm. high protruded from the smooth bottom. The only "rubbish" seen was a shoe sole. Most of the bottom seemed horizontal to the divers except for one slope of about 5^{o}. The extent of this slope was not detectable.

A single fish, probably a sculpin (*Myoxocephalus* sps.), was seen. Adults of two species of crabs *(Cancer irroratus* and *Cancer borealis)* were collected and an American lobster *(Homarus americanus)* was seen on the sediment surface. A small unidentified crustacean was observed leaving a 3 mm.-diameter hole and swimming across the surface. The bottom was marked by distinctive straight trails made by lobsters and crabs.

The bottom showed little evidence of wave or current activity. Ripple marks were seen in only one area. These, with a wavelength of about 10 cm., were of very low amplitude. They seemed to be made visible by sorting of light- and dark-colored sediment particles.

These observations were extremely valuable in describing the active dumping area. In the future divers should return to this area to assess the effects of winter storm waves on the surface sediments. Dives should also be made on the edges of the dump site where animal colonization has begun.

CONCLUSIONS

Within the limits of the precision of bathymetric surveys, the volume of spoil on the disposal area was the same as that reported dumped; no large-scale loss had taken place during or after the dumping operation. The presence of a layer of incohesive silt/clay on the spoil surface during the summer indicated a non-erosive physical environment during that period.

Much of the organic spoil from Providence Harbor deposited during the early part of the

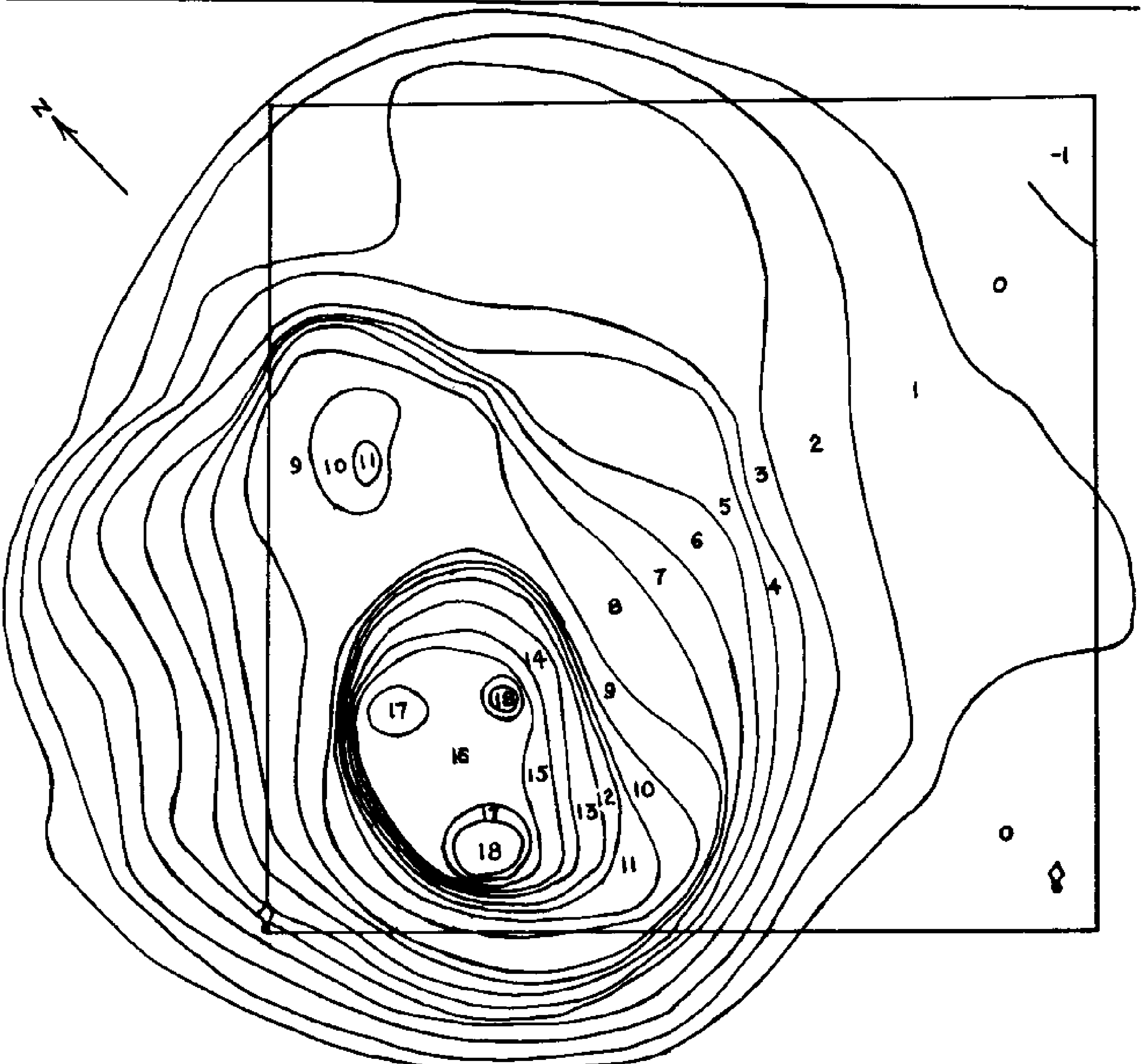


Fig. 6-2. Isopach map of dump site representing the difference between the depths prior to dumping and after 8,500,000 cubic yards had been dumped. Calculated spoil volume is 8,300,000 cubic yards. The contour interval is 1 foot.

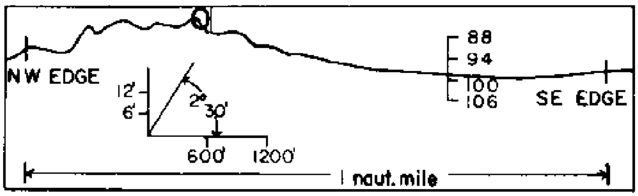


Fig. 7-1. Trace of an echo sounder record of a NW-SE traverse over the highest part of the spoil ¼ mile from the SW perimeter of the designated dumping zone. The spoil is up to 18 feet thick. The feature circled has a 2° 30' slope and probably represents a single barge load.

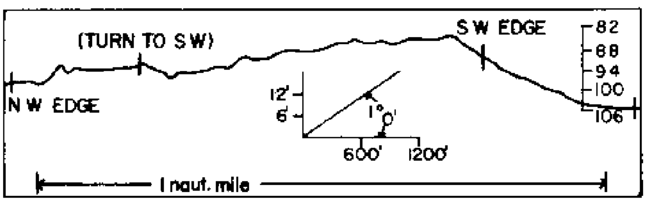


Fig. 7-2. Trace of an echo sounder record of a NE-SW traverse over the highest part of the spoil ¼ mile from the NW perimeter of the designated dumping zone. This section is at a right angle to that shown in Figure 7-1. The slope on the SW edge is about 1°.

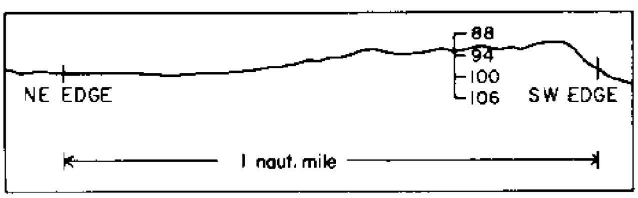


Fig. 7-3. Trace of an echo sounder record of a SW-NE profile bisecting the designated dumping zone. The general slope of the original bottom dips toward the SW.

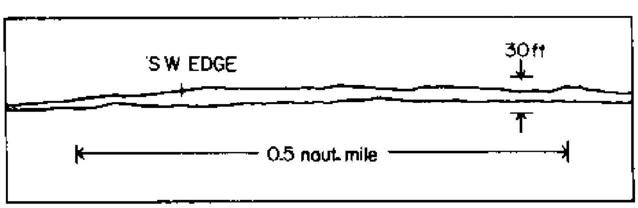


Fig. 8-1. Trace of a near sub-bottom profile of a SW-NE traverse ¼ mile from the NW perimeter made with the Raytheon FACT/CESP system (2^{o}-3^{o} beam, 1 KH_z). This section is the same as that shown in Figure 7-2. The original bottom can be seen under the spoil.

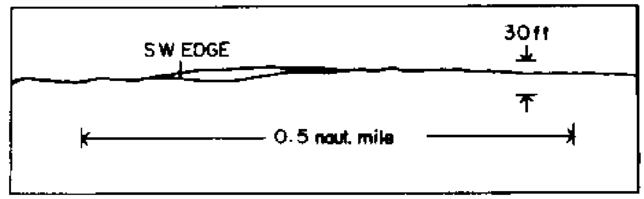


Fig. 8-2. Trace of a near sub-bottom profile of a SW-NE traverse bisecting the designated dumping zone made with the Raytheon CESP system (40^{o} beam, 3.5 KH_z). This section is the same as that shown in Figure 7-3. The spoil can be seen on the slope of low ridge with a SE strike.

---

dredging project was buried by less organic sediment from upper Narragansett Bay. Harbor spoil was left unburied outside the dumping area to the northwest and inside the dumping area in the north and east corners. Spoil was found as far as 1 mile outside the dumping area on the route from Narragansett Bay to the dump site.

The combined effect of dumping pattern, sediment properties, and hydrographic variables has produced a low cone of spoil approximately 1 mile in diameter, indicating that the 1-square-mile assigned dumping area was of adequate size. Spoil extended outside the designated area to the west and south only because the center of dumping was close to the west corner.

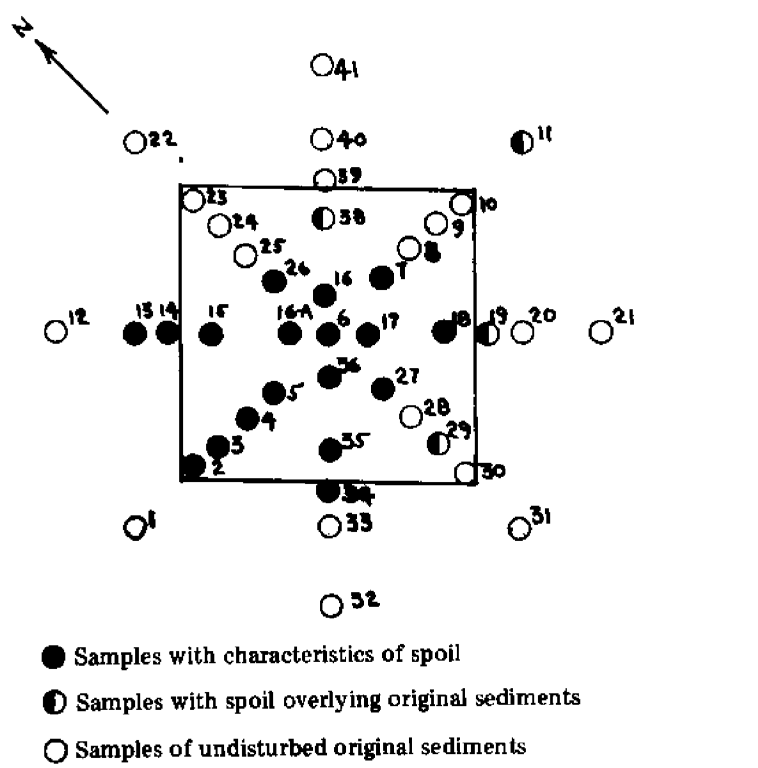


Fig. 9. Core samples taken from the dump site and its vicinity during August, 1969.

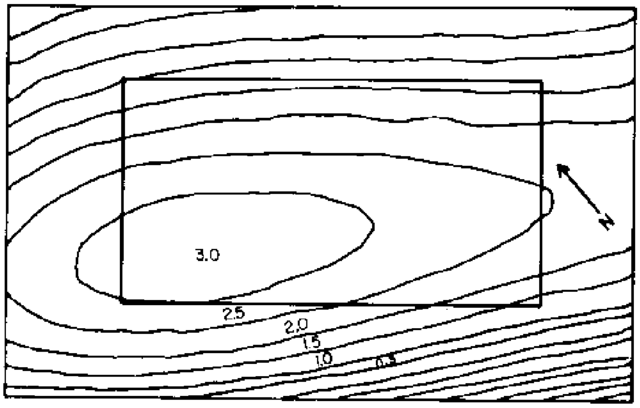


Fig. 10-1. Percent carbon in sediments August, 1969. Third-degree trend surface fit. Contour interval 0.5 percent. Designated dumping area is outlined.

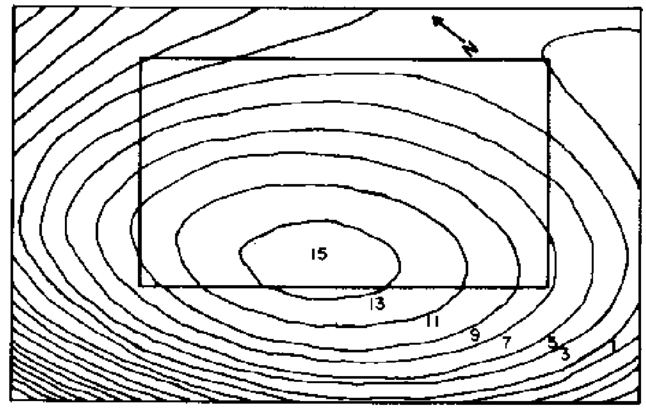
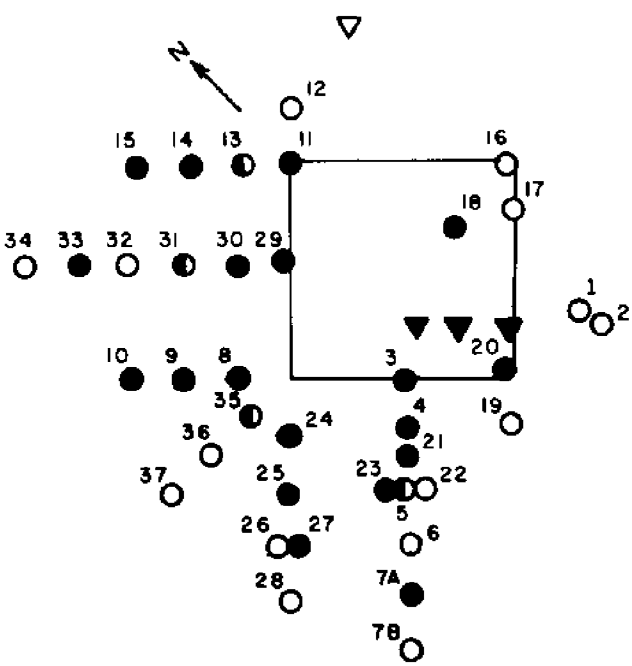


Fig. 10-2. Percent silt and clay in sediments August, 1969. Third-degree surface fit. Contour interval 2.0 percent. Designated dumping area is outlined.



● Samples with characteristics of spoil

◒ Samples with spoil overlying original sediments

○ Samples of undisturbed original sediments

Fig. 11. Grab samples from the dump site and its vicinity taken July-September, 1970. Sample numbers are shown in Figure 2.

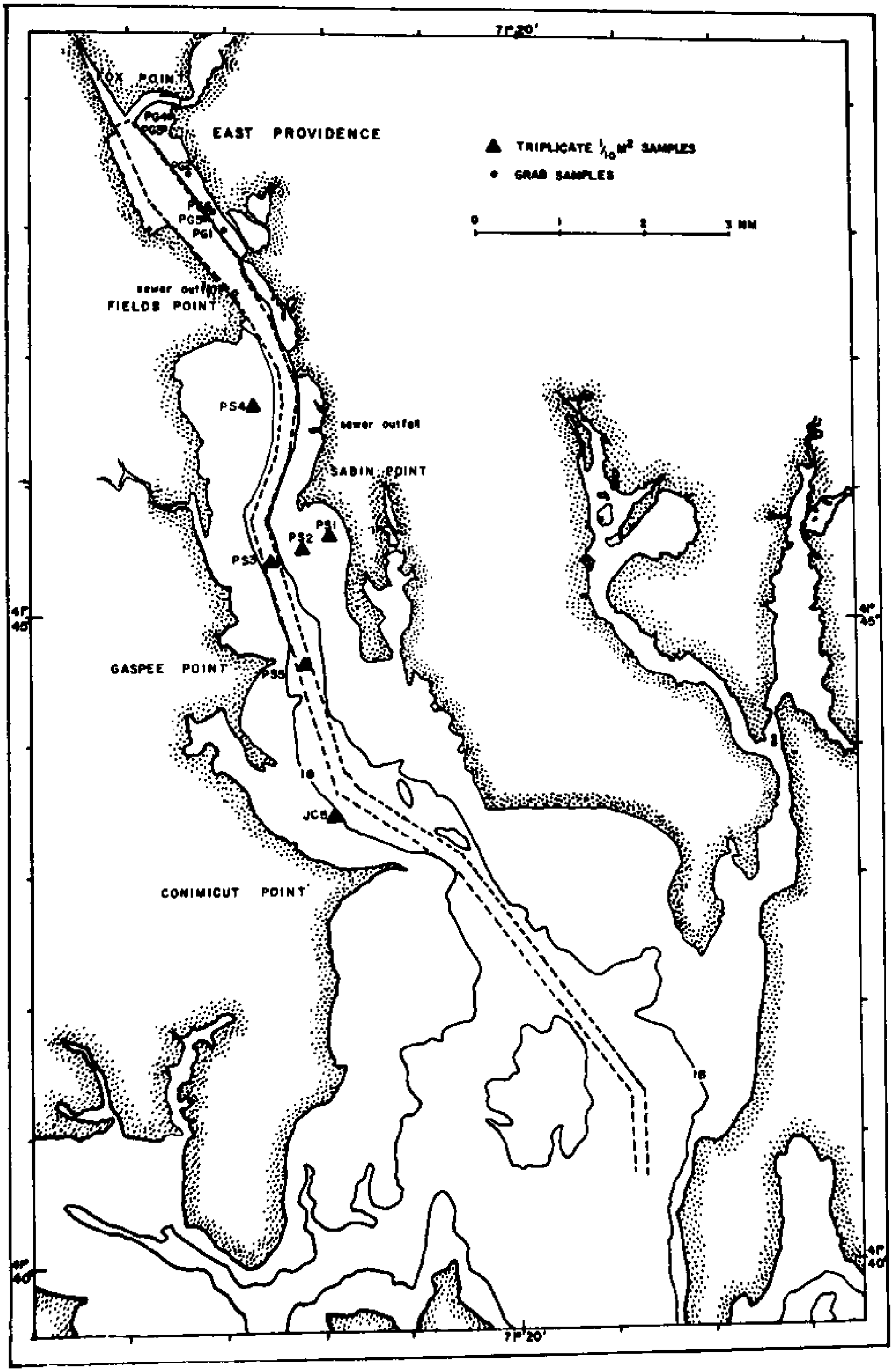


Fig. 12. Location map showing the following areas mentioned in the text: (1) Providence Harbor, north of Fields Point; (2) Providence River, between Fields Point and Conimicut Point; and (3) Upper Narragansett Bay, south of Conimicut Point.

Sediments of the Dredging and Disposal Areas

The sediments encountered in this study are described to provide a basis for (1) distinguishing spoil materials from natural sediments, (2) predicting the stability of the spoil under the hydrographic conditions of Rhode Island Sound, and (3) studying animal-sediment relationships.

Selected sediments were analyzed using a combination hydrometer and dry-sieve method (ASTM, 1968). Material remaining in suspension after 60 minutes in the hydrometer settling tube was reported as clay. Sieves at a ½ ϕ interval were used. Percent frequency and cumulative percent frequency of the weight of size fractions were graphed. Median grain size and the geometric sorting coefficient, *So*, were derived from these graphs. *So*, a measure of spread around the mean, varies from 1.18-1.25 for well sorted beach sands to 4.76 for unsorted glacial till (Krumbein and Sloss, 1963). The percentage of loss on combustion was used to indicate the amount of organic matter in the sediments. Three subsamples were dried at 80° C. and combusted for three hours at 575° C. The weight losses of the subsamples in all cases were within 1 percent of each other.

SEDIMENTS OF THE DREDGED AREA

The dredge spoil included sediments of types presently being deposited in Providence Harbor, the Providence River, and upper Narragansett Bay as well as those deposited under various sedimentary regimes after the last ice advance.

Providence Harbor is an area of active sedimentation. Between 1945 and 1955, a total of 1.1 million cubic yards was removed from the harbor to maintain design depth (U.S. Army Corps of Engineers, 1959). This was 46 percent of the total amount dredged from the ship channel in that interval. This sediment could have had a variety of sources.

Clays entering in river water would flocculate immediately at the reported salinities of 10-27 o/oo at the surface and 27-30 o/oo at the bottom (Hicks, 1959). These sediments, however, show a paucity of clay-sized particles. Suspensions in both aquaria and settling tubes became clear in about 90 minutes. Microscopic examination of the sand-sized particles from shallow samples (map, fig. 12) revealed that most were worm fecal pellets, 0.25 mm. by 0.12 mm., which yielded very fine particles when disaggregated with hydrogen peroxide. The worms that mat the bottom with densities of $100{,}000/M^2$ ingest the fine surface sediments and produce sand-sized particles of low density. It was not possible to determine the depth to which these pellets remained aggregated, but Moore (1955) states that they may remain complete for up to 100 years.

The U.S. Army Engineer Waterways Experiment Station modeled sediment transport in the Providence River (U.S. Army Corps of Engineers, 1959) and found that easily transported materials, initially distributed throughout the channel, accumulated in the Harbor, indicating that fine materials from downstream are probably an important source of sediments in the Harbor. Sources of particles with high organic content include the highly polluted Blackstone River entering at the head of the estuary, the Pawtuxet River entering opposite Sabin Point, and the sewage treatment plants at Fields Point and in East Providence.

The harbor sediments examined had a loss on combustion of 10-12 percent and were anaerobic below the immediate surface. Silica frustules of diatoms and much plant detritus were found preserved in these sediments. Petroleum was present in these samples but did not affect the sediment texture. Highest values for hexane-extractable material in spoil, given by Saila, Polgar, and Rogers (1968), of 0.76 percent of dry weight were presumably from harbor sediments. Hexane-soluble materials include fats and oils from sewage and natural sources as well as hydrocarbons from oil spills.

The surface sediments from the channel of the Providence River between the harbor and upper Narragansett Bay have been generally classified as organic silt (Hard, 1970). McMaster and Clarke (1956) report that though the sediments are generally fine grained, the silt-clay fraction varies from 94 percent in shoaling areas to 3.3 percent in constricted areas where erosion predominated. A high proportion of wood, leaves, and seeds are characteristic of the sandy silts at stations PS 3 and PS 5; these contributed to the 4-6 percent loss on combustion of these samples. Surface sediments are characterized by the shells of a very abundant bivalve, *Mulinia lateralis*, while abundant oyster and scallop shells in the deeper sediment represent former populations eliminated by pollution.

Stations at PS 1 and PS 2 in shallow water along the edges of the channel had very soft black sediments that had a 12 percent loss on combustion, much higher than that of the channel-bottom sediments. Reduced current velocity and polluted surface water seemed to be responsible for this concentration. Some preliminary determinations of hydrocarbons in sediments from this area (Farrington, 1971) gave values of .05-.57 percent of dry weight. These hydrocarbons appeared to be "aged" petroleum, made up of cyclic saturated compounds.

The sediments of upper Narragansett Bay reflect a reduction in current velocity with an increase in cross section. McMaster (1960) reports a clay content of 10-30 percent in this area, a high value for Narragansett Bay sediments. The silt content is 60-65 percent and the sand content is 10-25 percent. These sediments are well oxidized and are inhabited by a normal estuarine fauna.

The dredging operations frequently penetrated into layers of sediment deposited under different conditions than those found today. These include silts and sands deposited in the post-glacial river valley previous to saltwater intrusion. Beneath these were found laminated fine sands, silts, and clays deposited during the last glacial retreat.

SEDIMENTS IN THE DUMP SITE AREA

McMaster (1960) showed the general pattern of sediments in Rhode Island Sound (fig. 13). The bottom is generally sandy, but becomes silty in a depositional area east of Point Judith. Lag deposits of gravel and cobble mark the location of eroded glacial moraines.

The sediment at station 7-3 (map, fig. 2; graph, fig. 14) was a clean yellow sand representative of the original sediments on the dump site and to the north and east of it. Cores 40, 39, 23, 25 and 20 (fig. 9) also sampled this type of sediment. All were 95-99 percent sand with a grain-size mode of 0.25-0.10 mm.; and all were very well sorted. The loss on combustion for station 7-3 was only 1 percent. These sands contained fragments of bivalve shells and sand dollar skeletons. Quartz grains were subrounded and stained with iron oxide.

Large areas of this sand were covered by dense mats of the tubes of amphipod crustaceans. These mats had trapped suspended sediment and the fecal matter of the amphipods. The sediment color was olive brown, and the grain-size distribution (station 14-2, fig. 14) showed added fine particles. The loss on combustion was 3 percent for the tubes and 2 percent for the sediment.

Fine sediment, winnowed from shallow waters or transported from Narragansett Bay after storms, is presently being deposited east of Point Judith (McMaster, 1960). The sediment at station 9-2 (fig. 14) was extremely well-sorted silt with a median grain size of 0.06 mm., with no particles larger than 0.177 mm. and with only 7 percent clay. Apparently wave and current energy is not capable of carrying coarser sediments to this area, while clays remain in suspension and are deposited elsewhere. The loss on combustion was 4 percent.

SPOIL SEDIMENTS

The sediments found on the dump site were very heterogeneous. Stations 8-1 and 8-3 yielded coarse sand with shells. This sediment showed poor sorting and no grain-size mode (fig. 14). The presence of the shells of the soft shell clam *(Mya arenaria)*, quohog *(Mercenaria mercenaria)*, oyster *(Crassostrea virginica)*, jingle shell *(Anomia simplex)*, and common mussel *(Mytilus edulis)* indicate an estuarine origin. Strong currents in the area of origin probably concentrated shells from both rocky shore and soft bottom. Loss on combustion was 0.6 percent.

Samples at station 8-2 were made up of mixtures of black silt, light-colored sandy clay, granules, and pebbles up to 2 inches in diameter (fig. 14). These may have represented natural estuarine sediments or could have been "manufactured" during dredging and dumping. They were easily separable from the original sediments of the area on the basis of the presence of pebbles, clay and plant detritus and poor sorting values. Loss on combustion varied from 2.7 percent to 3.8 percent.

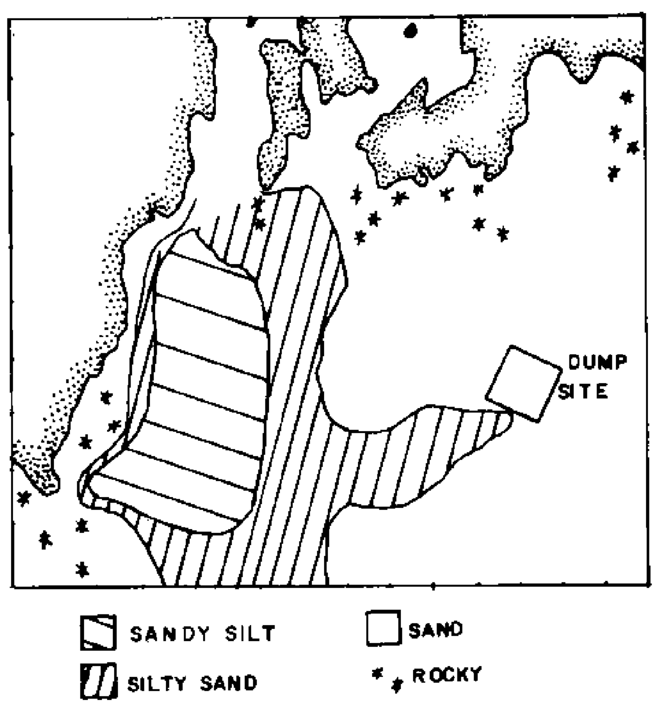
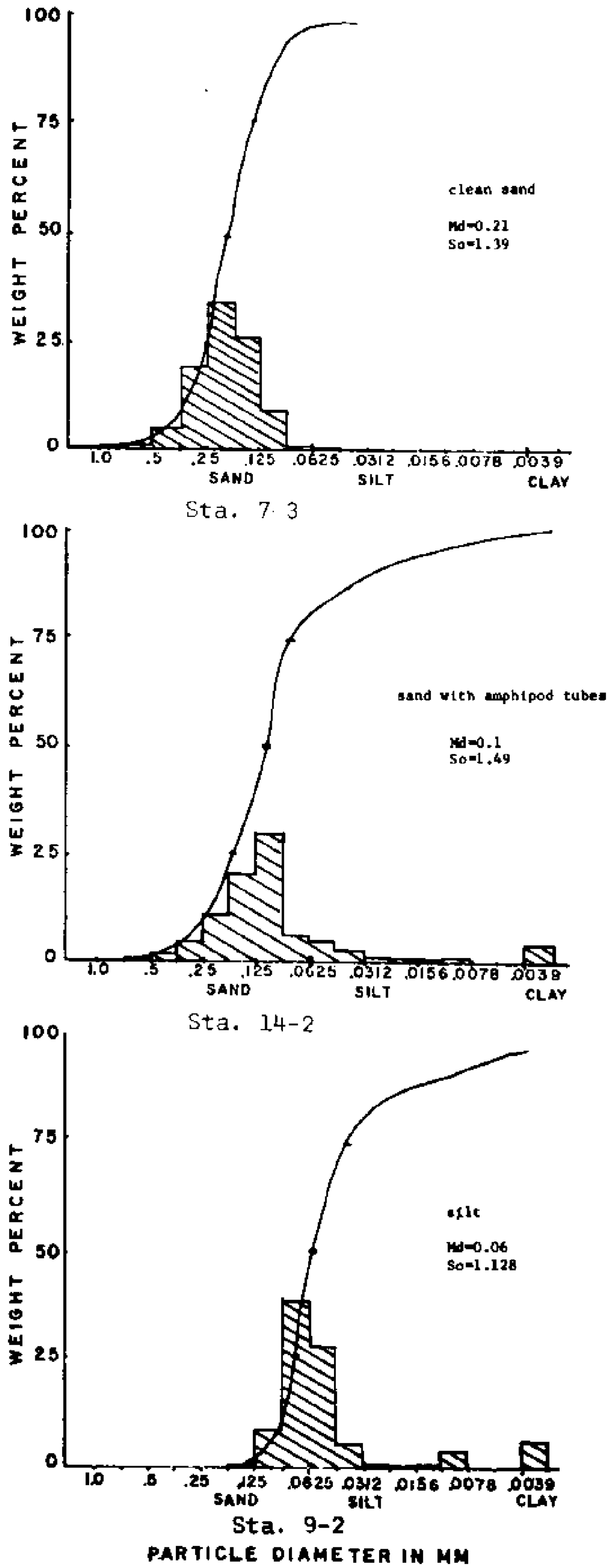


Fig. 13. General surface sediment distribution of northwest Rhode Island Sound. (From McMaster, 1960.)



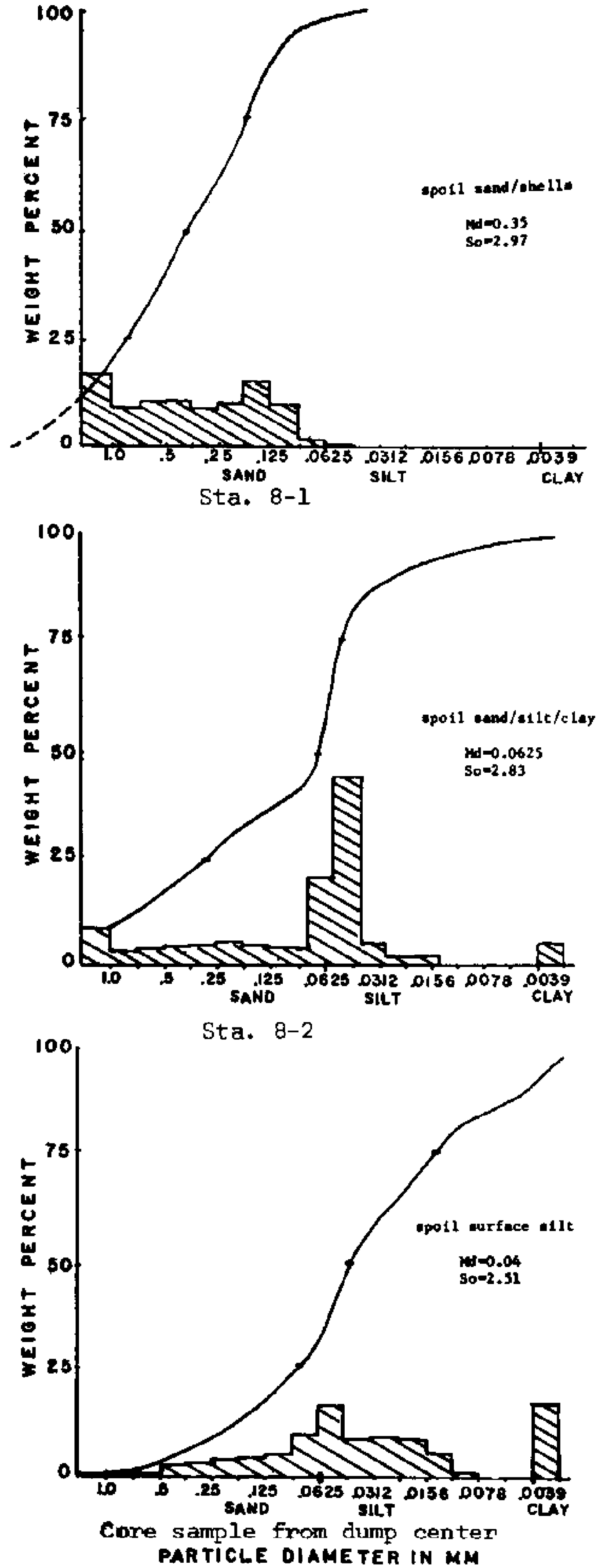


Fig. 14. Grain size distribution of typical Rhode Island Sound sediments, (Stations 7-3, 14-2, and 9-2) and of various spoil sediments (8-1, 8-2, and dump center).

The grain-size distribution of a soft gray silt which was found mantling the active area of the dump site is shown in figure 14 (core sample from dump center). The median grain size was in the silt range, and clay made up 17 percent of the total weight. Sizes over 1 mm. were absent. It is believed that this material was formed during the dumping process. Silt suspended during spoil dumping and from spoil impact with the bottom would have fallen more slowly than sand and pebbles and would have produced a graded bed. The core from which this sediment was taken had a sandy horizon 8 cm. beneath the surface. A series of shallow cores would indicate whether this stratigraphy is widespread.

Although much of the spoil had a smaller median-grain size and a higher percentage of organic matter than the natural sediments in the dumping area, these were not always distinguishing characteristics. Poor sorting and the presence of the shells of estuarine mollusks were more reliable indicators. The presence of clay, pebbles, plant detritus, oil globules, and gray or black color also identified spoil.

No attempt was made to identify spoil which had been transported away from the dump site by waves and tides; these particles would have nearly the same grain size as those of the area to which they had been transported. Qualitative differences among the particles could be used to identify their source, however. Wood fragments, recovered southwest of the dump site, indicated transport in that direction. Petrography and shape analysis of sand grains could be used to identify transported sand. McMaster (1962) showed that the amphibole/opaque ratio of sands from the Providence River was 4:1, while the ratio in the area of the dump site was 1:4. The quartz grains in the offshore sands were more spherical and more rounded than those in the spoil.

If it is assumed that well-sorted sands of the dump site area are in equilibrium with the hydrographic regime at that location, it is possible to assess the relative stability of the various spoil sediment types. The thin layer of soft silt/clay that mantles the spoil surface is probably easily eroded, but the denser mixed sediments underlying the surface might be rather erosion resistant. It would appear that some silt will be lost from less dense mixed sediments until a protective sandy lag deposit develops. The depth of lag necessary to provide protection is conjectural; however, the absence of ripple marks in this area suggests that a relatively shallow layer would be sufficient.

It seems important to obtain data on the suspension of spoil sediments during storms and on their rate of settlement in order to assess possible effects on fisheries.

Colonization of the spoil by populations of tube-building animals could slow the rate of erosion. Amplescid amphipods have covered the sediment in parts of the dump area with dense mats of soft tubes, which may protect the sediment from erosion and act as traps for fine materials. Mills (1967a) found that ampelisca colonies on intertidal flats undergo periods of erosion during storms. No information is available, however, on the resistance of mats to storm waves or on the permanence of colonies in deep water.

Characteristics of the Physical Environment

INTRODUCTION

Examination of the current and wave regimes of the physical environment in the dump site area provides some useful conclusions regarding the disposition of dumped sediments.

Spread of sediments from the designated area can take place immediately after the dump, when a considerable amount of sediment may stay in suspension for the order of hours (Saila, Polgar and Rogers, 1968). In this case, the currents prevailing at the time, the settling velocities and the sea state will determine the range and direction of the dispersion. Settled sediment may also be transported out of the area in time. Although known bottom velocities in Rhode Island Sound (see for example Shonting, 1969) can act only occasionally to resuspend settled sediments, wave action may frequently accomplish this, and consequently the suspended matter may be transported away from the dump site by the prevailing currents. The range and direction of spread will depend on the factors mentioned above, while the amount of matter going into suspension in the presence of waves and currents will be a function of sediment surface stability, average wave height and period, water depth and current speed. Finally, transport out of the dump site area may possibly be effected by rolling and saltation of sediment particles under the action of waves and currents.

In the following discussion, some particulars of the transport mechanisms will be examined in order to evaluate the extent of spread which may be expected from the dump site area.

CURRENT SYSTEMS IN THE SOUND

Two recent studies on Rhode Island Sound circulation provide a framework for the results of field current measurements at the dump site. Non-tidal circulation in Rhode Island Sound was investigated by Cook (1966). Shonting (1969) conducted a detailed 13-day study of currents, recorded by a square-kilometer array of self-recording current meters, in the summer of 1967. The study area of this latter work was located approximately 6 nautical miles from the dump site, bearing 150° (magnetic). The water depth was approximately 115 feet.

Shonting's investigation revealed that upper-layer motion may be characterized as a westward-migrating drift in long meanders. The bottom motions were described as anticyclonic (clockwise) swirls with small net displacements (drifts). These characteristics indicate that tidally driven inertial flows combined with tidal motions dominate the current regime. The mean speeds (obtained from arithmetic averages) in the upper layer did not exceed 0.5 knots for the period of observation, while similar means computed for the bottom layer resulted in values not greater than 0.3 knots. The unusually high mean bottom-speed values result from the application of arithmetic averages to the data. It is more meaningful to compute the mean velocity by vector averaging, which in this case yielded smaller mean speeds, along with their respective directions. The mean velocity can be interpreted as the non-tidal component of motion.

In effect, the mean speed and direction, obtained by the vector averages of velocities over several tidal cycles, indicate the resultant net displacement of water masses and suspended particles over the time interval included in the average. Oscillating tidal motion is eliminated by the averaging process; hence, the mean velocity thus obtained approximates the non-tidal circulation component. The greater the time interval used, the more accurate the net displacement estimate. If the flow patterns are fairly regular and are repeated over two tidal cycles (approximately daily), then daily averages may be used to investigate the variation of net displacement with time. Shonting reports a consistently west-southwest net motion in the upper layer, but the bottom flow displayed small and random net transport components.

The observed instantaneous variability in current vectors in both layers indicated the presence of eddies having scales of less than a kilometer. The current fluctuations indicated that the upper layer contained approximately five times more turbulent energy than the lower layer. However, the same analysis also indicated a strong local increase in turbulence close to the bottom, where the mean flow interacts with bottom frictional elements.

In summary, the major findings of Shonting's study were: (1) the semidiurnal tide controls variations in current velocity in both layers; (2) the tidal components appear to control the bottom motion more directly, resulting in smaller net displacements; (3) the larger net displacements in the upper layer appear to result from tidally induced, secondary inertial flow; (4) abrupt and prolonged changes, characterized by more unstable oscillations, may be the result of large-scale perturbations which cause reduced mean motion, allowing ambient tidal forces to appear amplified, and (5) the turbulent intensities increase close to the bottom.

Cook (1966) used drift bottles and seabed drifters to investigate the non-tidal component of circulation in Rhode Island Sound over prolonged periods of time. Due to the method, there is a large degree of uncertainty both in the direction and range of displacements. The findings of the drift studies are summarized by season in the table below:

SEASON	SURFACE DRIFT	BOTTOM DRIFT
Spring	N and E	NW
Summer	N	NW
Autumn	S	N
Winter	S	N
SPEED RANGE:	1.1 to 7.6 n.m./day	0.05 to 1.6 n.m./day

These results are generalized for the whole Rhode Island Sound region, and do not detail significant local variations. Within the report, a more extensive discussion of non-tidal patterns ensues, and Shonting's study more closely agrees with Cook's non-tidal measurements than it appears from the general results noted above.

The majority of bottles and drifters were not recovered. Although some were found by vessels, most were recovered at the shore. Large numbers of shore recoveries were interpreted to mean northerly displacements, while no shore returns were assumed to indicate southerly transport.

Cook notes, significantly, that in western Rhode Island Sound the surface and bottom water showed net westward drifts in July, which is in good agreement with Shonting's (1969) results, even if the general pattern of non-tidal circulation is northwesterly on the bottom for the greater part of Rhode Island Sound.

Based on the return data, there is evidence for the intermittent appearance of a large-scale cyclonic (counter-clockwise) eddy in the region, which is thought to encompass nearly all of northern Rhode Island Sound. The dump site location is near the center of this transient eddy system. Because of the location, however, the eddy would contribute little to the flow energy at the dump site even if the non-tidal pattern were considerably altered by it on the bottom from time to time.

Boat operators have consistently noted a strong southwest surface current in Rhode Island Sound at the time of the incoming tide. This may well be reflected in the direction of bottom motions. Although the response of the bottom layer to surface current changes may be sluggish, the adjustment of bottom flow will take place if conditions remain sufficiently uniform in time.

These studies, then, seem to indicate that the larger velocities may run west to southwest on the bottom in the summer months. The net bottom transport may be randomly directed, with a speed in the order of 0.10 knot or less, resulting in a possible maximum daily net displacement of approximately 2.4 nautical miles.

The flow patterns are probably dominated by the semidiurnal tidal component. One cannot expect simple anticyclonic rotation of velocity vectors in the dump site area, however, since it is located in a region which comes directly under the influence of currents from such extended water bodies as Narragansett Bay, Long Island Sound and Buzzard's Bay. Although the dump site may not be an energetic current environment, it is located in an interactive zone of several current influences. Shonting's measurements were made farther offshore, where the bottom water may not have been affected by the north-south tidal flow oscillations of Narragansett Bay, while the stronger influence of the east-west tidal flow associated with Long Island Sound probably did dominate the currents at these stations.

Bottom net transport measured at the dump site can be reasonably expected to result from interactions of tidal flows. If the estuarine circulation of Narragansett Bay were to play a major role in modifying the bottom circulation, conservation of salt would require a consistently northwest net transport. It is unlikely that any salt-wedge return flow into Narragansett Bay will be an important part of net bottom transport here, although salinity modifications of Bay origin may be measurable at the site.

CURRENT MEASUREMENTS AT THE DUMP SITE

A Hydro-Products model 502 recording current meter was used to gather bottom current data. The meter was placed near the west corner of the dump site in early March, 1970. The current meter record obtained at this time was unsatisfactory for analytical processing; the second record was of good quality, and was obtained from near the south buoy of the dump site between July 20 and July 24, 1970. The rotor of the current meter was approximately 1 foot from the bottom for this series of measurements.

The current meter was adjusted to operate at a rate of 6 sampling cycles per hour. Each cycle contained speed and direction points, taken alternately at four-second intervals for three minutes of each cycle. Cursory examination of the records showed that good mean (net displacement) velocities could be obtained by vector averaging 150 sampling cycle means which constituted the record for a 25-hour period. This time interval was chosen so that the average could be taken over two complete semidiurnal (dominating tidal component) periods, 12.4 hours each.

Figures 15-18 summarize the findings for the indicated periods. The data for each 25-hour period are presented in distribution diagrams. The left compass roses indicate the percentage of time the current was flowing in each of twelve compass sectors. An arrow marks the *direction of net displacement* for the period presented. The right diagrams show the speed probability density in intervals of 0.05 knots. The *net displacement speed* is marked on the speed distribution diagram. Directions refer to degrees magnetic, and speeds are in knots.

Before any comparisons are made between these measurements and previous work, one should note that the record is relatively short and may not be typical of behavior over a long period of time. The measurements were taken when tidal heights in the area were unusually large.

In contrast to Shonting's findings, the bottom records for the 4-day period exhibited and retained definite, regular and repeating patterns. Over the 4 days the speed distribution shifted toward the low end of the spectrum (to lower velocities in general). The shift was also reflected in the consistent decrease of the net displacement speed. Peak velocities were recorded in the first day and were between 0.30 and 0.35 knots.

The direction histograms show a "figure 8" configuration, with two major lobes about 150° apart. This pattern seems stable over the 4-day period. The current at no time (daily) flows in a 90° sector, i.e., no flow occurs in directions 270°-360° or 300°-030°. The speeds are also radically reduced in a direction 180° opposite the empty quadrant.

The speed distribution within each 30° direction sector indicates that the greatest velocities occur in the west-southwest sector in general, with subsidiary maxima in the in east-southeast and east-northeast sectors. However, the direction histograms show that west-southwest directions occur for a greater percentage of time than any other. This finding seems to substantiate the observation of area boat owners that the strong surface west-southwest currents on the incoming tide also dominate the bottom flow for the period of measurement.

The net transport velocities may be summarized in tabular form:

DATE	SPEED (kn)	DIRECTION (°magnetic)
July 20-21	0.08	157°
July 21-22	0.08	186°
July 22-23	0.05	162°
July 23-24	0.03	156°

While net transport direction changes from day to day do not follow a regular pattern, the speed decreases monotonically in time. Examination of the direction histograms indicates that the decrease in net transport speed may be closely correlated with the counterclockwise rotation of the "figure 8" flow pattern in time.

The general picture of circulation emerging from these limited measurements at the dump site indicates that this location is equally under the influence of tidal motions in and out of Narragansett Bay and the east-west tidal motions in Rhode Island Sound. Although the pattern may be stable for only shorter periods of time, it is characteristic of motions that can be attained by a combination of two, possibly interdependent, oscillations, as indicated above. Certainly, for the period of measurement, a more definite and regular circulation regime results in this nearshore location than at the offshore location studied by Shonting. Pattern rotation, with a simultaneous net movement decrease, is also indicative of flows that could arise from two oscillations. The considerable decrease of velocities in all directions, at a time of the month when tidal heights are maximum, further underlines the combined oscillatory nature of the flow. Depending on amplitude and phase differences of such oscillations, a "destructive interference" condition may well serve to effect such a decrease in flow velocities. Shonting postulated that reduced mean motions (net transport velocities) at the site studied by him may be due to the amplified appearance of tidal motions caused by large-scale perturbations. The dump site records indicate, however, that such reduced mean motions here, and the real amplification of tidal effects, may simply be due to the interaction of two oscillatory (semidiurnal) tidal components associated with Narragansett Bay (north-south) and Rhode Island Sound (east-west).

In summary the following conclusions may be reached about the bottom circulation at the dump site for the period of measurement. (1) The circulation is dominated by the semidiurnal tidal component; (2) the net transport is the daily average resultant of the tidal flow and is small; (3) the magnitude (speed) of the net "non-tidal" component of circulation may depend directly on the interaction of tidal currents in Narragansett Bay and Rhode Island Sound; (4) the direction of the non-tidal net component was consistently south-southeast, with a possible range of transport between 0.7 to 1.9 nautical miles per day, and (5) largest instantaneous speeds were recorded in the west-southwest direction.

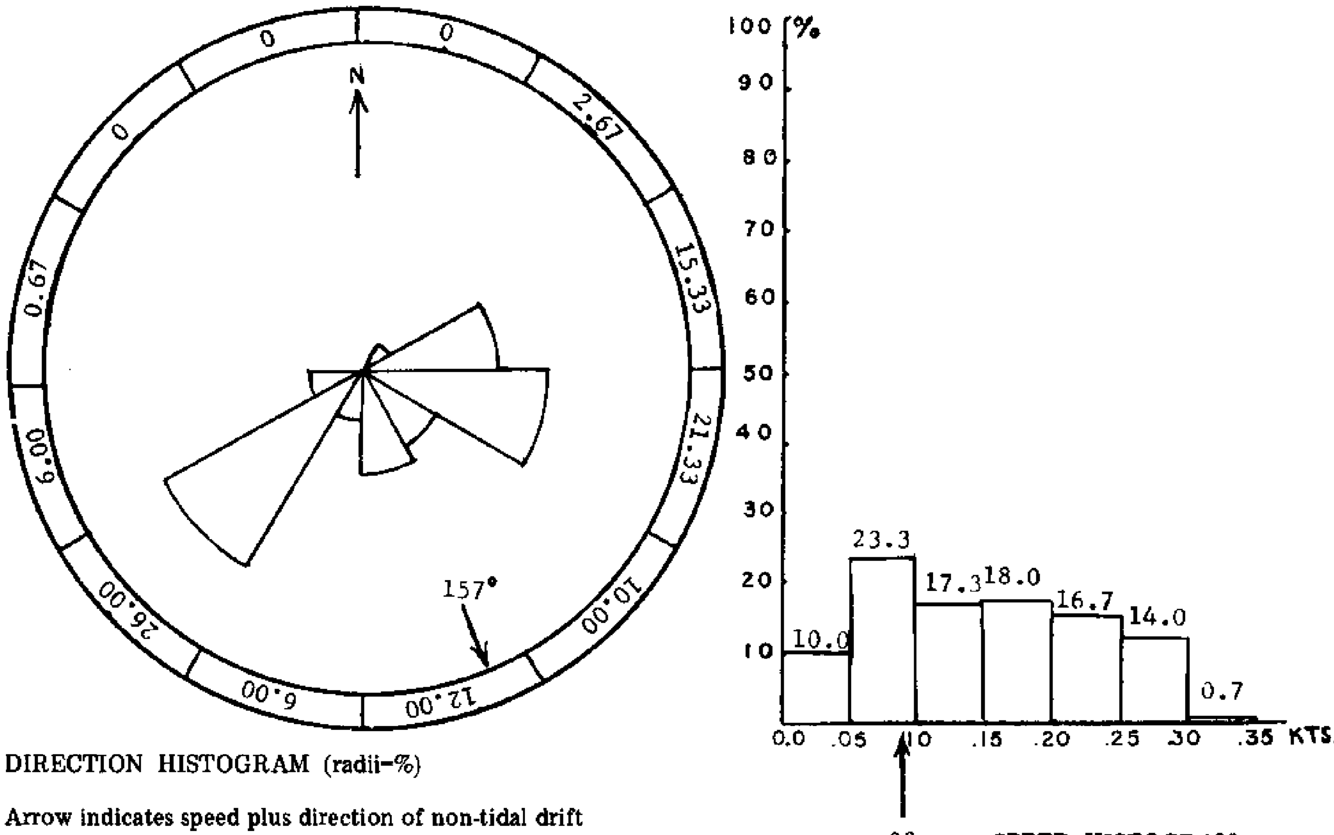


Fig. 15. Current meter records 1430 EST July 20-1520 EST July 21, 1970.

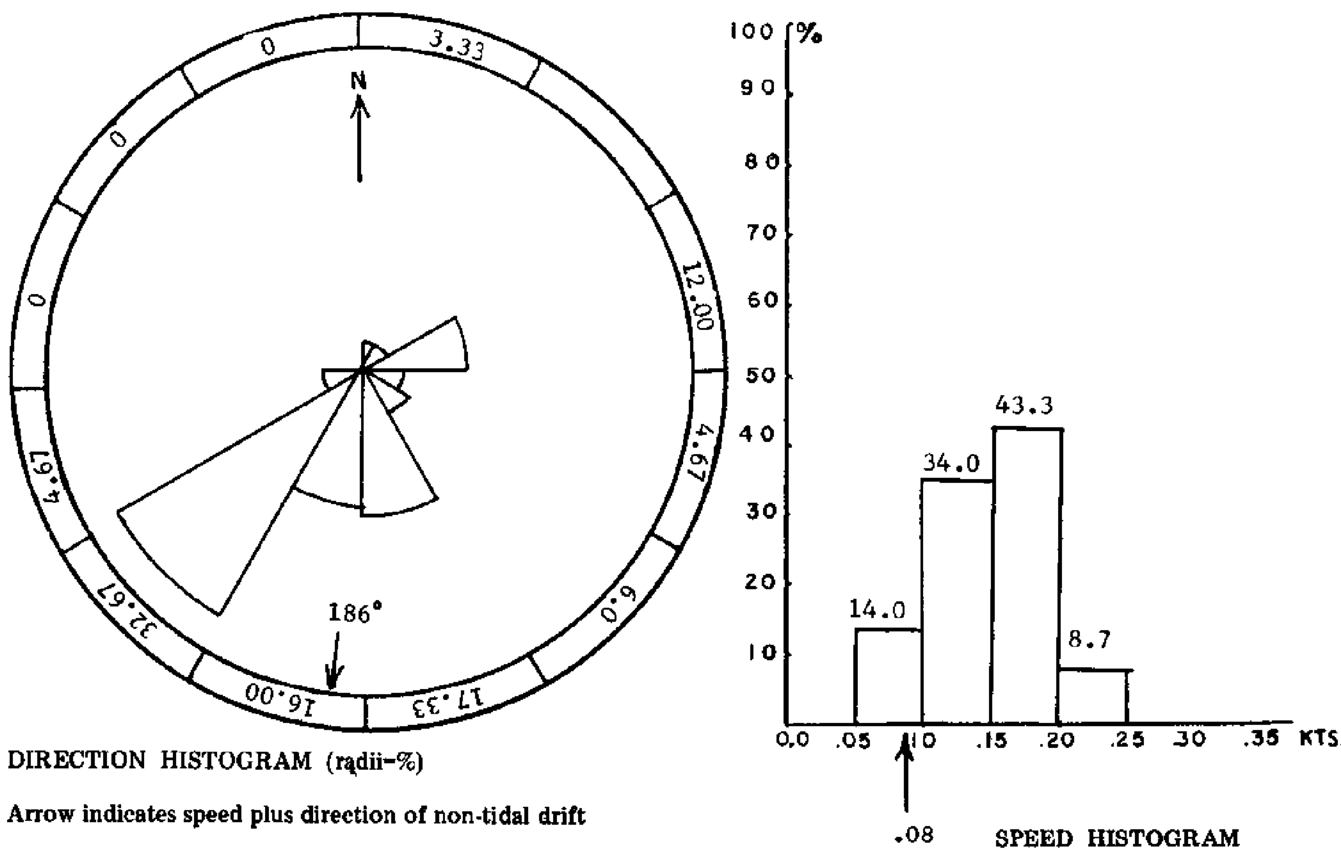
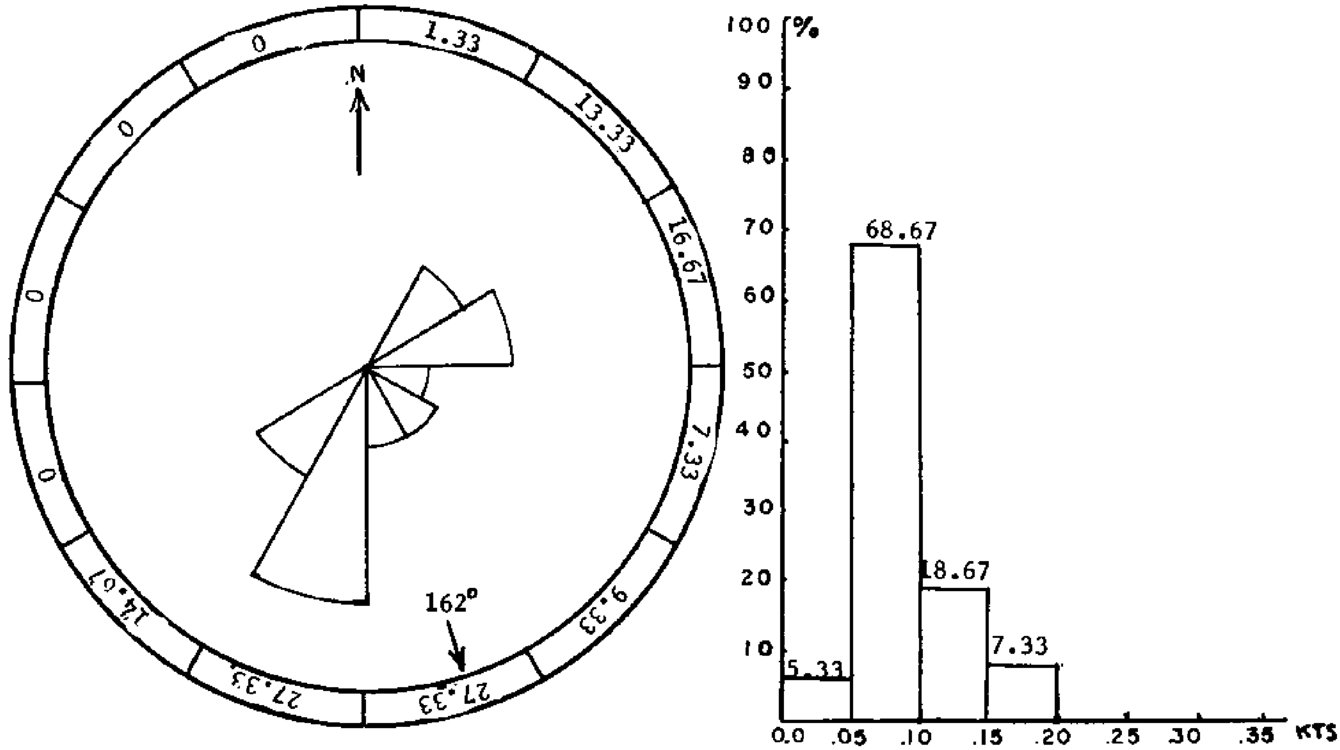


Fig. 16. Current meter records 1530 EST July 21-1620 EST July 22, 1970.

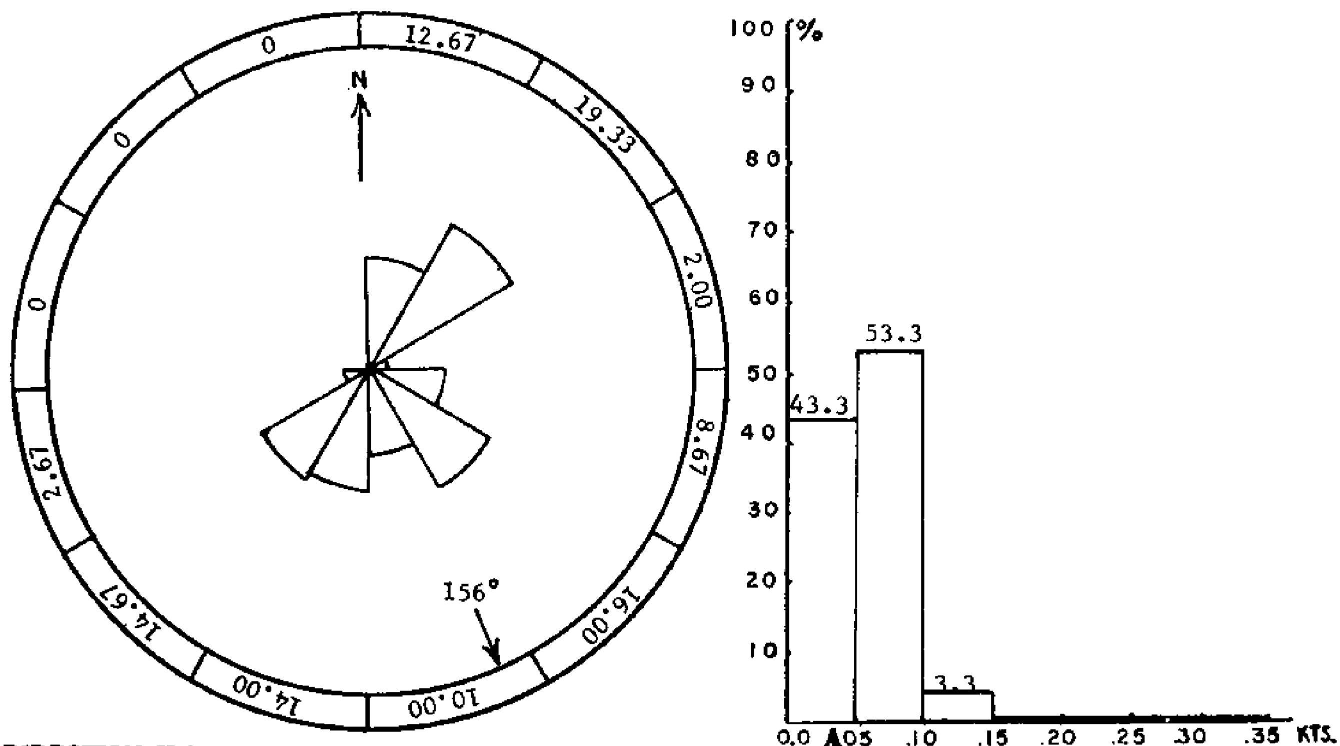


DIRECTION HISTOGRAM (radii=%)

Arrow indicates speed plus direction of non-tidal drift

.05 SPEED HISTOGRAM

Fig. 17. Current meter records 1630 EST July 22-1720 EST July 23, 1970.



DIRECTION HISTOGRAM (radii=%)

Arrow indicates speed plus direction of non-tidal drift

.03 SPEED HISTOGRAM

Fig. 18. Current meter records 1730 EST July 23-1820 EST July 24, 1970.

SURFACE WAVES KINEMATICS RELEVANT TO SEDIMENT DISTRIBUTION

The environment created by water movements of wave origin differs radically from that existing in their absence. Waves play a dual role in determining the distribution of sediments, acting both as a resuspending (erosion) and a transporting mechanism.

Once the dumped sediments settle on the bottom, re-entrainment into the water column is most likely to be effected by water particle motions produced by wave action. Currents in the dump site area are generally insufficient in magnitude to produce resuspension of settled sediments. As soon as the material is put into suspension by waves, it is available to the tidal currents for transport. Wave motion also induces a net transport drift at all depths in shallow water; this drift is sometimes referred to as a wave current. The wave drift is generally smaller than the instantaneous tidal current. Even so, wave drift may be significant in determining the total displacement of resuspended sediments.

Several wave theories help explain the role of waves in sediment transport. The theory of irrotational Stokes waves, however, seems to represent adequately the observed natural phenomena associated with surface gravity waves. Although wave energy is propagated by the motion of the surface deformation, waves also induce particle motions in the water column as the surface disturbance passes. Particle motions associated with gravity waves consist of an oscillatory motion with a small mass transport velocity superimposed on it in the direction of wave propagation.

The wave-induced motion of a particle in deep water is circular at any depth, with the orbital diameters decreasing exponentially from the surface to depth. As the wave proceeds into shallow water, bottom effects elongate the circular orbits, changing their shapes into ellipses. The vertical axes of elliptical orbits decrease linearly from the surface to a value of zero on the bottom. The horizontal axes also decrease; however, the change is relatively slower with depth. Shallow-water bottom effects start to dominate particle motions when the water depth is less than or equal to half of the wavelength. The average depth at the dump site results in considering the significant waves passing through the area as shallow water waves. The effect of surface waves will be felt on the bottom most of the time.

The magnitude of the horizontal component of orbital velocity is the primary factor in resuspending settled sediments. Since the motions are oscillatory, the peak velocity will determine the degree of resuspension of any particular sediment size. The maximum horizontal speed is directly proportional to wave height, and inversely proportional to wave period and depth.

The mass transport (wave drift) velocity mentioned above originates from open orbits developing for higher amplitude waves in a shallow water environment. This result is a measured departure arising from the theoretical assumption of small amplitudes which ceases to be valid when wave amplitudes become large. The particle, therefore, does not return to its original position in the orbit after a full cycle. Theoretical corrections for waves of finite height show that the particle motion is greater in its forward movement than in its backward movement. The particle, after one complete wave cycle, arrives forward of its initial position. A second order drift thus develops in the direction of wave propagation.

POTENTIAL EFFECTS OF WAVES ON DUMPING SEDIMENTS

Having examined the characteristics of surface gravity waves relevant to resuspension and wave-induced transport of sediments, it is instructive to consider the current speeds necessary for sediment erosion and transport. Figure 19 is a reproduction of a graph derived from the experimental measurements of Hjulstrom (1939). The plot specifies within the indicated bounds the current velocities required to erode, deposit and transport particulate matter of different grain sizes. The results apply to unconsolidated silica detritus which has been deposited in the environment normally, i.e., slow deposition, grain-by-grain, from suspension.

The material easiest to erode is within the 0.1- to 1.0-mm. size range. It is expected that if the sediment surface behaves as a normally deposited bottom environment, the smallest velocities that may cause resuspension must be at least in the order of 15 cm./sec. (0.3 knots). From the current

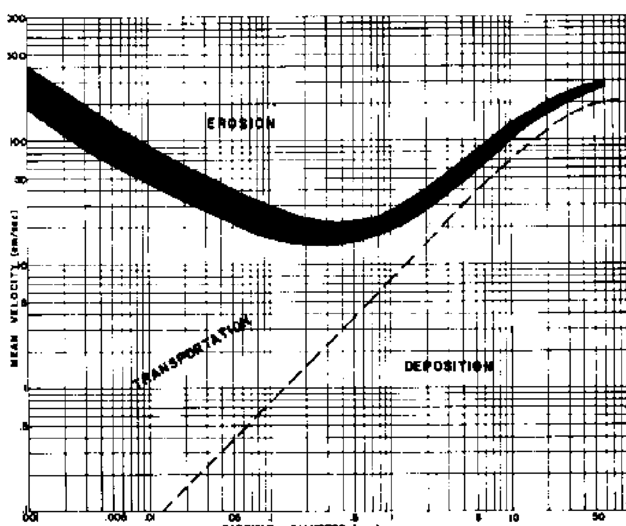


Fig. 19. Current velocity necessary for erosion, transportation, and deposition of sediments of various particle diameters (Hjulstrom, 1938).

record analysis (for the short-term measurement at the dump site), and from Shonting's (1969) and Cook's (1966) studies, it seems reasonable to conclude that bottom currents alone are not able to effect resuspension of normally deposited sediment. Yet Morton (1967) indicates an ample presence of suspended sediments in Rhode Island Sound waters, derived from various natural sediment sources in the area. Thus, it is necessary to examine the extent to which wave action in the Rhode Island Sound area is capable of developing the required bottom orbital velocities which are effective in resuspending deposited sediments.

The available wave data which provide estimates of the percentage of time that maximum particle velocities exceed 0.3 knots in the area come from two sources. Hogben and Lumb (1967) present a large set of visual estimates of wave height, period and direction made from many oceangoing ships, compiled according to internationally standardized procedures. The data are presented in tabular form for large areas over which sea-state conditions are assumed to be relatively homogeneous. Oviatt (1969a, 1969b) presents wave data recorded at the Point Judith Coast Guard Station between July, 1968 and February, 1969.

Wave heights and periods increase in the winter months, and greatest erosion of sediments can be expected at that time. For geologically significant waves, the heights vary from 1 to 10 feet and the periods are in the 5- to 16-second range from July to February at Point Judith. According to Hogben and Lumb (1967) the wave-induced maximum particle velocities should exceed 15.2 cm./sec. ($\sim$0.3 knots) 32 percent of the time (yearly) in Rhode Island Sound for 100 feet of water depth. In addition, velocities also exceed 30.5 cm./sec. ($\sim$0.6 knots) 18 percent of the time at this depth.

The following tabulation of calculated values fixes the wave heights necessary to yield a maximum bottom particle velocity of 15.2 cm./sec. ($\sim$0.3 knots) for different period waves at 100-foot water depth.

PERIOD (sec.):	7	10	13	16	19
HEIGHT (ft.):	7.08	2.99	2.34	2.12	2.00

Such significant waves as were recorded at Point Judith fall within the calculated values presented above. In fact, during a storm November 12-13, 1968, a total of 25 percent of the larger waves were capable of producing bottom velocities between 15 to 30 cm./sec. at 200 feet. These larger waves occurred for approximately 6 percent of the time during the storm, constituting 1.7 hours of real time of a 27-hour recording period.

The statistical evidence indicates that resuspension activity by waves should be relatively important at the roughly 100-foot depth of the dump site. This seems valid for most of the year, but such activity is especially significant during the winter months. Morton's (1967) results agree with this degree of activity and indicate that resuspension by currents and waves produces significant concentrations of suspended sediments in the water column.

It is difficult to assess the effectiveness of local waves in transporting suspended sediments out of a given area. A theoretical transport velocity resulting from averaging over the 5 periods in the tabulation above (waves which all produce velocities of 15.2 cm./sec.) results in a new daily displacement of 235 feet. This is small compared even to the net tidal velocity which can result in a maximum daily displacement of 2.4 nautical miles, as calculated from the dump site current measurements.

PHYSICAL EROSION MECHANISMS AND DUMP SITE DISPOSITION

Referring to figure 19 and to mechanical analyses performed on cores (obtained from the dump site in the summer of 1969), there is reason to believe on the basis of the evidence on currents and waves, that substantial alteration of the sediment distribution should have taken place. Roughly 80-90 percent of sediment grain sizes in most samples fall in the 0.1 to 1.0 mm. range for which erosion velocities are minimum. Currents and waves acting together would pose no difficulty to the erosion of the dumped material in theory (as discussed above). Bathymetric surveys over the past two years and recent observations of the spoil surface indicate that this is not the case.

The failure of theory and physical measurements to predict the state of the dump site configuration resides partially in the lack of extensive measurements, but more basically in the mode of deposition and physical disposition of the dredged material. Some of these factors and conjectures on dredged sediment behavior are outlined below.

1. The dredged sediments were compact and relatively free of water. The angular appearance of the dredged materials on barges attests to this.

2. Although most of the material was comprised of fine fractions, the spoil samples contained granules and pebbles. Lumps of clay were also fairly common. These erosion-resistant fractions may have sheltered the finer matrix from erosion.

3. The mode of deposition allowed the dumped material to stay together. Probably only a small amount of spoil went into suspension during dumping; most of the material was deposited as a mass unit.

4. Compaction may have taken place in the barge where the buoyant effect of water on original surface layers was absent.

5. The sediment surface of the dumping area was probably stabilized by selective removal of fines from the suspended fraction which originated at the time of the dump. Heavier unconsolidated fractions, put into suspension by the precipitous

nature of the dumping process, settle faster than the fine suspended matter. The graduated sorting of the surface layer results in the erosion of smaller sizes first, which leaves the coarse material as a pavement, or lag deposit. This erosion and lag deposit formation would be expected to take place during the winter.

6. Tube-building benthic organisms may have produced further erosion resistance on some parts of the dumping area. This effect will become more important when colonization of the spoil is complete.

Keeping these considerations in mind, it may be concluded that Hjulstrom's (1939) curve is not readily applicable to the theoretical prediction of dump site disposition on the basis of presently available physical data. Both the mode of deposition and the nature of the dumped material invalidate the minimum values of current velocity required to resuspend the dredged sediments for all particle sizes.

Under certain circumstances, currents and waves will result in the transport of fine materials from the dumping grounds. This may occur at the time of the dump or during a storm. Considering the distance to shore and transport velocities, it is likely that no larger-sized particles would reach the beaches before these would resettle. Smaller size fractions could reach the shore, but turbulent wave action in the breaker zone, especially during storms, acts as an effective barrier to deposition of fine materials. These materials will eventually settle in an area with similar grain size.

SUMMARY

1. Currents in the dump site region are dominated by the semi-diurnal tide. Instantaneous bottom currents rarely exceed 0.3 knots, whereas the net tidal transport velocity is no greater than 0.1 knots.

2. Currents alone are not effective in resuspending sediments.

3. During a significant portion of the year waves in the area could develop bottom velocities sufficient for the resuspension (erosion) of unconsolidated sediments.

4. The mode of deposition and mechanical characteristics of dredged materials apparently results in an erosion-resistant deposition. The dumped material cannot be considered unconsolidated, and theoretical predictions based on the behavior of unconsolidated sediments are not applicable.

5. Beaches in the region should remain free of dredge spoil traces from the dump site.

Review of Some Direct Effects of Spoil Dumping on Marine Animals

BURIAL

From a knowledge of the behavior and morphology of an animal under natural conditions it is possible to predict its relative ability to resist the pressure of an added layer of sediment and to burrow to the surface. *Nephtys incisa*, a large active polychaete, burrows freely through dense sediment. This species is expected to attain the surface after relatively deep burial. Bivalves of the genera *Macoma*, *Yoldia*, and *Nucula* which move horizontally are also expected to be able to recover from burial. Glude and Landers (1955) found no mortality of the hard clam *(Mercenaria mercenaria)* as the result of smothering from silt raised by shellfish dredging operations.

Attached sessile species are killed by burial. There have been several instances in which valuable oyster grounds have been destroyed as the result of either direct burial by the dumping of dredged spoil or by the sedimentation of silt raised by dredging operations (Masch, 1965; St. Amant, 1950).

Although attached bivalves were absent from the dump area, several species are present that were thought to have limited burrowing ability. Shafer (1962) stated that *Arctica islandica*, a commercially important species in the dump site area, could not survive in areas of rapid sedimentation in the North Sea because it was a weak burrower; Salenddin (1964), however, has described *Arctica* as a strong burrower. Experiments conducted by Hale (1972) show that some *Arctica* can reach the surface after burial by 4-5 cm. of spoil or 14 cm. of sand. Animals buried by 8-17 cm. of spoil established "blow holes" to the surface, but could not or did not burrow upward. These experiments indicate that slow sedimentation would probably not endanger the species.

Smaller animals of any type have the greatest chance of being destroyed. The fate of colonies of ampeliscid amphipods is of special interest due to the effect of their tubes in determining the nature of the sediment surface. Although these small animals (7 mm.) are probably destroyed by relatively shallow burial, they seem able to extend their tubes above a rapidly aggrading surface. Evidence of this was found in buried layers of tubes, underlying present surface colonies close to the dump site. Harrison (1967) observed a weekly deposition of more than ½ inch around amphipod tubes in Chesapeake Bay.

A burial experiment was conducted with animals from the lower Providence River in order to assess the likelihood of their surviving the dredging and dumping operation and becoming established on the offshore site. Sediment samples were taken with a Smith-McIntyre bottom grab at Station PS 5 (figure 12). The surface sediment containing most of the animals was separated from the dense subsurface sediment. Three cm. of the mixed surface sediment was placed in ten small aquaria (27 x 14 cm.) and buried with up to 21 cm. of subsurface sediment. One half of the surface was sampled after 24 hours and the remainder after 48 hours. The samples were passed through a 0.75-mm. sieve and the retained animals counted. Fourteen species were recovered but only three were abundant enough to be considered.

Nephtys incisa attained the surface in less than 24 hours from all depths. *Streblospio benedicti*, a very abundant, 1-cm. long, tube-dwelling polychaete, was able to reach the surface through up to 6 cm. of sediment. *Mulinia lateralis*, a small filter-feeding bivalve, reached the surface from all depths but many individuals took over 24 hours. It was concluded from this experiment that detectable numbers of these species probably reach the surface of the dumped spoil.

TURBIDITY

The increased concentration of suspended particles in the water during the dumping operation and after resuspension could affect animals by causing mechanical damage to respiratory surfaces and by diluting with non-food particles the food particles utilized by filter feeders.

Aquatic animals are able to tolerate rather high concentrations of suspended sediments for short periods. Rogers (1969) investigated the effects of exposure to suspended mineral solids on four species of estuarine fishes. Twenty-four-hour median tolerance limits ranged in value from more than 300 gm./liter for *Fundulus heteroclitus* to 50 gm./liter (50,000 ppm) for the stickle-back *(Apeltes quadracus)*. He noted that damage to fish was more a function of the presence of large angular particles in suspension than the optical turbidity of the suspension. Ritche (1970) held four species of fish in cages close to the effluent of a hydraulic dredge in upper Chesapeake Bay and recorded no lethal factors. He also examined the gills of 11 species of fish caught in the spoil disposal area and found no tissue damage.

Saila, Polgar, and Rogers (1968) exposed lobsters *(Homarus americanus)* to suspensions of up to 3,200 ppm of unpolluted estuarine silt and 900 ppm of Providence Harbor spoil sediment for 24 hours. No mortality was recorded which was directly attributable to sediment concentration. In a bottom-choice experiment made as part of the present study, four groups of eight lobsters were held for 48 hours in a large tank partially floored with Providence Harbor silt. As they burrowed in the silt the lobsters passed dense clouds of sediment through their gills. No mortality was recorded during the experiment or in a two-week period afterward. In tests at the Sandy Hook Marine Laboratory (1969) lobsters and crabs *(Cancer irroratus)* held in aerated aquaria with sewage sludge and dredge spoil remained alive for extended periods. It is concluded from these studies, and from observations indicating that mass resuspension of spoil probably occurs only during periods of heavy swell, that there will be no mortality of fish and lobsters in the dump site area caused by sediment load alone.

Until a sandy bottom is formed over the spoil dump, there will be more fine-grained particles in suspension there than there would be over natural bottom in the area. Filter-feeding benthic invertebrates take their food from water immediately off the bottom. Any excess suspended sediment must be either ingested or sorted from food particles before ingestion.

Selective feeding ability has been found in many filter feeders. It has been particularly well described in estuarine bivalves where sorting takes place on the gills and labial pulps. Rejected particles are entrapped in mucus strands and passed out as pseudo-feces. It seems likely that species found outside the estuary are less efficient at limiting their intake of mineral matter and may suffer a selective disadvantage on a bottom with excess fine sediment.

ANOXIA

Sewage sledge and the highly organic sediments of inner harbors have a high oxygen demand. Reduced chemical compounds take up oxygen immediately, while bacteria consume organic matter producing a biological oxygen demand continuing over a longer period. If these sediments are dispersed in a body of water with restricted mixing, dangerously low oxygen levels could be produced. Measurements of dissolved oxygen over the sewage sludge dumping grounds in New York Bight (Pearce, 1970) showed reductions from 7 ppm to less than 1 ppm 3 feet above the bottom. The factors important in the formation of anoxic bottom waters are rate of organic matter input, particle dispersal, and water mass circulation.

The organic matter content of Providence River sediments varied from a high of 10 percent in the inner harbor to a low of 1-3 percent in upper Narragansett Bay. Some of this organic matter consists of cellulose plant remains and hexane-soluble fractions which are resistant to microbial action. Dispersal of spoil during dumping is probably minimal as the dense material plunges immediately to the bottom forming a layer several feet thick. Only the upper few millimeters of this layer can contribute to oxygen removal from the water. Although only moderate currents pass over the bottom (.05-.30 knots), the volume of water and of dissolved oxygen seems ample to rapidly oxidize the surface of the spoil.

Animals buried by anaerobic sediments may die of anoxia before they can reach the surface. The most vulnerable group of animals may be the small crustaceans whose response to oxygen deficiency is increased ventilation. Some bivalve mollusks can incur oxygen debt, while some polychaetes lower their activity and metabolism when oxygen is low (Nicol, 1960). These mechanisms would aid escape from burial.

Sediments with a high percent of organic matter will remain anaerobic beneath the surface. Bader (1954) states that more than 3 percent organic matter in sediments may limit the concentration of non-tolerant infauna. The species found in Providence Harbor are examples of animals physiologically and behaviorally adapted for survival at low oxygen levels. Burrowing bivalves *(Mya)* and tube-dwelling polychaetes *(Streblospio* and *Pectinaria)* have efficient pumping mechanisms to carry dissolved oxygen to respiratory surfaces. Adults and larvae of *Polydora ligni* can tolerate oxygen concentrations as low as 1.5-2.5 ppm and 0.6-2.1 ppm, respectively (Richards, 1969). The deposit-feeding polychaete *Capitella capitata* survives in highly-polluted, low oxygen sediments throughout the world (Reish, 1959).

HYDROCARBONS

Saila, Polgar, and Rogers (1968) reported concentrations of 0.54-0.76 percent (dry-weight basis) of hexane extractable material in spoil samples from Providence Harbor which had been selected for analysis because of their high organic matter content. Farrington (1971) determined the hydrocarbon fraction of sediments from the Sabin Point area of the Providence River. The average value for three sampling dates was .2 percent dry weight. Gas chromatographic analysis indicated that these hydrocarbons had the characteristics of "aged petroleum." They were resistant higher boiling alkanes and aromatics. Farrington states that these fractions are relatively toxic. Low boiling hydrocarbons had apparently been lost by evaporation and biochemical modification.

The fact that most of the spoil on the dump site surface came from unpolluted areas decreases the possibility of adverse effects of hydrocarbons on animals colonizing the spoil. Concentrations below toxic levels may have ecological effects, however. Blumer (1969) has suggested that certain oil fractions in very low concentrations could interfere with the chemical senses of marine animals which mediate finding of food, escape from predators, selection of habitat, and sex attraction. Recent studies by Boylan *et al* (1972) show that water-soluble fractions of kerosene interfere with chemotaxis in a scavenging snail *(Nassarius)* and that various hydrocarbon fractions affect stress, feeding and social behavior of lobsters *(Homarus)*. On the spoil dumping ground, hydrocarbons could change the settling pattern of the larvae of benthic invertebrates or interfere with the ability of lobsters and crabs to find food.

Non-polar chemicals are many times more soluble in oil than in water and will become concentrated in sedimented oils. Hartung and Klingler (1970) reported calculated and empirical concentration factors of 1 million for DDT in an oil-water system. Although traces of dieldrin and chlordane have been found in quahogs from the Providence River by the Rhode Island Department of Health, total pesticide input probably has been quite low (Olney, 1970). Polychlorinated biphenols, which are widely used in plastics manufacture, are as toxic as chlorinated pesticides and would be expected to be concentrated in oil.

Toxic substances in oil would have varying effects on different species on the dump site. Detritus feeders and their predators would assimilate higher concentrations of these substances than would filter feeders which are consuming phytoplankton from unpolluted waters (Odum *et al.*, 1969; Woodwell *et al.*, 1967). Crustacea seem particularly sensitive to pesticides as well as heavy metal poisoning and may be the first group to show the effects of sediment pollution.

HEAVY METALS

Toxic metals have probably entered the sediments of Providence Harbor through effluents from metalworking industries and sewage treatment plants.

At the National Marine Water Quality Laboratory, West Kingston, Rhode Island, various workers are studying the concentrations of heavy metals in the sediments and benthic invertebrates of the Providence River and the toxicity and histopathologic effects of these metals on invertebrates and fish. Cadmium has attracted special interest due to acute toxicity (Eisler, 1971), synergistic effects with zinc and copper (Shuster and Pringle, 1969) and presence in electroplating wastes. High zinc levels have been found in both sediments and in quahogs *(Mercenaria mercenaria)* in the Providence River (Phelps, 1972).

In the dump site area polluting metals would be found in the sediment and not in the overlying water. Benthic infauna could accumulate metals through uptake from interstidal water and from ingested detritus or prey. Body loads of the various metals will be a function of the ability of each species to regulate the metals and the physical-chemical state of the metals in the sediment-water system.

Bryon and Hummerstone (1971) found that zinc was actively regulated in a polychaete *(Neries)*, while Cross *et al* (1970) ascribed a lack of correlation between zinc and in polychaetes and in sediments to regulation or to limited availability in the sediment. In contrast to the regulation of zinc, Bryon and Hummerstone (1971) found that *Neries* copper concentrations were correlated with concentrations in the sediment. In highly polluted areas populations had developed a tolerance to potentially toxic levels of copper.

Metals may be in a more available form in the subsurface environment than at the surface. Phelps *et al* (1969) found that selective deposit-feeding polychaetes (surface feeders) had lower levels of zinc than nonselective deposit feeders, carnivores, and omnivores (subsurface feeders).

The only values for heavy metal concentrations of the deposited spoil presently available are the results of four samples released by the Corps of Engineers, New England Division. These are given below with the Environmental Protection Agency criteria for determining acceptability of spoil disposal. Average values of these metals in granites (Turekian and Wedepohl, 1961) suggest that some of the lead and zinc in fine detrital sediments may have a natural origin.

	R.I. SOUND SPOIL				EPA CRITERIA	GRANITE ROCK HIGH CA	LOW CA
A.	2.18	0.75	0.82	1.27	6.0	—	—
B.	15.5	8.1	7.9	55.7	50	15	19
C.	0.6	0.24	0.21	0.19	1.0	.08	.08
D.	63.7	48.7	23.8	62.1	50	60	39

A. volatile solids (%); B. lead (ppm); C. mercury (ppm); D. zinc (ppm).

Although many more samples are necessary to characterize the dump site because of the patchiness of the sediments, it is believed that much of the spoil from areas where metal pollution might be expected has been buried by spoil from areas with low metal levels.

CHANGE IN GRAIN-SIZE DISTRIBUTION

Dense populations of subtidal filter feeders are found on well-sorted fine-sand bottoms. They are adapted to an environment with moderate circulation and physical stability (Sanders, 1958; Carriker, 1967). Deposit feeders, those that either select food particles from the sediments or ingest the sediment completely, are more abundant on fine sediments where more food is found on the bottom than is available from weak currents. Sanders (1956, 1958) correlated high numbers of small deposit feeders with sediments containing 20-40 percent clay. The type of tube, the depth of burrowing, and the type of food collection of benthic fauna are adapted to both the hydrographic regime and to sediment characteristics which are correlated with the hydrography. When fine-grained spoil sediments are dumped in an area which normally supports a sandy bottom community it is not possible to predict, *a priori*, whether sediment characteristics or hydrographic characteristics will determine the makeup of the colonizing community.

Any cobbles or boulders on the surface of the spoil will be available for colonization by barnacles, sponges, hydroides, and other epifauna.

Effects of Spoil Dumping on the Benthic Invertebrates of the Sound

INTRODUCTION

Studies of environmental disturbance can emphasize the response of either individual species or of the assemblage of animals in an area taken as a whole. This study emphasizes the latter, or synecological approach. The variables at this level include species diversity, patterns of species abundance, and similarity between collections. It is believed that a realistic assessment of disturbance to an environment can be made at this level. Before valid conclusions can be made about the effect of dredge spoil on any individual species it is necessary to have a thorough knowledge of its spatial and temporal distribution, feeding habits, and ability to select substrate. This information is available for few estuarine species and probably for no offshore ones.

Any natural sea bottom has an assemblage of invertebrate animals living in the sediment (infauna) and on the surface (epifauna). A total of 40-100 species of macrobenthic species might be found on a square meter of bottom in an estuary or on the continental shelf in temperate regions. Macrobenthic species are often operationally defined as those animals which are retained on a 1 mm. sieve. The species found and their relative abundance vary with the properties of the water and sediment. This variation is neither continuous nor random. Reoccurring assemblages or communities characterized by the same dominant species and having the same pattern of subdominants cover wide areas. The muddy bottoms of Long Island Sound, Narragansett Bay, and Buzzards Bay all support populations of *Nephtys incisa*, a polychaete worm, and *Nucula proxima* and *Yoldia limatula*, deposit-feeding bivalves. Sanders (1956, 1958) named this the *N. incisa-Y. limatula* community in Long Island Sound and the *N. incisa-N. proxima* community in Buzzards Bay. All three of these estuaries have ampeliscid amphipod colonies on sandy bottoms. Sanders (1958) named these *Ampelisca* spp. communities.

Such assemblages were first named only as statistical units to aid in the determination of the fish food potential of the sea floor (Thorsen, 1957). The hypothesis was soon made, however, that there was biological interaction and accommodation within such communities.

There is variance of opinion as to the degree of this interaction. One view holds that the species found in an area are merely all adapted to the level and variability of the physical parameters of the environment and have successfully competed with the other species for space and food. The contrasting view is that the community is a superorganism whose parts (the species) have naturally evolved to provide efficient use of space and energy and to adjust for environmental variations in a way that preserves the community. The groups of animals found in the polluted and physically variable Providence River can best be described in the first way. The communities of the more stable Rhode Island Sound environment may be expected to show more species interaction.

Neither the theory of species interaction in benthic communities nor the validity of the measures used to indicate this interaction has been rigorously tested. This analysis of the recolonization of spoil-covered bottom provides an opportunity to test the utility of some of these measures.

METHODS

Quantitative samples of the bottom were taken with a 1/10 M^2 Smith-McIntyre grab. This grab has been shown to be reliable in rough waters (Lie, 1968) and efficient in sampling motile epifauna (Wigley, 1967). One or two cores with a 28 $cm.^2$ surface area were taken from the grab for sediment analysis. In several samples these were used for counts of small, very abundant species. The water draining from the sampler was collected and filtered to retain any amphipods which had left the sediment surface.

The sediment was brought back to the laboratory and gently sieved with salt water through a nylon screen with 0.75-mm. mesh size. This size is a compromise between a 1 mm. mesh which would retain fewer animals and an 0.5 mm. mesh which would retain large quantities of sediment and detritus. These screens were clamped onto a box frame with an area of 1 square foot. The animals were relaxed with 7 percent $MgCl_2$, fixed with 10 percent formaldehyde and stained with rose bengal while still on the screens. Leaving the animals on the screens until they are fixed and stained minimizes loss of small species and damage to soft-bodied ones.

Animals were separated from the coarse sediment particles and plant detritus remaining on the screens, sorted by species and counted. Identifications were made using Smith (1964) for all groups; Pettibone (1963) and Hartman (1964) for polychaetes; Abbot (1954) for mollusks; and Kunkel (1918), Chevreux and Fage (1925), and Mills (1967b) for amphipods. The species list has not yet been verified.

This report is based on the results from stations for which species counts have been completed for duplicate or triplicate samples. Partially-counted samples from the Providence River, a series of samples from near the alternate dump site off Point Judith, and qualitative grab samples from the dump site all contributed to an understanding of how representative the samples reported on are.

RESULTS AND DISCUSSION

1. Fauna of the Providence River

Various parts of the dredge spoil source area were sampled to find what animals were being introduced offshore with the spoil. These data also indicate the general level of pollution in the spoil source area.

It was possible to distinguish the assemblage of species found in Providence Harbor from those of the seaward parts of the dredge area. The salinity of the surface water of the harbor varies from <10-27 o/oo (Hicks, 1959). No animals were found in samples from the harbor bottom itself. Recent dredging activity, an almost liquid surface

Table 1. *Fauna collected from the Providence River dredging area.*

Species	Providence Harbor Ekman dredge, pipe dredge (PG1) PG21	PG22	PG4	PG6	PG1	Providence River 1/10M² Smith-McIntyre grab PS11	PS12	PS31	PS32	PS33	PS41	PS42	PS51	PS52	PS53	Dredge spoil on barge (large animals)
ARTHROPODA																
Carinogammarus mucronatus			1													
Crangon septemspinosus								2								
Palaemonetes pugio			10													
Xiphosura polyphemus							*									*
POLYCHAETA																
Ampharete arctica										3			1	1		
Heteromastus filiformis						13	*	_4880+_	_600_				_920_	*	_70_	
Capitella capitata						10	*				2	*	_1100_	_600_	_70_	
Cirratulid						23	*									
Pherusa affinis							*			1			3	2		
Glycera americanus						1		3					1	1		
Glycinde solitaria						10	*		4	15			1			
Podarke obscura											68	*				
Nepthys incisa								30	24	29			13	16	15	
Nereis succinea	27	9	2	5	*						15	*				
Nereis virens								1			1					
Pectinaria gouldi								53	18	54						
Eteone heteropoda						3	*	1			17	*	5	16		
Eumida sanguinea						1										
Paranaites speciosa						1		10		1			2	1		
Polydora ligni	3	1			*			3	4	3	_138_	*	1	3		
Spio filicornis								1								
Streblospio benedicti	1000+	1000+	100+	1000+	*	29	*	_8500_	_5650_		_1000+_	*	_6450_	_9300_	_354_	
MOLLUSCA																
Yoldia limatula									_1360_						22	
Macoma balthica	2	2		1	*						1					
Mya arenaria	35	22			*				35	2	5	*		3	1	
Mulinia lateralis								_4220_	_8700_		_800_	*	_320_	_2660_	_1560_	
Mercenaria mercenaria						1	3		5							
Busycon canaliculatum																*
Nassarius trivittatus						3		12	15	87		*		4	12	
Nassarius obsoletus	24	1	50	29	*											
Polinices duplicata										1						*
ECHINODERMATA																
Asterias forbesi																*

*indicates that the species was present but not counted
+italicized numbers are those for 1/10M² based on 28.2 cm² subsamples

sediment layer, and low oxygen concentration all contributed to the absence of macrobenthos here. Grab samples taken from shallow bottom (3-10 feet deep) on the east side of the harbor (PG 1, PG 2, PG 4, PG 6) and from south of Fields Point (PS 4) yielded considerable numbers of the following species (fig. 12):

Nereis succinea, deposit-feeding polychaete
Streblospio benedicti, deposit-feeding polychaete
Mya arenaria, suspension-feeding bivalve
Macoma balthica, suspension-feeding bivalve
Nassarius obsoletus, deposit-feeding gastropod;

Polydora ligni, a deposit-feeding polychaete, and *Palaemonetes pugio*, an omnivorous decapod shrimp, were also present.

These species and genera are familiar pollution-resistant organisms. Wass (1967) compares *P. ligni*, *S. benedicti* and *N. succinea* to weeds "which proliferate over broad areas of man's disclimaxes." Dean (1970) identifies *S. benedicti* as a possible key pollution-indicator organism. It is necessary to consider, however, whether these species, all adapted to survive in highly variable environments, might be found in the Providence River if it were unpolluted. These same species are abundant in the brackish waters of unpolluted estuaries where salinity varies from 0-10 percent and in salt marsh areas where salinity is low and variable and oxygen is sometimes limiting.

It is necessary to consider the species missing from a natural brackish water fauna in order to show the effect of pollution. About 20 species would be expected in this salinity zone in an undisturbed environment (Hedgpeth, 1957; Sanders *et al.*, 1965; Stickney and Stringer, 1957). Some important species which are absent are the oyster *(Crassostrea virginica)*, the polychaetes *Scolecolepides viridis* and *Pygospio elegans*, the mollusks *Gemma gemma* and *Hydrobia sp.*, gammarid amphipods, and all intertidal bivalves and barnacles.

It may be concluded that the fauna of Providence Harbor are limited not only by low oxygen concentrations and low and variable salinity, but also by toxic materials in the water and/or sediment.

Below Fields Point the salinity varies from 20-30 o/oo and the water quality is considerably higher than in Providence Harbor. Table 1 lists 30 benthic species collected in a limited number of samples from this zone. The shallow bottom on either side of the dredged channel has high densities of quahogs (Saila *et al.*, 1967). Although stations PS 1 and PS 2 yielded quahogs, the sediment was soft, black and anarobic below the surface. The fauna were somewhat limited and included *Capitella capitata*, an indicator of high organic matter concentration.

The bottom of a part of the channel which had not been dredged yet, sampled at stations PS 3 and PS 6, had a characteristic appearance. Lineations and a lag deposit of empty shells indicated an appreciable current. The sediment was compact and the upper 5 mm. was oxygenated. The following species were abundant at these stations:

Nephtys incisa, deposit-feeding polychaete
Streblospio benedicti, deposit-feeding polychaete
Capitella capitata, deposit-feeding polychaete
Heteromastus filiformis, deposit-feeding polychaete
Glycinde solitaria, deposit-feeding polychaete
Pectinaria gouldi, deposit-feeding polychaete
Nassarius trivittatus, deposit-feeding gastropod
Mulinia lateralis, suspension-feeding bivalve
Yoldia limatula, deposit-feeding bivalve

The rapid sedimentation taking place in these areas apparently supplies an abundance of food to deposit feeders. As a result of the two-layered hydrographic structure of the estuary, bottom water with relatively high oxygen concentration and relatively constant salinity flows north, providing a less polluted environment than that found in the surface waters.

2. Benthic Communities of the Sound

The benthic invertebrate communities of Rhode Island Sound are easily separated from those of Narragansett Bay (Phelps, 1958). Although they have some species in common with the estuarine communities, often different species of the same genera are found on analogous bottom types. These species are adapted for life in full salinity seawater with less temperature variation and lower average suspended sediment load than are found in estuaries.

The sediment in the dump site area consists of fine sand. Medium sand is found in shallower water to the north and east. The silt content increases gradually toward the west and reaches a maximum just east of Point Judith (fig. 13). Stations were chosen which would sample the major sediment types in order to show whether they supported distinct faunal assemblages. A knowledge of these assemblages is necessary to recognize the source of species colonizing the spoil.

Various numerical measures have been used to show the similarity between collections of animals. In this report the percent similarity of species composition is used as an index to show how closely pairs of samples are related. This index, used by Sanders (1960) and Wiener (1960) with macrobenthic and meiofaunal samples from Buzzards Bay, is considerably more straightforward than indexes using prominence values. (Pearson *et al.*, 1967) or information theory (Horn, 1966). Percent similarity = $\Sigma \min(a,b)$ in which a and b are, for a given species, the percentages of samples A and B which that species represents. This index

Table 2. *Sediment characteristics of the 1/10 M^2 biological samples.*

Station	Depth (Feet)	Visual Description	Loss on Ignition (%)	Median Particle Size (mm.)	Sorting Coefficient
7-1		Clean yellow sand	—	—	—
7-2	90	Clean yellow sand	1.0	0.25	1.30
7-3		Tubes on olive/yellow sand	1.5	0.21	1.39
9-1		Grey/black silt,	—	—	—
9-2	106	surface oxidized,	4.0	0.06	1.13
9-3		fine worm tubes	4.0	0.06	1.27
8-1		Coarse grey sand/shells	0.6	0.350	2.97
8-2	96	Sand/silt/soft clay	3.0	0.062	2.83
8-3		Coarse grey sand/shells	—	—	—
10-1		Sand/silt/clay,	3.7	0.030	2.58
10-2	99	oil droplets,	3.6	0.035	2.23
10-3		varved sandy clay	3.0	0.042	2.32
11-1		Silt/dense clay, tubes	—	—	—
11-2	98	Silt/brown clay	3.4	0.25	2.71
11-3		Silt/pebbles/ clay, tubes	2.8	0.15	2.53
14-1		Olive sand	2.2	0.13	1.54
14-2	100	Many amphipod tubes	2.0	0.10	1.49

has been criticized as overvaluing shared dominant species to the neglect of differences in overall community composition (Whittaker and Fairbanks, 1958).

A percent similarity for each pair of samples compared in this report is placed in a matrix (fig. 20). The samples are rearranged so that closely related samples are in groups. Figure 21 shows the percent similarity after the dominant *A. agassizi* was removed from the records of five samples. Sanders (1960) obtained an average index value of 69.3 in replicate samples from a single station and 31.2 and 37.2 in samples from distinct community types in Buzzards Bay. In this study three faunal assemblages were identified on the basis of visual appearance, dominant species, and similarity between samples of over 30 percent.

The samples 7-1 and 7-2 are representative of the clean medium-sand found east and north of the dump site. The number of individuals and species from these samples were 426/29 and 351/25. Some characteristic species were:

- *Byblis serrata*, suspension-feeding amphipod
- haustoriid sp., deposit-feeding amphipod
- *Cirolana concharum*, scavenging isopod
- *Echinarachnius parma*, deposit-feeding echinoid
- *Jaculella obtusa*, detritus-feeding arenaceous foraminifera

These species are part of the sand-bottom fauna described by Wigley (1968) and Smith (1950) from areas with substantial wave and current activity.

Samples 7-3, 14-1 and 14-2 are closely related. They represent the amphipod-dominated bottom surrounding the spoil dump. Station 14 is treated as unaffected by spoil although it is close enough to the dump area to have received some sedimentation of spoil materials. The number of individuals and species from these samples were 1451/49 for 7-3, 3272/44 for 14-1 and 1999/46 for 14-2. Some abundant species were:

- *Ampelisca agassizi*, deposit-feeding amphipod
- *Ampelisca vadorum*, suspension-feeding amphipod
- *Byblis serrata*, suspension-feeding amphipod
- *Unciola irrorata*, deposit-feeding amphipod
- *Leptocherius pinguis*, suspension-feeding amphipod
- *Orchomella pinguis*, deposit-feeding amphipod
- *Phoxocephalus holbolli*, deposit-feeding amphipod
- *Ptilanthura tenuis*, deposit-feeding amphipod
- *Diastylis spp.*, deposit-feeding cumacid

Many polychaete species were represented by a few individuals. Small bivalves were nearly absent. *Arctica islandica*, a large bivalve which was too scattered to be properly sampled by a 1/10 M^2 grab, seemed to have a distribution correlated with the presence of ampelisca.

The dominant and subdominant species of these samples were generally similar to those of the *Ampelisca spp.* communities which Sanders (1956, 1958) described in Long Island Sound and Buzzards Bay. These samples differed from the more estuarine *Ampelisca* communities in the dominance of *A. agassizi.* This species is probably characteristic of silty sands on the continental shelf. Southern New England estuaries support *A. vadorum* (*A. spinipes* of Sanders) and *A. verrilli* (*A. macrocephala* of Sanders) on sandy bottoms and *A. abdita* (*A. spinipes* of Sanders [1958], Phelps [1958], and Stickney and Stringer [1957]) on silty bottoms. Mills (1967) stated that little is known of the choice of substrate or mode of feeding of *A. agassizi.* Preliminary observations in a saltwater flume indicate that it is a deposit feeder, scraping the bottom around its tube with its extremely long second antennae.

The samples from station 9 are representative of the silty area west of Point Judith. The faunal assemblage is very dissimilar from those of the sandy bottom stations. The numbers of individuals and species recovered were 576/41, 562/41, and 484/35. The characteristic species included:

- *Cerianthus americanus*, suspension-feeding anthozoan (anemone-like)
- *Edwardsia sp.*, suspension-feeding actiniarian (anemone)
- *Bostrichobranchus pilularis*, suspension-feeding tunicate
- *Pitar morrhuana*, suspension-feeding bivalve
- *Periploma papyratium*, suspension-feeding bivalve
- *Nucula delphinodonta*, deposit-feeding bivalve
- *Nucula proxima*, deposit-feeding bivalve
- *Ampelisca abdita*, suspension-feeding amphipod

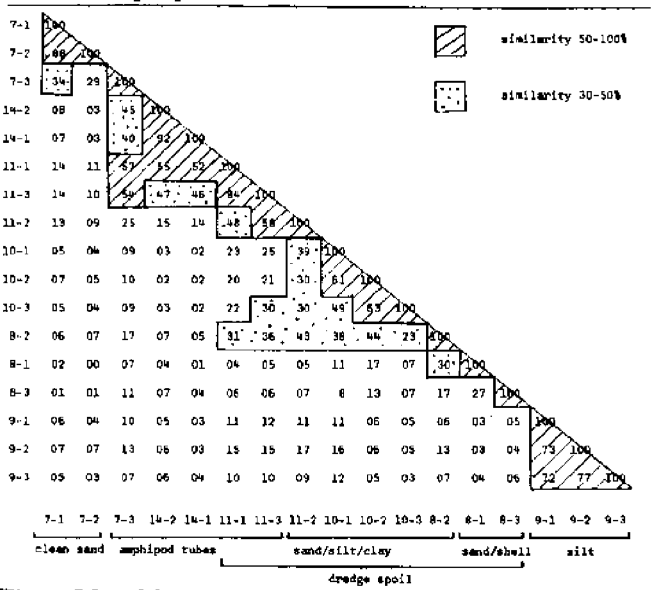


Fig. 20. Matrix of faunal similarity indexes between 1/10 M^2 samples.

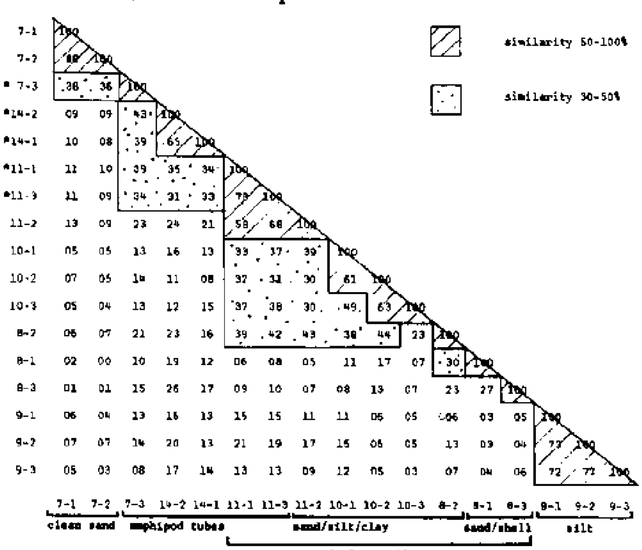


Fig. 21. Matrix of faunal similarity indexes between 1/10 M^2 samples with a record of 1 *Ampelsica agassizi* substituted for the actual number.

- sabellariid spp. (4), suspension-feeding polychaetes
- *Pherusa affinis*, deposit-feeding polychaete
- *Lumbrineris fragilis*, deposit-feeding polychaete
- *Clymenella torquata*, deposit-feeding polychaete
- *Owenia fusiformis* deposit-feeding polychaete
- *Sternaspis scutata*, deposit-feeding polychaete
- *Polycirrus sp.*, deposit-feeding polychaete

This assemblage includes species which occur in silt-clay estuarine sediments *(P. morrhuana, N. proxima, A. abdita, Pherusa affinis)* as well as species characteristic of silt-clay offshore sediments *(S. scutata, Polycirrus sp.).* The dominant species, however, are a unique group of suspension feeders adapted for a soft bottom. Although the sediment in this area is soft and muddy the clay content is only 7-10 percent (McMaster, 1970, station 9 this study). Apparently not enough organically rich particles settle out here to support a dominant detritus-feeding population. The current velocity is adequate to bring food to suspension feeders which are able to find purchase in the soft sediments. These suspension feeders occupy tubes or are buried in the sediment. This contrasts with the epifaunal habit of the familiar anemones, tunicates, and suspension-feeding polychaetes found on hard bottoms.

There are several other species which are characteristic of Rhode Island Sound bottoms, but which were not collected in the samples taken in this study. The bivalve *Cerastoderma pinnulatum* is found on sand bottoms at the mouth of Narragansett Bay (Phelps, 1958). *Ampelisca verrilli* occurs on sandy silt at the mouth of the west passage of Narragansett Bay. The bivalves *Astarte borealis, Cardita borealis*, and *Astarte undata* and the gastropod *Colus pygmaea* have been collected on silty sand in Rhode Island Sound.

A complete analysis of the silty-sand fauna of Rhode Island Sound would probably reveal a patchwork of species associations adapted to different hydrographic and sedimentary conditions. Such an analysis would be a formidable task because of the time required to sort and identify the individuals and species in the many samples required.

3. Fauna Found on the Spoil

Though spoil dumping was continuing during this study, the center of activity moved from the center of the dump site to the west corner. Areas of spoil on the southeast edge of the site had been exposed to animal colonization for periods which could have been as long as three years. Stations 8, 10, and 11 form a transect across this area (fig. 2), but the lengths of time these surfaces had been exposed is unknown. Progressively larger animal populations are found away from the dump center.

Table 3. *Number of individuals of each species recovered from 1/10 M^2 samples from Rhode Island Sound.*

Species	Station 7			9			8			10			11			14	
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2
PROTOZOA																	
Jaculella obtusa	*	*	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CNIDARIA																	
Cerianthus americanus	0	0	1	10	5	4	0	0	0	2	0	2	0	0	0	0	0
Edwardsia sp.	0	0	0	52	42	35	0	0	0	1	0	0	2	0	2	0	4
NEMERTEA																	
Cerebratulus lacteus	0	0	2	10	11	7	0	0	1	2	0	0	3	1	2	2	2
Nemertine sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARTHROPODA																	
Ampelisca abdita	0	0	0	11	7	1	0	0	0	0	0	0	0	0	0	0	1
Ampelisca agassizi	20	4	468	0	0	0	0	0	0	0	0	0	717	34	654	2875	1671
Ampelisca vadorum	2	0	109	0	0	0	0	0	0	0	0	0	2	0	1	0	0
Byblis serrata	251	211	163	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Corophium cylindricum	5	1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corophium sp.	0	0	1	3	1	0	0	0	0	0	0	0	1	0	0	0	0
Ericthonius hunteri	0	0	2	1	0	0	0	0	0	0	0	0	9	3	16	7	7
Ericthonius difformis	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0
Unciola irrorata	0	0	96	0	0	0	4	0	11	0	0	0	36	4	30	44	59
Leptocheirus pinguis	12	11	83	3	25	0	0	25	0	0	0	0	257	176	339	6	17
Photis reinhardi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0
Photis sp.	0	0	28	16	12	0	0	0	0	0	0	3	6	4	8	2	6
Orchomella pinguis	0	0	4	0	0	0	0	0	0	0	0	0	7	0	0	52	14
Tmetonyx cicada	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lysianassid sp. A	5	1	0	1	0	0	1	0	0	0	0	0	0	0	0	1	2
Lysianassid sp. B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Phoxocephalus holbolli	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	17	4
Monoculodes edwardsi	1	0	0	0	0	1	0	0	2	0	0	0	1	0	0	0	0
Stenothoe minuta	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Calliopiid sp.	0	0	0	0	0	0	0	0	0	0	1	2	3	5	1	0	0
Haustoriid sp.	5	7	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dulichia porrecta	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Amphipod sp. A	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Amphipod sp. B	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Amphipod sp. C	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0
Ptilanthura tenuis	4	2	18	0	0	0	0	0	0	0	0	0	3	0	1	16	13
Cirolana concharum	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Edotea triloba	0	0	0	2	3	6	0	0	0	0	0	0	0	0	0	0	0
Edotea sp.	0	0	*	0	0	0	0	0	0	0	0	0	*	*	*	0	0
Diastylis quadrispinosa	0	0	0	0	2	1	0	3	0	0	0	0	0	0	2	15	9
Diastylis sculpta	1	0	9	2	5	9	0	0	0	0	0	0	21	5	10	18	21
Eudorella hispida	0	0	112	7	2	12	0	5	1	0	0	0	60	5	28	66	79
Lamprops quadriplicata	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Peneus braziliensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Cancer sp. (megalops)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2
Balanus amphitrite neveus	0	0	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0
Ostracod sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
POLYCHAETA																	
Drilonereis longa	0	0	0	5	6	4	0	0	0	0	0	0	0	0	1	4	2
Ampharete arctica	0	0	0	3	5	6	1	0	0	5	0	0	4	0	5	0	4
Heteromastus filiformis	0	0	36	2	4	0	0	5	0	22	35	218	36	0	42	4	7
Capitella capitata	1	0	5	0	0	0	0	0	0	0	0	0	1	0	4	7	4
Cirratulid	0	0	0	8	3	15	0	0	0	0	0	0	0	0	0	0	0
Tharyx acutus	13	13	62	0	0	0	0	5	0	28	27	188	179	40	155	6	7
Pherusa affinis	0	0	1	34	18	24	0	1	0	0	0	0	5	3	10	2	2
Ophioglycera gigantea	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lumbrineris tenuis	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lumbrineris fragilis	1	1	0	13	15	22	0	0	0	0	0	0	0	0	0	0	0
Ninoe nigripes	0	0	0	7	25	7	0	11	0	8	0	3	26	20	39	5	4
Clymenella torquata	5	7	13	42	21	5	0	0	0	0	0	0	25	0	4	3	1
Aglaophamus circinata	14	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nephtys caeca	0	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nephtys incisa	0	0	0	12	7	8	1	32	1	36	37	45	8	40	40	3	8
Nereis sp.	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0

Species	Station 7			9			8			10			11			14	
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2
Ammotrypane aulogaster	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1
Scoloplos acutus	3	0	13	5	6	5	0	0	0	0	0	0	0	0	0	3	1
Owenia fusiformis	0	0	1	16	0	12	0	0	0	0	0	0	0	0	1	3	2
Aricidea jeffreysii	2	3	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pectinaria gouldii	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Eteone heteropoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0
Eteone lactea	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Eteone longa	0	0	0	0	0	0	0	0	0	0	13	23	21	5	16	1	2
Paranaitis speciosa	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Phyllodoce mucosa	1	2	11	0	0	0	0	0	0	0	0	0	5	1	3	6	2
Harmothoe extenuata	0	0	0	0	0	0	0	0	0	3	1	5	8	9	15	10	6
Euchone rubrocincta	0	0	0	4	1	0	0	0	0	0	1	1	5	0	6	0	0
Potamilla reniformis	0	0	0	4	3	3	0	0	0	0	0	0	0	0	1	1	0
Chone infundibuliformis	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	2
Sabellariid sp.	0	0	0	6	13	2	0	0	0	4	0	1	29	6	15	0	1
Scalibregma inflatum	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Pholoe minuta	11	3	38	29	8	9	0	0	0	0	3	0	15	4	33	10	1
Sthenelais limicola	2	4	2	0	0	0	0	0	2	0	0	0	0	0	2	0	1
Laonice cirrata	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polydora quadrilobata	0	0	0	5	0	1	0	0	0	0	0	0	14	0	3	0	0
Prionospio malmgreni	0	0	14	0	3	0	0	4	0	11	3	54	66	28	153	46	7
Spio filicornis	8	1	2	1	0	0	0	0	0	5	2	9	1	0	1	0	0
Spiophanes bombyx	13	10	28	0	2	0	0	0	0	0	0	0	2	0	3	3	1
Streblospio benedicti	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Sternaspis scutata	0	0	0	11	8	12	0	0	0	0	0	0	0	0	0	0	0
Exogone verugera	0	0	45	0	0	0	0	0	0	0	0	0	2	0	2	3	5
Polycirrus sp.	0	0	0	34	12	21	0	0	0	4	0	0	2	0	1	0	0
Terebellides stroemi	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0
MOLLUSCA																	
Nucula delphinodonta	0	0	0	49	51	34	0	0	0	0	0	0	0	0	0	0	0
Nucula proxima	2	0	3	102	153	143	0	0	0	1	0	0	3	3	0	2	8
Yoldia limatula	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0
Macoma balthica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Macoma calcaria	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
Tellina agilis	2	0	2	1	0	0	1	0	0	0	2	1	10	1	3	0	0
Ensis directus	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lyonsia hyalina	0	0	0	0	0	0	0	0	0	0	0	0	4	0	3	0	0
Mulinia lateralis	0	0	1	0	0	0	15	33	2	6	14	17	0	0	0	0	0
Spisula solidissima	0	0	1	0	0	0	0	0	0	0	0	4	13	0	21	0	0
Pitar morrhuana	0	0	0	3	4	5	0	0	0	14	2	0	2	2	6	0	1
Arctica islandica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Astarte borealis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Astarte undata	0	0	0	1	4	3	1	0	0	4	4	3	3	0	3	0	0
Cerastoderm pinnulatum	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
Divaricella quadrisulcata	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Periploma papyratium	0	0	0	31	48	49	0	0	0	0	0	0	0	0	0	1	0
Cylichna alba	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Lunatia heros	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Mitrella lunata	6	3	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nassarius trivittatus	0	0	1	0	0	0	3	1	0	0	0	0	0	0	0	0	1
Pyramidellid sp.	0	0	0	10	10	10	0	0	0	0	0	0	0	0	0	0	0
ECHIURIDA																	
Echiurus pallasii	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	0	0
ECHINODERMATA																	
Asterias vulgaris	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Echinarachnius parma	3	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thyone scabra	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
PHORONIDA																	
Phoronis architecta	0	0	3	0	0	0	0	2	0	38	10	23	8	31	13	0	2
CHORDATA																	
Bostrichobranchus pilularis	0	0	0	12	10	5	0	0	0	0	0	0	0	0	0	0	0
Number of individuals	426	351	1451	576	562	484	27	131	23	196	154	603	1163	438	1712	3272	1999
Number of species	29	25	49	41	41	35	8	14	10	20	14	19	53	26	49	44	46

*indicates presence of species too small or too abundant to count

This could be the result of the time of exposure or of distance from the center of dumping activity.

The samples from these stations fall into three general categories on the basis of sediment composition and fauna.

The bottom at stations 8-1 and 8-3 consisted of coarse sand and shell. The numbers of individuals and species recovered from these stations were, respectively, only 27/8 from 8-1 and 23/10 from 8-2. The species appearing in these samples had two apparent sources. Those probably introduced with the spoil included *N. incisa*, *M. lateralis*, and *N. trivittatus*, but *Unciola irrorata* and four other amphipod species and *Sthenelais limicola*, a polychaete, are active Rhode Island Sound species and probably entered this area as adults.

Samples 8-2, 10-3, 10-1, 10-2 and 11-2 were all taken on mixed sand/silt/clay bottoms. The numbers of individuals and species found were 131/14, 603/19, 154/14, 196/20, and 438/26. The fauna, of mixed origin, included: (a) Species entering with dredge spoil, *N. incisa* and *M. lateralis*; (b) Species entering as adults from adjacent areas, *Leptocheirus pinguis* and other amphipods; (c) Species which settled as larvae, *Pitar morrhuana*, *Phoronis architecta* (a lophophorate suspension feeder), *Prionosprio malmgreni*, *Eteone longa*, *Tharyx acutus*, and *Heteromastus filiformis*, all small deposit-feeding polychaetes present as subdominants in the natural *Ampelisca* community.

Samples 11-1 and 11-3 were taken from spoil with characteristics much like those of the previous group but with many more amphipod tubes. The number of individuals and species found were 1163/53 and 1712/49. The similarity indexes, calculated with *A. agassizi* included, relate these samples to the natural *Ampelisca* community sampled in 7-1, 14-1 and 14-2. When these stations are compared with *A. agassizi* removed, an affinity is shown between them and the previous group of samples of colonized spoil. The density of *A. agassizi* in these samples was about 1/4 of that at stations 14-1 and 14-2 (717 and 654 versus 2875 and 1671). *Leptocherius pinguis*, a large amphipod, was found in much greater abundance here than in stations 14-1 and 14-2 (257 and 339 versus 6 and 17). Other species which were more abundant on the newly colonized spoil than on natural bottoms included:

- *Nephtys incisa*, deposit-feeding polychaete
- *Eteone longa*, deposit-feeding polychaete
- sabellarid spp, suspension-feeding polychaete
- *Phloe minuta*, deposit-feeding polychaete
- *Prionospio malmgreni*, deposit-feeding polychaete
- *Spisula solidissima*, suspension-feeding bivalve
- *Echiurus pallasii*, deposit-feeding echiurid worm
- *Phoronis architecta*, suspension-feeding, worm-like lophophorate coelomate

Two species that were present at stations 14-1 and 14-2, but absent in the colonized spoil stations were *Orchomella pinguis*, an amphipod, and *Ptilanthura tenuis*, an isopod.

4. Fauna Introduced with the Dredge Spoil

Four species from the dredge area were found on the spoil dump. Three of these, a polychaete, *Nephtys incisa;* a gastropod, *Nassarius trivittatus;* and a bivalve, *Mulina lateralis*, occur in the natural fauna of Rhode Island Sound. The individuals of these species which reach the spoil surface after dumping can be expected to become permanent members of the spoil dump population. *Streblospio benedicti*, a small polychaete abundant in the dredge area, was also found in the dump site. This species is adapted to brackish water and feeds on organic deposits on the sediment surface. It probably does not survive long at the dump site where detrital food is less available and salinity is high.

There seems to be little possibility that the transplantation of adult benthic invertebrates from the spoil source areas will establish any new permanent populations offshore. The planktonic larvae of these same species would have colonized the area previously if the environment had been suitable.

5. Colonization of the Spoil

When a new sediment surface is formed by spoil dumping, it is available for colonization by the adults of motile species and by the planktonic larvae of both motile and sessile species. The order in which species appear on the spoil is a function of their motility and the extent to which they are attracted to, and can survive on, the new sediment surface.

Colonization may involve changes in species representation through time as the spoil is modified by activities of the animals. This primary succession is well described in terrestrial plants. When bare ground is exposed, a pioneer stage of quick growing plants develops. This is followed by a series of other plant groups, each modifying the environment in a way that makes it possible for the next group to become established. The final community is called the climax and is correlated with climate. Some of the characteristics of a climax community on land are permanence, high-standing crop, and high diversity of species.

There have been few opportunities to study succession in marine bottom communities. Shelford *et al.* (1935) suggested that a soft-bottom community gave rise to a hard-bottom community in Puget Sound, Washington. Reish (1961), however, found no evidence of succession in the colonization of a new harbor in southern California. Carriker (1967) reviewed the ways in which benthic organisms modify their environment and concluded that these modifications would make the habitat suitable for new species and succession would take place.

An important aspect in the colonization of new sea bottom is the ability of many benthic species to select the surface on which they settle. Wilson (1958) reviewed the factors mediating settling – texture of the surface, particle size, and the presence of substances which induce metamorphosis or have olfactory attraction. The presence of adults of the same species was frequently an attractive factor. A fresh spoil surface would differ markedly from the natural bottom in the quality and quantity of each of these factors. Some species might not settle until the sediment has been modified by exposure to seawater, by the addition of natural sediment, or by the presence of less selective colonizers.

Some of the studies made on the repopulation of marine and estuarine sediments are reviewed as a basis for interpreting results of this study.

In each case, spoil-disposal operations studied in upper Chesapeake Bay by Pfitzenmeyer (1970) and lower Chesapeake Bay by Stone (1963), the spoil was dumped close to where it was dredged and was distinguishable from natural sediments only by bulk properties. The natural populations in both areas were characterized by large seasonal variations in numbers. Recruitment of juveniles and mortality were both high, making interpretation of repopulation of the spoil and the dredged channels difficult. In both areas repopulation was by the same species that had occupied the area before the dredging and was accomplished in 1½ years. In the lower Chesapeake Bay *N. incisa* and *Retusa canaliculata*, a small carnivorous gastropod, were early colonizing species on the spoil banks; errant polychaetes were colonizers of the dredged channel, but bivalve mollusks were absent from both environments for a longer period.

In a study of a newly dredged harbor, Reish (1961) found that the clay bottom was colonized by deposit-feeding polychaetes of the genera *Lumbrineris*, *Prionospio*, *Spiophanes*, *Tharyx*, *Capitita*, and *Dorvillea*. There was no evidence of a sequence of species colonizing the area, and the principal species were dominant during the entire three-year period of the study.

Howell and Shelton (1970) studied the effect of china clay waste deposited on a former sand and gravel bay bottom in England. Close to the discharge area, the clay was deposited at a high rate and the bottom was nearly sterile. Where the rate of deposition was less, a rich community had developed, consisting of species specialized for soft bottoms; a burrowing sea urchin and a brittle star were dominant species. Other important species included *Nephtys* sp., a sedentary polychaete (*Melinna* sp.), three small bivalves (*Tellina* sp., *Abra alba*, and *Cultellus* sp.), and a holothurian (*Labridoplax* sp.). This fauna was more productive than the original. The small bivalves and sedentary polychaetes were eaten by commercially important fish.

Pearce (1970) studied the effect of sewage sludge and polluted dredge spoil dumping in New York Bight. Little or no macrofauna were reportedly found on either the sludge or the spoil. Marginally polluted areas were identified having a characteristic fauna dominated by *Cerianthus americanus*. It was hypothesized that the impervious tube which this species occupies confers protection from toxic materials in the environment. Other members of this fauna are:

- *Yoldia limatula*, deposit-feeding bivalve
- *Nucula proxima*, deposit-feeding bivalve
- *Nephtys incisa*, deposit-feeding polychaete
- *Prionospio malmgreni*, deposit-feeding polychaete
- flabelligerid sp., deposit-feeding polychaete
- lumbrinerid sp., deposit-feeding polychaete
- maldanid sp., deposit-feeding polychaete

The abundance of these deposit feeders was explained on the basis of high organic matter (10 percent of dry-weight in several samples) and fine grain-size. *Unciola irrorata* was the only amphipod species found on the impoverished portion of the dumping grounds; the marginally polluted areas also had few amphipod species. It was hypothesized that amphipods as a group are sensitive to the effects of pollution.

The pattern of colonization of the spoil in Rhode Island Sound has elements in common with those found in the studies reviewed. *Nephtys incisa* was a colonizer in several of the areas; this active species is found in muddy bottoms over a wide range of salinities and is able to live in moderately polluted environments. It was found in most of the spoil samples taken in the present study. The presence of small individuals (5-10 mm.) indicates that the spoil was attractive to settling larvae.

On the spoil several polychaete species were found which belonged to groups colonizing muddy bottoms in other areas. These include *Prionospio malmgreni*; *Cymenella torquata* (Maldanidae); *Pherusa affinis* (Flabelligeridae); *Tharyx acutus*, and *Ninoe nigripes* (Lumbrineridae).

Colonizing species which were members of the sandy-silt fauna of Rhode Island Sound sampled at station 9 included the polychaetes *C. torquata*, *P. affinis*, and *N. nigripes*; a bivalve, *Pitar morrhuana*, and a small sabellarid polychaete. The relationship between these fauna and the spoil fauna was slight, however. Dominant soft-bottom species which were rare or absent from the spoil include *Nucula* spp., *Cerianthus americanus*, *Edwardsia sp.*, *Periploma papyratium*, and *Bostrichobranchus pilularis*.

Several species of small polychaetes which were present in the natural amphipod colonies were abundant on the spoil; these include *P. malmgreni* and *T. acutus*, both mentioned previously, and

Eteone longa, Pholoe minuta, Heteromastus filiformis and *Harmothoe extenuata.* The colonization of the spoil by these, rather than by silty bottom species, may be due to the abundance of their larvae in the water over the spoil site. It is possible, however, that these polychaetes show less substrate selection and are less specialized and faster growing than soft-bottom species and, thus, are better adapted to colonize the new bottom.

Ampelisca agassizi colonies were found only near the edge of the spoil dump. Their density at stations 11-1 and 11-3 was about ¼ that in the natural community at stations 14-1 and 14-2, indicating that the spoil is an acceptable substrate for juvenile amphipods, but that it might take several years to establish a dense colony. Although *A. agassizi* sweeps recently deposited detritus from the sediment surface it may be less sensitive to sediment quality than species feeding under the sediment surface.

Mills (1967a, 1969) described the biology of *A. abdita* on tidal flats. Dense colonies of this species produced a mat of tubes and fine material which had been removed from the water. These areas were unstable and often eroded away in patches. The juveniles colonized bare sediment where there was less competition from adults and less chance of a "wash out." *A. abdita* was described as a "fugitive species" adapted to frequent changes of the area occupied; *A. abdita* communities were described as "dynamically instable" with little species constancy or biological accommodation.

There is no way of assessing the permanence of *A. agassizi* colonies on the dump site at the present time. An initial hypothesis is, however, that these offshore populations are more permanent than those of the intertidal region. Evidence of stable colonies might be found in adaptation by the juveniles of offshore species for settling among adults.

Leptocheirus pinguis, a large suspension-feeding amphipod, differs from the ampeliscids in that its tubes are temporary and it frequently moves across the bottom. *L. pinguis* of several age groups were abundant at station 11. It is possible that this species selects bottom areas where a mat of permanent tubes is not well developed.

Only a few species abundant in the *A. agassizi* community were rare or absent at station 11. These include *Ptilanthura tenuis*, an isopod; *Orchomella pinguis* and *Phoxocephalus holbolli*, amphipods; and *Diastylis quadrispinosa*, a cumacid. These may be specialized for existence in the fully developed amphipod colony.

In the discussion about the sedimentary geology of the spoil, "Characteristics of the Physical Environment," a prediction was made that the spoil would develop a stable surface with a grain-size distribution near that found on the area before dumping began. If this takes place, the sandy surface will become less attractive to deposit feeders unless amphipod colonization has taken place. These colonies will trap and store organic matter.

The general pattern of colonization of the spoil seems to be that species are added in the order of their powers of dispersal. According to this view, motile adults move onto the spoil soon after it is dumped, and within a year colonization takes place by abundant, non-selective larvae of opportunistic species. Indications are that colonization by more selective or rarer larvae of longer-lived species adapted for silty bottoms will be cut short by *Ampelisca* dominance. A series of yearly surveys following cessation of dumping would show the progress of any such colonization.

6. Species Diversity and Patterns of Abundance

The number of species and the relative abundance of each species are important community characteristics. A community with a large number of species can be assumed to have occupied a stable environment over a long period of time (Sanders, 1969; Slobodkin and Sanders, 1969). Measures of diversity based on information theory take into account both species richness and the evenness, or equitability, of the distribution of individuals among species (Patten, 1962). Stable environments are expected to have not only a large number of species, but also many moderately abundant species; each species would be a specialist in the efficient use of some resource and the degree of biological accommodation would be high.

In environments where animals are stressed by natural variations in temperature or salinity or by pollutants, the number of species is low but the dominant species are superabundant. These "opportunist" species are controlled by the physical elements of the environment rather than by the biological elements.

Diversity may be expressed as the degree of uncertainty attached to the specific identity of any randomly selected individual (Pielou, 1966a). In a sample with many abundant species this uncertainty is great and the diversity of the sample is large. Pielou (1966a, 1966b) indicated that Brillouin's formula for the information (in bits per individual)

$$H = (1/N)(\log N! - \sum_{1}^{s} Ni!)$$

is the appropriate index for describing a single collection. Pfitenmeyer (1970) used this index in a study of Chesapeake Bay spoil dumping. Several benthic ecologists (Phelps, 1964; Boesch, 1970; Lie, 1968) have used the Shannon and Weaver formula which gives an estimate of H for a randomly sampled population:

$$H' = \sum_{1}^{s} P_i \log P_i$$

where P_i is the percent composition of each species in the sample. (H' was used in this study to facilitate comparison with the three studies mentioned.)

Boesch (1970) gives a summary of the value of macrobenthic diversity indexes calculated for samples from a variety of sources. H' values of 4-5 are found on the outer continental shelf and slope and in stable, cool Puget Sound. H' values near 3 seem typical of shallow shelf and unpolluted estuaries. H' values between 1 and 2 are found in the brackish parts of estuaries and in polluted areas.

Even the most stable and diverse communities do not have species abundances approaching equality. There are always a few dominant species and a greater number of less abundant species. There has been speculation that the distribution of individuals among species in an undisturbed community conforms to certain statistical distributions. MacArthur (1960) suggests that a Whitworth distribution will result from division of resources among species with nonoverlapping requirements. Preston (1962) showed that this expectation seems to fit collections of territorial species, but that samples from a variety of environments have a distribution with common species too common and rare ones too rare. Table 1 shows that the assemblages sampled in this study which have been grouped by sediment type and similarity of fauna also had characteristic patterns of species diversity and abundance.

Table 4. *Diversity index values for 1/10 M^2 samples.*

Station	Number (individuals)		Number (species)	H^1 (bits/individual)	
7-1	426		29	1.85	
7-2	351		25	1.77	
7-3	1451	984*	49	2.58	2.89*
9-1	576		41	3.05	
9-2	562		41	2.88	
9-3	484		35	2.75	
8-1	27		8	1.46	
8-2	154		14	2.07	
8-3	23		10	1.81	
10-1	196		20	2.43	
10-2	131		14	2.04	
10-3	603		19	1.79	
11-1	1663	947*	53	2.24	2.76*
11-2	438		26	2.24	
11-3	1712	1059*	49	2.23	2.53*
14-1	3275	398*	44	0.92	2.99*
14-2	1999	329*	46	0.73	2.91*

***indicates values of the number of individuals and the bits/individual when a record of one *Ampelisca agassizi* was substituted for the actual number found**

Samples 7-1 and 7-2 from clean sand had relatively few species, 21 and 25, and were dominated by a single amphipod, *Byblis serrata.* The diversity index values were low, 1.85 and 1.77.

Samples 7-3, 14-1, and 14-2, sand colonized by amphipod colonies, had many species, 49, 46 and 44. They differed in that 7-3 has several abundant species and a moderate diversity value of 2.58, while 14-1 and 14-2 were dominated by a single species, *Ampelisca agassizi,* and had very low density index values of 0.73 and 0.92.

Diversity indexes usually are used to compare groups of organisms with overlapping requirements. The differences between the numerically and physically dominant tube-building amphipods and the remaining subdominant species may be so great that they should be considered separately. When *A. agassizi* was removed from the records of samples 14-1 and 14-2 and the diversity indexes recalculated, they increased to 2.91 and 2.99, indicating that the sub-dominants are relatively evenly distributed.

Samples 9-1, 9-2, and 9-3, all from a sandy silt-bottom, had moderate numbers of species, 41, 41 and 35, and high equitability giving high diversity values of 3.05, 2.88 and 2.75. Sample 9-1 has an abundance pattern close to the Whitworth distribution. Samples 9-2 and 9-3, like most of the samples in this study, had patterns varying from the Whitworth distribution in that abundant species were too abundant and rare species too rare.

Samples 11-1 and 11-3 from colonized dredge spoil had large populations of *A. agassizi* and a high species total, 53 and 49. The diversity index values were moderate, 2.24 and 2.23, and increased when *A. agassizi* was removed (2.74 and 2.53).

Samples 11-2, 10-1, 10-2 and 10-3, all on less well-colonized spoil, had a reduced number of species (26, 20, 14 and 19). Diversity index values were moderate (2.24, 2.43, 2.04 and 1.79) due to the evenness of species abundance. These samples do not represent functional communities. The species found in them are only samples from other communities; they had been deposited with the spoil, had entered as motile adults, or had settled as larvae or juveniles.

These analyses show that differences in species richness and diversity are not correlated in a simple way with disturbance of the bottom by spoil dumping. The controlling effects of the presence or absence of amphipod colonies on these indexes detract from their usefulness. Further sampling and analysis will be necessary to determine the utility of changes in subdominant groups as indicators of disturbance.

7. Benthic Invertebrates Eaten by Fish

The area of sea bottom directly affected by spoil is small when compared with the total area of

Rhode Island Sound of over 500 square miles. It is nevertheless important to consider the recolonization of this area in terms of fish attraction and productivity; the change in fisheries potential of this area can help in the assessment of the effects of dumping or dredging in other offshore areas.

Unfortunately many of the species that are important as food for bottom fish are large and motile and are not sampled by a 1/10 M^2 grab. These include crabs *(Cancer spp.)* and shrimp *(Crangon septemspinosus)*, all important food items of cod, hake and eelpout. These motile species can be expected to respond to sediment quality and the presence of their prey.

Smith (1950) analysed the food of the dominant fishes in Block Island Sound. The bottom in this area is sand and sandy-silt, and so can be taken as representative of the bottom around the dump site. The fishes feeding on bottom invertebrates in Block Island Sound include winter flounder *(Pseudopleuronectes americanus)*, skate species, sculpin, eelpout, and sea-robin. The annual consumption of bottom invertebrates by weight consisted of 90 percent crustacea, 60 percent amphipod crustacea, and 46 percent *Leptocheirus pinguis*. Another amphipod, *Unciola irrorata* made up 8 percent of the food consumed annually. The recolonization of the spoil area by amphipods, and in particular by the species *L. pinguis* and *U. irrorata*, would provide food for these fishes.

Richards (1963) studied the food of fishes in both a muddy and a sandy area of Long Island Sound. She found that winter flounder ate at least 73 different species of benthic invertebrates; on muddy bottoms, polychaetes made up a large proportion of their diet. The only other fish found to eat a high proportion of polychaetes was scup *(Stenotomus chrysops)*.

When stomach contents of flounder caught on muddy bottom west of the dump site were examined, the major food items found were the polychaetes *Pherusa affinis*, *Glycera* sp., and *Nephtys incisa* and the anemone-like *Cerianthus americanus*. Thus, it is concluded that if a muddy bottom fauna were to develop on the spoil, flounder and scup would be best able to take advantage of it. Flounders appear to feed on the largest available polychaetes and amphipods; large amphipods and large *N. incisa* are already found on the edges of the spoil area, but it may be some time before other polychaetes or *C. americanus* can colonize the spoil and grow to full size.

SUMMARY

1. A small number of pollution resistant benthic species were found in Providence Harbor, and although low oxygen seemed to be the major stress, toxic substances are probably also present in this area.

2. More than 30 benthic species were found in the lower Providence River; this indicated a relatively low level of pollution in that part of the spoil source area.

3. Although several species were found on the spoil dump which had been transported from the dredge area, the only abundant transported species which seemed well adapted for Rhode Island Sound conditions was *Nephtys incisa*, a polychaete occurring there naturally.

4. The natural faunal assemblage on sandy sediments in the spoil dump area was dominated by *Ampelisca agassizi*, a tube-building amphipod crustacean. These dense mats of *Ampelisca* tubes determined sediment quality and provided a habitat occupied by subdominant species.

5. Much of the spoil was recently dumped and had few animals on it. However, some surfaces which had been exposed to colonization for between one and three years yielded large numbers of species (up to 53 per 1/10 M^2 sample). The presence of these animals indicates that these spoil surfaces lacked gross toxic or repellent properties.

6. Although the spoil was generally silty, only a few colonizing species were recognized as members of the offshore silt-bottom assemblage. However, lack of information on the presence of the larvae of these species in the overlying water made it difficult to ascribe this absence to sediment properties.

7. Most of the species colonizing the spoil were members of the surrounding sand-bottom assemblage. Several species of deposit-feeding polychaetes and an amphipod crustacean, *Leptocheirus pinguis*, were found in greater abundance on the spoil than in their natural habitat.

8. *A. agassizi* was found on some spoil areas indicating that colonization is independent of the quality of underlying sediment where the hydrographic regime is suitable. It seems likely that this species will eventually dominate the spoil as it did the surrounding area, but it is not possible to estimate the time necessary to establish this dominance.

9. Although the faunal assemblages sampled in this study had characteristic diversity index values, these could not be simply interpreted. Some spoil samples had relatively high values, indicating little disturbance, while the natural *A. agassizi* assemblage had extremely low values.

10. Several of the species which were abundant on the colonized spoil have been reported to be used for food by commercially important fish.

Fisheries Resources in the Dump Site Area

The establishment of a dredge-spoil dumping ground in Rhode Island Sound is an example of the general phenomenon of a shifting zone of exploitation. In the recent past dredge spoil, solid waste, and sewage sludge have been dumped into Narragansett Bay. Various state regulatory agencies, responding to the public view that Narragansett Bay should be reserved for food production and recreation, now cooperate to prevent unhealthy and unsightly exploitation of its estuarine waters. At the same time that the volume of materials to be disposed of increases, constraints have been placed upon open burning on land, sand and gravel quarrying on land, and the use of estuarine waters for power plant cooling. Nearshore waters and the sea floor are now being used or being considered for use in disposal, incineration, heat discharge, mining, oil production, and cable transmission — all uses, which compete with the traditional uses of recreation, navigation and various types of fishing.

While various federal agencies have limited regulatory powers concerning ocean dumping, fishing, and navigation, none has the power to assign portions of the sea floor for specific uses. This division among users is often a function of "who gets there first" and who can defend his claim most persuasively.

Before any agency can rationally allocate sea-floor areas, it will be necessary to know the location of all resources presently being utilized and those which may be used in the future. A lack of specific knowledge concerning the location of Rhode Island Sound fishery resources made the choice of a dump site for Providence River spoil difficult. Local fishermen voiced strong objection to the location of three sites which were used for short periods before the present site was chosen. The first site ("A," fig. 22) was in the center of an important lobster fishing area, while the second and third ("alternate site," fig. 1, and "C," fig. 22) are near important trawling areas.

Several contrasting types of commercial fishing are carried on in Rhode Island Sound; each has its own area and gear and has been affected by spoil dumping to a different degree. Figure 23 shows the general location of trawling grounds for bottom fish in nearshore Rhode Island Sound. Deposits of cobbles and boulders along the paths of former glacial moraines restrict trawlers to well defined areas. A single "short dump" of soft silt in such an area may close it for years; the otter boards ("doors") of the trawls can dig into the silt and anchor the net to the bottom. Inaccurate dumping in the channel near the alternate dump site in 1967 caused considerable problems. Reportedly this material presently is either spread out or compacted enough so that gear is no longer caught; one fisherman reports that the spoil is better able to support trawling in the winter than in the summer. This agrees with R. L. McMaster's (1967) observations of sediment compaction and dilatancy.

The present dump site is on trawling grounds of secondary importance; the area available for trawling is small and surrounded by patches of rocky bottom. It is, however, one of only two areas available to small day-boats from Newport. Larger boats from Point Judith fish here, using rollers to keep the trawl free of the rocky bottom.

During the winter, cod *(Gadus callarias)*, blackback flounder *(Pseudopleuronectes americanus)*, and yellow tail *(Limanda ferruginal)* are caught on hard bottom to the east of the dump site. Sea herring *(Clupea harengus)* are caught to the west. Sculpin *(Myoxocephalus spp.)*, eelpout *(Macrozoarces americanus)*, skate *(Raja spp.)*, and goosefish *(Lophius americanus)* are taken as industrial or "trash fish."

In the spring and summer scup *(Stenotomus chrysops)* is caught on hard bottom to the northeast while whiting *(Merluccius bilinearis)*, and hake *(Urophycis chuss)* are caught on soft bottom to the northwest. Butterfish *(Poronotus triacanthus)* is taken in summer and fall northeast in 90-foot depths.

Although there has been a general lack of butterfish and scup in this area for the last three years, it is not possible to ascribe this to spoil dumping activities; natural variations in abundance are considered a more plausible explanation. Catches of cod and flounder southeast of the dump site have remained excellent, augmented by large catches of cod in areas where the fish have been attracted by quahog dredging.

Four fish-trap areas assigned by the State of Rhode Island are shown in figure 23. Here expensive, fixed nets are set up to catch scup, butterfish, mackerel *(Scomber scombrus)*, cod, and menhaden *(Brevoortia tyrannus)*. This fishery has been extremely poor for the last three years. It can be hypothesized that surface-feeding fish, like mackerel and menhaden, with higher oxygen utilization, more mobility and more visual acuity than bottom fish, would be sensitive to water quality and actively avoid turbid water around the dump site. However, observations made during this study and others by fishermen do not suggest that turbidity increases in the area outside of the immediate vicinity of the dump site other than immediately after large storms.

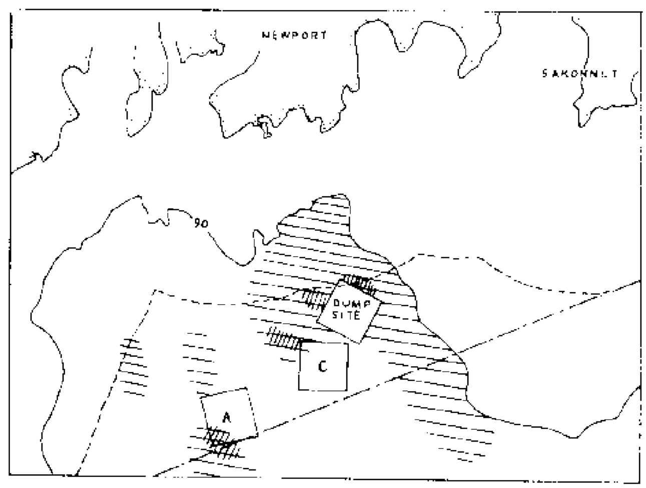
It is a fact that fish catchability for bottom trawling is low during post-storm turbidity. Several fisherman interviewed say that the period of turbidity following storms which produces ground swell now lasts a week rather than the three days of pre-dump years. This turbidity is reported to be spread throughout Rhode Island Sound rather than moving one way or another from the dump site. Data on the frequency of storms producing ground swell and on the pattern of winter fishing are necessary to assess the actual losses which might be incurred from this effect.

Lobster fishing with strings of pots is carried on throughout this area during the warm months, with high pot densities in large areas on or near rough bottom. A knowledgeable fisherman who had been lobstering in the dump site area for eight years has continued to fish close to the spoil area. He has placed pots within the dump limits on the south, southeast, and east and has asked the dredging project managers and the towboat operators to avoid this area if possible. He reported that pots close to the dump zone often come up with a ½-inch layer of gray silt-clay on them, yet may have a good-to-excellent catch per pot. He suggested that lobsters may be attracted to this soft bottom to bury themselves for the winter. It seems more likely, however, that lobsters which enter this area during natural inshore-offshore movements continue to move across the bottom in search of food and, thus, are likely to discover a trap. This fisherman reported that sea bass *(Centropristea striatus)*, a valuable food fish, was caught in pots close to the dump site much more frequently than elsewhere. While a few other lobstermen have experimented with fishing close to the spoil, most avoided the area for fear of low or polluted catches and loss of gear by burial or tow lines cutting buoys.

The dump site is located near the center of a discrete patch of ocean quahogs *(Arctica islandica)*. (See fig. 22.) Although the location of this has been known for more than 20 years, *Arctica* was not being used at the time the dump was established. During the study period, at least four boats were dredging for *Arctica* in this area. This area was preferred since the next nearest concentrations are 10-12 miles offshore. These boats frequently operate near the boundaries of the spoil area. Dead *Arctica* have been recovered by these boats at several locations (fig. 23), and in each case spoil sediments were recognized at these. The animals near the dump site probably had been buried by spoil dumped near the site perimeter and by sediments which had been suspended during dumping and flowed beyond the designated disposal area. The dead animals in the area southwest of the dump site were probably buried by spoil dumped in area "A" during the 20-day period it was used in 1967..

Burial experiments have been conducted by Hale (1972) to determine the depth of spoil necessary to kill *Arctica*. These indicate that while escape would be likely after burial by thin layers of transported sediment (1-4 cm.), thick coverage (over 6-8 cm.) leads to their eventual death.

In conclusion it is clear that there is no such thing as unused sea bottom in these inshore waters. Most users of this area agree that future dumping should be on the existing site unless a new site can be established very far offshore. However, use of the Rhode Island Sound sea floor for drege spoil disposal will be acceptable only if it is possible to



General location of ocean quahog grounds.

Areas from which dead ocean quahogs and dredge spoil have been reported by fishermen.

Present Rhode Island state line.

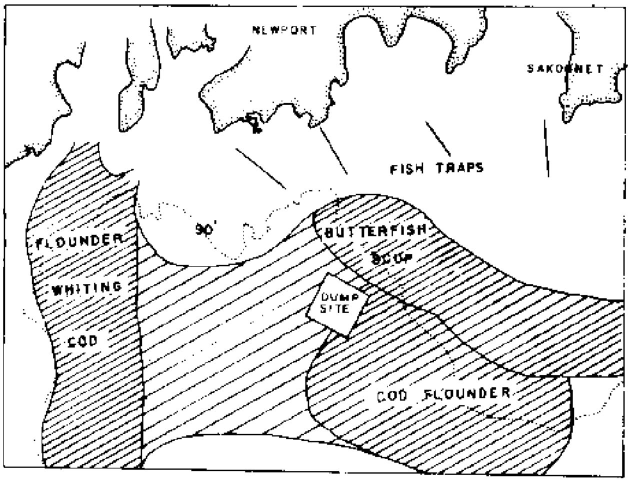
Rhode Island state line under proposed amendment GL 42-1-1.

A Original contract disposal area used 21 September-10 October, 1967.

C "Navy garbage dump" disposal area used 20 November-8 December, 1967.

Fig. 22. Areas important in the *Arctica*, or ocean quahog, fishery in Rhode Island Sound. Lobster pots are set throughout the area in the summer except on the west trawling grounds.

guarantee that there will be no errors in the location of dumping. The effects of resuspension and sedimentation around the dump site are probably small, but a "short dump" in a trawling or dredging area could effectively close it to fishing for years.



Primary trawling grounds   Secondary trawling grounds

Fig. 23. General areas used by various fisheries in the dump site area.

References

Abbott, R. T., 1954. American seashells. Van Nostrand, Princeton, N.J.

American Society for Testing and Materials, 1968. Standard method for grain-size analysis of soils. ASTM Designation: D 422-63.

Bader, R. G., 1954. Role of organic matter in determining distribution of pelecypods in marine sediments. Jour. Mar. Res. 13: 32-47.

Blumer, M., 1969. Oil pollution of the ocean. Hoult, D. P. (ed.). Oil on the Sea. Plenum Press, N.Y.

Boesch, D. F., 1970. Patterns of marine macrobenthic species diversity in the Virginia area. Presented at Am. Soc. of Limnol. Oceanog. Annual Meeting, 26 Aug. 1970, Kingston, R.I. Virginia Inst. Mar. Sci., Gloucester Point, Virginia. Mimeo Report.

Boylan, D. B., J. Atema, J. Todd, and S. Jacobson, 1971. The importance of chemical signals in stimulating behavior of marine organisms. Effects of altered environmental chemistry on animal communication. Presented at the 162nd ACS National Meeting, Washington, September 1971. Submitted for publication to the Advances in Chemistry Series, American Chemical Society.

Boyan, G. W. and L. G. Hummerstone, 1971. Adaptation of the polychaete *Nereis diversicolor* to estuarine sediments containing high concentrations of heavy metals. In: General Observations and Adaptation to Copper. J. Mar. Biol. Assn. UK 51: 845-863.

Carriker, M. R., 1967. Ecology of estuarine benthic invertebrates: a perspective. In: Estuaries. Lauff, A. H. (ed.) AAAS, pp. 442-487.

Chevreux, E. and L. Fage, 1925. Amphipodes. In: Faune de France. 9: 1-488.

Cook, G. S., 1966. Non-tidal circulation in Rhode Island Sound. Naval Underwater Weapons Research and Engineering Station. TM No. 369.

Cross, F.A., T.W. Duke and J.N. Willis, 1970. Biogeochemistry of trace elements in a coastal plain estuary: distribution of manganese, iron, and zinc in sediments, water and polychaetous worms. Chesapeake Sci. 11: 221-234.

Dean, D., 1970. Water quality-benthic invertebrate relationships in estuaries. Ira C. Darling Center for Research, Teaching and Service, Walpole, Maine. Mimeo Report.

Eisler, R. 1971. Cadmium poisoning in *Fundulus heteroclitus* (Pisces: Arprinodontidae) and other marine organisms. J. Fish. Res. Bd. Canada 28: 1225-1234.

Farrington, J.W., 1971. Benthic lipids of Narragansett Bay -- fatty acids and hydrocarbons. Ph.D. thesis, Graduate School of Oceanography, University of Rhode Island.

Gross, M. G., 1970. Preliminary analyses of urban wastes, New York Metropolitan Region. Tech. Rept. No. 5, Mar. Sci. Res. Center, State University of New York.

Hale, S.S., 1972. Some reactions of the ocean quahog *Arctica islandica* upon burial. Graduate School of Oceanography, University of Rhode Island, Kingston, R.I. Mimeo Report.

Hard, C., 1970. Unpublished data. U. S. Army Corps of Engineers, N.E. Div., Waltham, Mass.

Harrison, W., 1967. Environmental effects of dredging and spoil desposition. Proceedings World Dredging Conference 1967, World Dredging Conference, 2516 Via Tejon, Palos Verdes Estates, Calif. (Pub.). pp. 535-559.

Hartman, O., 1969. Atlas of the sedentariate polychaetous annelids from California. Allan Hancock Foundation, University of Southern California, Los Angeles, Calif.

Hartung, R. and G. W. Klingler, 1970. Concentration of D.D.T. by sedimented polluting oils. Environ. Sci. and Technol., 4: 407-410.

Hedgpeth, J. W., 1957. Estuaries and lagoons. II. Biological Aspects. Geol. Soc. Am. Mem. 67(1): 693-749.

Hicks, S. D., 1959. The physical oceanography of Narranganset Bay. Limnol. Oceanog., 4: 316-327.

Hjulstrom, F., 1939. Transportation of detritus by moving water. In: Recent Marine Sediments, Trask, P. D. (ed.). Amer. Assoc. of Petrol. Geol., Tulsa, pp. 5-31.

Hogben, N. and F. E. Lumb, 1967. Ocean Wave Statistics. D. R. Hillman and Sons, Ltd., London.

Horn, H. S., 1966. Measurement of "overlap" in comparative ecological studies. Am. Naturalist, 100: 419-424.

Howell, B. R. and R. G. J. Skelton, 1970. The effect of china clay on the bottom fauna of St. Amstell and Mevagissy Bays. Jour. Mar. Biol. Ass. UK, 50: 593-607.

Kunkel, B. W., 1918. The arthrostraca of Connecticut. Conn. Geol. and Nat. Hist. Survey, 26: 1-261.

Krumbein, W. C. and L. L. Sloss, 1963. Stratigraphy and Sedimentation. W. H. Freeman, San Francisco.

Lie, F., 1968. A quantitative study of benthic infauna in Puget Sound, Washington, U.S.A. in 1963-1964. FiskDir. Skr. Ser. HavUnders. 14: 229-556.

National Marine Fisheries Service, 1970. Unpublished data. National Marine Fisheries Service, Woods Hole, Mass.

MacArthur, R., 1960. On the relative abundance of species. Am. Naturalist, 94: 25-32.

Masch, F., 1968. Shell dredging -- a factor in estuarine sedimentation. Proceedings of Speciality Conference on Coastal Engineering, N. Y. Amer. Soc. Civ. Eng.

McClennen, C. E., 1971. Wave and current effects on continental shelf sediments. Graduate School of Oceanography, University of Rhode Island, Kingston, R.I. Mimeo Report.

McKinney, T. F. and G. M. Friedman, 1970. Continental shelf sediments of Long Island, New York. J. of Sed. Petrol., 40: 213-248.

McMaster, R. L., 1960. Sediments of the Narragansett Bay system and Rhode Island Sound, Rhode Island. J. Sed. Petrol., 30: 249-273.

——, 1962. Petrography and genesis of recent sediments in Narragansett Bay and Rhode Island Sound, Rhode Island. J. Sed. Petrol., 32: 484-501.

——, 1967. Compactness variability of estuarine sediments; an in-site study. In: Estuaries, Lauff, G. H. (ed.), AAAS, pp. 261-267.

——, 1970. Unpublished data. Graduate School of Oceanography, University of Rhode Island, Kingston, R. I.

—— and W. B. Clarke, 1956. A survey of bottom surface sediments in upper Narragansett and Mt. Hope Bays. University of Rhode Island, Narr. Mar. Lab., Mimeo Report, 56-14.

—— and L. E. Garrison, 1966. Mineralogy and origin of southern New England shelf sediments. J. Sed. Petrol., 36: 1131-1142.

Mills, E. L., 1967a. The biology of an ampeliscid amphipod crustacean sibling species pair. J. Fish. Res. Bd. Canada, 24: 305-355.

Mills, E. L., 1967b. A re-examination of some species of Ampelisca (Crustacea: amphipoda) from the east coast of North America. J. Zool. Canada, 45: 635-652.

Mills, E. L., 1969. The community concept in marine zoology, with comments on continua and instability in some marien communities: a review. J. Fish. Res. Bd. Canada, 26: 1415-1428.

Moore, H. B., 1955. Faecal pellets in relation to marine deposits. In: Recent Marine Sediments, Trask, P. D. (ed.). Spec. Publ. 4, Soc. Econ. Paleontologists Mineralogists, pp. 516-524.

Morton, R. W., 1967. Spatial and temporal observations of suspended sediment: Narragansett Bay and Rhode Island Sound. Naval Underwater Weapons Research and Engineering Station, TM No. 396.

Nicol, J. A. C., 1960. The Biology of Marine Animals. Interscience, N.Y., pp. 135-201.

Odum, W. E., G. M. Woodwell, and C. F. Wurster, 1969. DDT residues absorbed from organic detritus by fiddler crabs. Science, 164: 576-577.

O'Leary, M., R.H. Lippert, and O.T. Spitz, 1966. Fortran IV and MAP program for computation and plotting of trend surfaces for degrees 1 through 6. Computer Contrib. No. 3, Kansas Geological Survey, University of Kansas.

Olney, C. E., 1970. Personal communication. Dept. of Agricultural Chemistry, University of Rhode Island, Kingston, R.I.

Oviatt, C., 1969a. Wave record report. Unpublished manuscript to Harvard School of Public Health, Boston.

——, 1969b. Final report. Unpublished manuscript to Harvard School of Public Health, Boston.

Patten, B. C., 1962. Species diversity in new phytoplankton of Raritan Bay. Jour. Mar. Res., 20: 57-75.

Pearce, J.B. 1970. The effects of solid waste disposal on benthic communities in the New York Bight. FAO Technical Conference on Marine Pollution and its Effects on Living Resources and Fishing, Rome 9-18 December 1970.

Pearson, E. A., P. N. Storrs and R. E. Selleck, 1967. Parameters of marine pollution. In: Olsen, T. A. and F. J. Burgess, Pollution and Marine Ecology, Interscience, pp. 297-315.

Pettibone, M. H., 1963. Marine polychaete worms of the New England region, Part 1. Bull. U. S. Nat. Mus., 227.

Pfitzenmeyer, H. T., 1970. Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay, Project C: Benthos. Natural Resources Institute Sp. Rept. No. 3. Chesapeake Biological Laboratory, Solomons, Md.

Phelps, D. K., 1958. A quantitative study of the infauna of Narragansett Bay in relation to certain physical and chemical aspects of their environment. M. S. thesis, University of Rhode Island.

——, 1964. Functional relationships of benthos in a coastal lagoon. Ph.D. thesis, University of Rhode Island.

——, R.J. Santiago, D. Luciano, and N. Irizarry, 1969. Trace element composition of inshore and offshore benthic populations Proc. 2nd. Natn. Symp. Radioecol., Ann Arbor, Mich., 15—17 May 1967. D.J. Nelson and E.C. Evans. (eds.).

——, 1972. Personal communication. National Marine Water Quality Laboratory, West Kingston, R. I.

Pielou, E. C., 1966a. Shannon's formula as a measurement of specific diversity and its use and misuse. Amer. Naturalist, 100: 463-465.

——, 1966b. The measurement of diversity in different types of biological collections. J. Theoret. Biol., 13: 131-144.

Preston, F. W., 1962. The canonical distribution of commonness and rarity. Ecology, 43: 185-215, 410-432.

Reish, D. J., 1959. The use of marine invertebrates as indicators of water quality. In: Proceedings of 1st International Conf. on Waste Disposal in the Marine Environment. Pearson, E. A. (ed.). Pergamon, N. Y.

——, 1961. A study of benthic fauna in a recently constructed boat harbor in southern California. Ecology, 42: 84-91.

Richards, S. W., 1963. The demersal fish population of Long Island Sound. II. Food of the juveniles from a sand-shell locality. III. Food of the juveniles from a mud locality. Bull. Bingham Oceanogr. Coll., 18: 32-101.

Richards, T. L., 1969. Physiological ecology of selected polychaetous annelids. Ph.D. thesis, University of Maine. Cited in: Dean, D., 1970. Water quality and benthic invertebrate relationships in estuaries, Ira C. Darling Center for Research, Teaching and Service. Walpole, Maine.

Richie, D. E., 1970. Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay, Project F: Fish. Natural Resources Institute, Spec. Rept. No. 3, Chesapeake Biological Laboratory, Solomons, Md.

Rogers, B. A., 1969. The tolerance of fishes to suspended solids. M.S. thesis, University of Rhode Island.

Saila, S. B., J. M. Flowers and M. T. Cannario, 1967. Factors affecting the relative abundance of *Mercenaria mercenaria* in the Providence River, Rhode Island. Proc. Nat. Shellfish. Ass., 57: 83-89.

——, T. T. Polgar and B. A. Rogers, 1968. Results of studies related to dredged sediment dumping on Rhode Island Sound. Proc. Ann. Northeastern Reg. Anti-pollution Conf., 22-24 July 1968. pp. 71-80.

St. Amant, L. S., 1950. Some trends in the biological investigations of various oyster problems in Louisiana.

Salenddin, A.S.M., 1964. Observations on the habit and functional anatomy of *Cypriva islandica* (L.). Proc. Mal. Soc. Lond. 36: 149-162.

Sanders, H. L., 1956. The biology of marine bottom communities. X. Bull. Bingham Oceanog. Coll., 15: 345-414.

——, 1958. Benthic studies in Buzzards Bay. I. Animal-sediment relationships. Limnol. Oceanog., 3: 245-358.

——, 1960. Benthic studies in Buzzards Bay. III. The structure of the soft-bottom community. Limnol. Oceanog., 5: 138-153.

——, 1969. Benthic marine diversity and the stability-time hypothesis. Brookhaven Symposia in Biology, 22: 71-81.

——, P. C. Mangelsdorf and G. R. Hampson, 1965. Salinity and faunal distribution in the Pocasset River, Massachusetts. Limnol. Oceanog., 10: R216-R229.

Shafer, W., 1962. Aktuo-Palaontologie nach Studien in der Nordsee. Verlag Waldermar Kramer, Frankfurt. Am Main.

Shelford, V. E., 1935. The major communities. Part I. In: Some marine biotic communities of the Pacific coast of North America. Ecol. Monogr., 5: 251-292.

Shonting, D. H., 1969. Rhode Island Sound square kilometer study, 1967: flow patterns and kinetic energy distribution. J. of Geophys. Res., 74:(13).

Shuster, C.N., Jr., and B.H. Pringle, 1969. Trace metal accumulation by the American oyster, *Crossostrea virginica*. Proc. Nat. Shellfish Ass. 59: 91-103.

Slobodkin, L. B. and H. L. Sanders, 1969. On the contribution of environmental predictability to species diversity. Brookhaven Symposia in Biology, 22: 82-95.

Smith, F. E., 1950. The benthos of Block Island Sound. I. The invertebrates their quantities and their relation to the fishes. Ph.D. thesis, Yale University.

Smith, R. I., 1964. Keys to Marine Invertebrates of the Woods Hole Region. Systematics — Ecology Program, Marine Biological Laboratory, Woods Hole, Mass.

Stickney, A. P. and L. D. Stringer, 1957. A study of the invertebrate bottom fauna of Greenwich Bay, Rhode Island. Ecology, 38: 111-122.

Stone, R. B., 1963. A quantitative study of benthic fauna in lower Chesapeake Bay with emphasis on animal-sediment relationships. M.S. thesis, School of Marine Science, College of William and Mary.

Thorson, G., 1957. Bottom communities (sublittoral or shallow shelf). Geol. Soc. Am. Mem. 67(1): 461-534.

Turekian, K. K. and K. H. Wedepohl, 1961. Distribution of the elements in some major units of the Earth's crust. Bull. Geol. Soc. Am. 72: 175-192.

U.S. Army Engineer Waterways Experiment Station, 1959. Effects of lower bay barriers on salinities, shoaling and pollution in Narragansett Bay. Hydraulic Model Investigation. Appendix C in Hurricane Damage Control Narragansett Bay and Vicinity, U.S. Dept. of the Interior, Fish and Wildlife Service, Boston, Mass.

Wass, M. L., 1967. Biological and physiological basis of indicator organisms and communities. In: Olson, T. A. and F. J. Burgess, Pollution and Marine Ecology, Interscience, N.Y. pp. 271-283.

Wilson, D. P., 1958. Some problems in larval ecology related to the localized distribution of bottom animals. In: Perspective in Marine Biology, Buzzati-Traverso, A. A., (ed.), pp. 87-103. University of California Press, Berkeley, Calif.

Whittaker, R. H. and C. W. Fairbanks, 1958. A study of plankton copepod communities in the Columbia Basin, southeastern Washington. Ecology, 39: 46-65.

Wigley, R., 1967. Comparative efficiencies of the vanVeen and Smith-McIntyre grab samples as revealed by motion pictures. Ecology, 48: 168-169.

Wigley, R., 1968. Benthic invertebrates of the New England fishing banks. Underwater Naturalist, 5: 8-13.

Woodwell, G. M., C. F. Wurster, P. A. Isaacson, 1967. DDT residue in an East Coast estuary: a case of biological concentration of a persistent insecticide. Science, 156: 821-823.