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DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-77-22

FIELD STUDY OF THE EFFECTS OF STORMS ON THE STABILITY AND FATE OF DREDGED MATERIAL IN SUBAQUEOUS DISPOSAL AREAS

by

Henry J. Bokuniewicz, Jeffrey Gebert, Robert B. Gordon
Peter Kaminsky, Carol C. Pilbeam, Matthew Reed, Catherine Tuttle
Department of Geology and Geophysics
Yale University
New Haven, Connecticut 06520

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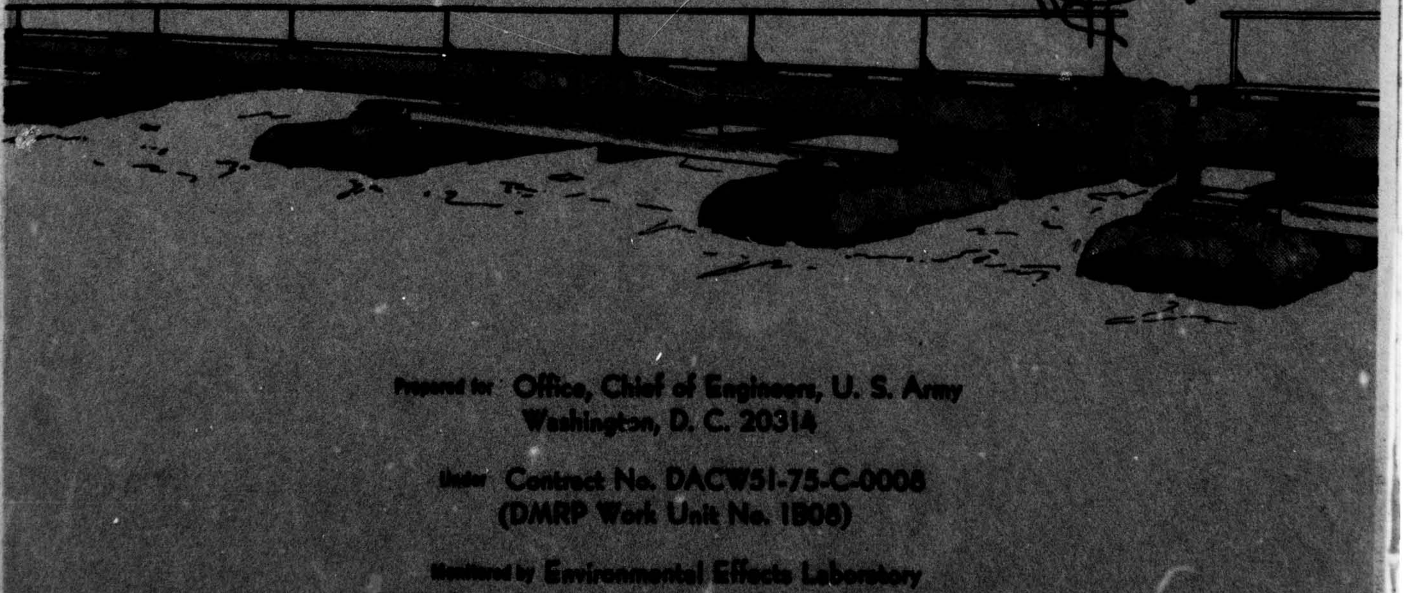

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1. The technical report transmitted herewith represents the results of Work Unit 1B08 of Task 1B, Movements of Dredged Material, of the Corps of Engineers' Dredged Material Research Program (DMRP). It has been a part of the Environmental Impacts and Criteria Development Project (EICDP), which has a general objective of developing techniques for determining the spatial and temporal distribution of dredged material discharged into various hydrologic regimes. The study reported on herein was part of a series of research contracts developed to achieve the EICDP general objective.

2. Regardless of the location or character of a disposal site, an integral part of the problem of assessing the environmental impact of open-water disposal operations is the ability to determine the fate of dredged material mounds subjected to storm conditions. Dredged material placed on an estuarine bottom is subject to dispersion by the tidal stream, estuarine circulation, waves, and disturbances of the hydraulic flow by storms. In shallow coastal waters, sediment may be transported periodically by tidal currents or episodically by storm-generated currents. Storms may play a major role in the movement of sediment but occur irregularly and with variable intensity. A major objective of this investigation was to evaluate the susceptibility of sub-aquatic dredged material mounds to these disturbances.

3. This report describes investigations conducted in Long Island Sound where the dominant source of energy for the suspension and transport of sediment is the tide. However, dredged material placed on the bottom may be affected by currents and waves from other energy sources. Selected dump sites in Long Island Sound were investigated following winter storms and a hurricane and the studies utilized continuous records of quantities such as wind velocity, water level, and current speed for at least a year to estimate the intensity of infrequent major events.

4. The study concluded that the tidal stream is the dominant source of energy for the resuspension and transport of sediment and that waves do not contribute significantly to dispersion in water depths greater than 60 ft. During a storm, fluctuations in water velocity increase in intensity and are important agents of sediment resuspension. During extreme storm conditions, resuspension of the bottom in deep water is limited to a layer of sediment with an average thickness of less than 1 cm. Bathymetric surveys of a dredged material dump site showed that after initial self-consolidation of the mound, no significant changes in site configuration occurred over a three-year period. The data obtained show that to best contain silt-clay dredged material, the disposal site should be a naturally accreting mud bottom; the disposal operation should emplace a large volume of material on the site expeditiously; and the deposits should be built to an optimum configuration.

5. The information and data published in this report are contributions to the further understanding of the complex nature of sediment transport and stability of sub-aquatic dredged material deposits and establish a baseline from which to develop meaningful evaluations for the selection of an environmentally compatible disposal alternative. It is expected that the methodology employed in this study and the resultant interpretation of the physical interactions will be of significant value to those persons concerned with CE dredged material permit programs.

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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Long Island Sound is a large estuary. Dredged sediment placed on the bottom of the Sound is subject to dispersion by the tidal stream, estuarine circulation, waves, and disturbances of the hydraulic flow field by storms. The tidal stream is the dominant source of energy for the resuspension and transport of sediments; waves do not contribute significantly to dispersion in water depths greater than 60 ft. Random fluctuations in the water velocity

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are detected at all depths. During a storm fluctuations in velocity increase in intensity and are important agents of sediment resuspension. Direct, wind-driven flow over the bottom is weak, but storm winds cause water level increases up to 3 ft above the usual tidal level. The energy available for sediment transport is then greatly increased. Water level records are used to evaluate seasonal and long-term changes in storm energy release in the Sound. During extreme storm conditions resuspension of the bottom in deep water is limited to a layer of sediment with an average thickness of less than 1 cm. Despite this activity, silt is accumulating in the central Sound at rates as high as 10^3 gm/(m^2 yr). Repeated bathymetric surveys of a deposit of dredged material at the New Haven disposal site show that after initial self-consolidation of the mound, no significant changes in pile configuration occurred over a three-year period; erosion of the deposit is not detected. The data obtained show that to best contain silt-clay dredged material, the disposal site should be on a naturally accreting mud bottom, the disposal operation should emplace a large volume of material on the site expeditiously, and the deposit should be built to an optimum configuration. The capacity of the disposal site is limited by the maximum height of the disposal mound and the maximum slope of the pile sides which present a minimum disturbance of the natural hydraulic regime. The capacity of the New Haven site is estimated to be up to 1.7 × 10^6 yd^3 of unarmored, silty, dredged material. Larger volumes may be contained if the surface of the deposit is armored with coarser material.

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EXECUTIVE SUMMARY

In shallow coastal waters, sediment may be transported periodically by tidal currents or episodically by storm-generated currents. An important characteristic of any repository for dredged materials is its susceptibility to these disturbances. Storms may play a major role in the movement of sediment but occur irregularly and with variable intensity. As a result, evaluating their effects on the transportation of material requires continuous records of quantities such as wind velocity, water level, and current speed for at least a year coupled with some method of estimating the intensity of infrequent major events. Such a field evaluation of storm effects was made for Long Island Sound.

The silt bottom of central Long Island Sound is regularly resuspended by the tidal currents. Because the Sound is nearly surrounded by land, large-wavelength water waves are not generated and waves do not significantly disturb the bottom sediment in water depths greater than 60 ft. Strong winds, however, may produce fluctuations in the water velocity near the sediment-water interface which are as large as the tidal velocities. These random fluctuations in the flow may resuspend sediment even in the deepest waters of the Sound.

Storm winds may increase the volume of water in the Sound by an amount comparable to the tidal prism. This results in a large increase in the energy available for the transport of sediment. Turbidity observations show that the amount of sediment in suspension can be increased by a factor of three during stormy periods.

Both yearly and seasonal variations in storm energy may be estimated from wind records and water level data. This information is routinely collected and is available from the Coast Guard, National Oceanic and Atmospheric Administration (NOAA), airports, or the National Weather Service. The amount of storm energy entering the Sound is about a factor of three greater during the winter months than during the summer months. The winter storm energy may vary from year to year

by a factor of two. The evidence indicates that disturbances of the bottom sediment are limited to a layer less than a half inch thick in the deeper waters of Long Island Sound.

At the New Haven disposal site in Long Island Sound (water depth = 60 ft) 1.5 million yd^3 of silt and sand was emplaced and monitored by repeated bathymetric surveys over three years. The disposal operation produced a conical mound of sediment about 30 ft high with a 1200-ft radius. During the first 200 days the mound self-consolidated by about 25 percent of its height, but thereafter no large changes were detected even though several intense winter storms and a hurricane passed over the area. Apparently, during this period, any dredged material that was displaced from the disposal site was removed from a thin layer on the surface of the mound. The thickness of this layer is estimated to be between 4 in. and 2 ft. The former value is the depth to which benthic animals mix bottom sediments and the latter value is the smallest change in height that could have been distinguished by the bathymetric surveys.

On the basis of these observations, a capacity of a disposal site may be estimated as that volume of dredged material that can be placed at the site without a significant fraction of material being dispersed. The capacity of the New Haven disposal site ranges up to 1.7 million yd^3 of unarmored silt-sized, dredged material, but larger volumes can be contained if the deposit surface is armored with sand.

PREFACE

A study of the role of storms in determining the fate of dredged material in Long Island Sound at the New Haven and Eatons Neck disposal sites was made as part of the environmental impacts and criteria development project in the Dredged Material Research Program (DMRP) of the U. S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, Mississippi. This study was performed under Contract No. DACW51-75-C-0008 to Yale University, Work Unit 1B08, monitored by Mr. Barry Holliday, Environmental Resources Division of the Environmental Effects Laboratory (EEL), WES. The Contracting Officer was COL Thomas C. Hunter.

This report was written by Henry J. Bokuniewicz, Jeffrey Gebert, Robert B. Gordon, Peter Kaminsky, Carol C. Pilbeam, Matthew Reed, and Catherine Tuttle, all of the Department of Geology and Geophysics, Yale University. Many of the measurements reported were made by Matthew Reed and Robert Kerley. This report was edited by Jane Higgins, who also drafted many of the figures, and the typing was done by Wanda Stark and Peggy Keating, all of the Department of Geology and Geophysics, Yale University. Barbara Ford, of Branford, Connecticut, read current meter records. Tidal data were obtained from the Tides Branch, Oceanographic Division of the National Ocean Survey.

Directors of WES during the study and preparation of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
yards	0.9144	metres
fathoms	1.8288	metres
miles (U. S. statute)	1.609344	kilometres
miles (U. S. nautical)	1.852	kilometres
square feet	0.09290304	square metres
square yards	0.8361274	square metres
square miles (U. S. statute)	2.589988	square kilometres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
miles (U. S. statute) per hour	0.44704	metres per second
knots (international)	0.5144444	metres per second
foot-pounds (force)	1.355818	newton-metres
degrees (angular)	0.01745329	radians

PART I: INTRODUCTION

1. Dredged material that is placed on the sea bottom at an open-water disposal site with the intention that it remain in place may be moved by tidal currents or by waves generated during storms. Thus, an important characteristic of any site selected as a repository for dredged material is its susceptibility to disturbance by these natural agents. The "stability" of the dredged material placed on a given site is measured in terms of the fraction of material which remains immobile. In this report we address the problem of determining the stability of dredged material placed at an open-water disposal site. We do this by first identifying the various ways in which deposited material can be dispersed in a coastal or estuarine area and then describing a program of measurements that can be used to evaluate the importance of these sources of disturbance. Emphasis is placed on defining a program that can be completed in a relatively short time and which makes maximum use of oceanographic and meteorological data most likely to be already available for a given area. The analysis is developed by a study of disposal sites in Long Island Sound that have been used recently to receive dredged material.

2. It is unlikely that disposal can continue indefinitely at any given site without a large fraction of the dredged material being widely dispersed. At most localities there will be, therefore, a site capacity that is defined in terms of the site characteristics and some set of criteria that establish the unacceptable consequences of continued use of the site. It may be anticipated that there is also a maximum rate at which a disposal site can accept dredged material. When disposal sites in Long Island Sound are examined in these terms it is found that a natural limit to the amount of material that can be successfully retained on them may be set in terms of the susceptibility of the deposited material to dispersion. The capacity of the New Haven disposal site with respect to these criteria is estimated by way of example to show how such evaluations might be made for other localities.

PART II: STUDY AREA

3. For purposes of this study, data were obtained in Long Island Sound (see Figure 1) with particular attention given to the New Haven and Eatons Neck disposal sites. Long Island Sound is an estuary 80 miles long and 18 miles at its greatest width; it receives fresh water from the Connecticut, Housatonic, and East Rivers (and a number of lesser streams) and communicates with the sea principally through the Race at its eastern end. The length and depth of the Sound are such that it forms a naturally resonant basin. Consequently there is a strong tidal oscillation (Redfield, 1950); the tidal range increases to 6 ft at the western end while spring tide currents in the Race attain speeds of 4 knots. Superimposed on the tidal oscillation is an estuarine circulation (Riley, 1952 ; Gordon and Pilbeam, 1975 ; and Wilson, 1976) with inflow of saline bottom water, outflow of fresher surface water, and strong mixing in zones bordering the north and south shores. The margins of the Sound and the eastern end have a sandy bottom while the center contains a large deposit of marine mud. Essentially all sediment entering the Sound is retained (Bokuniewicz, Gebert, and Gordon, 1976). Both disposal sites studied are located on the mud bottom. Many important characteristics of Long Island Sound are summarized in a recently published book by Koppelman, et al. (1976).

4. There are few records of early dredging and disposal activity in Long Island Sound. Major harbor improvements were undertaken more than 100 years ago at New Haven and were vigorously pursued along the Connecticut coast as long as coastwise trade remained economically viable. Disposal sites appear to have been chosen for each harbor on the basis of the shortest haul to water 10 fathoms deep, this having been judged a sufficient depth to prevent disturbance of the dredged material by waves. Shoreside sites for the disposal of dredged material are not generally available, and the cost of hauling dredged material outside the Sound is great. The size and frequency of disposal operations since 1954 can be determined from records of the U. S. Army Corps of Engineers contracts. The maintenance and improvement

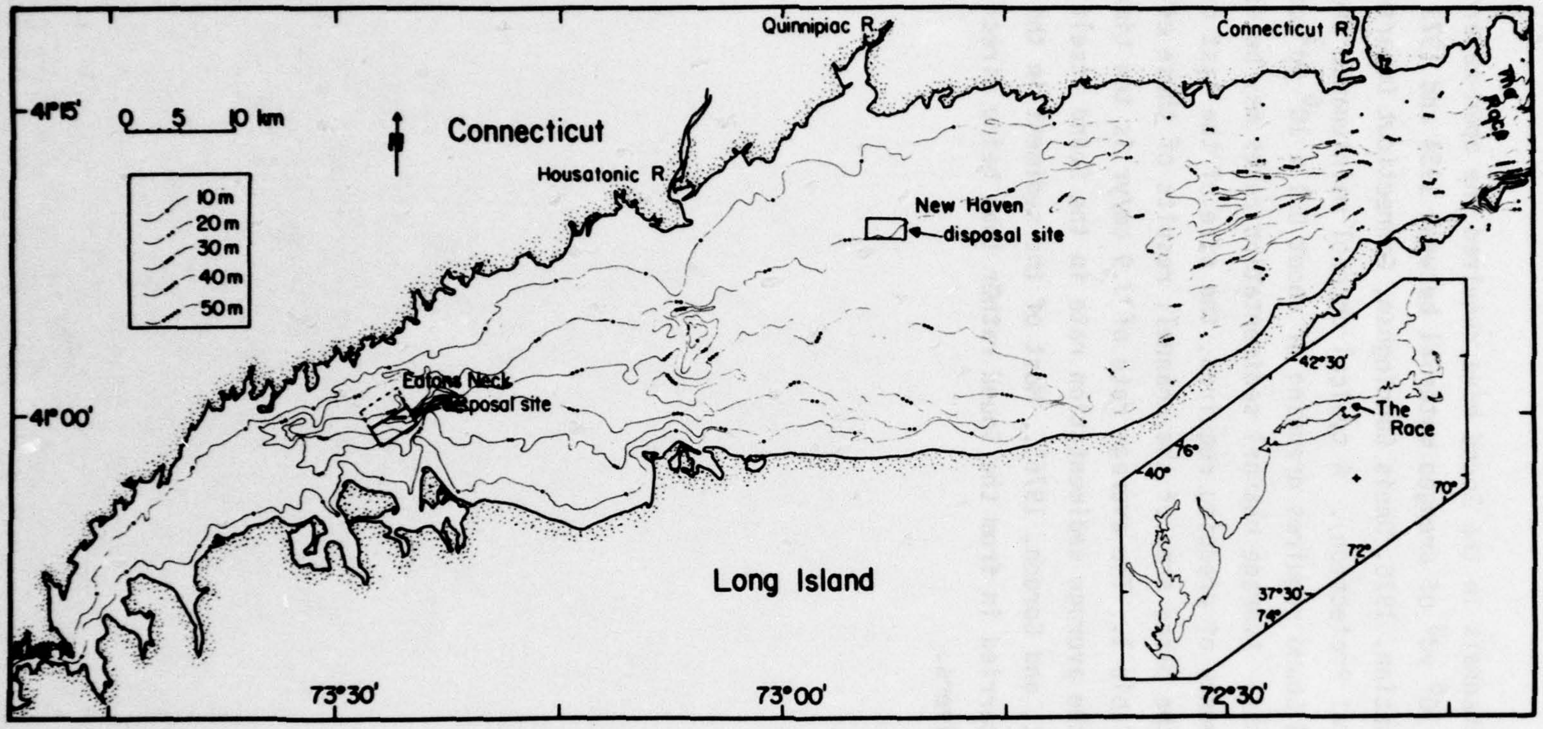

Figure 1. Index map of the study area.

of navigable channels in the Sound have required the open-water disposal of about 25 x 10^6 yd^3 of dredged material between 1954 and 1973 (personal communication, 1976, Denis Cunningham, Connecticut Department of Environmental Protection). A typical channel maintenance program in Long Island Sound requires dredging of about 0.1 x 10^6 yd^3 of sediment every 100 months. Average channel sedimentation rates may be estimated from the frequency of dredging required, the size of the last dredging project, and the plane area of the channel; results of these estimates are given in Table 1. The average rate of 3.9 cm/yr is ten times greater than the average sedimentation rate in the Sound itself (Bokuniewicz, Gebert, and Gordon, 1976). Most of the sediment in the harbors was probably carried in from the Sound rather than being directly supplied by rivers.

Table 1

Dredging Characteristics

of Connecticut Harbors

Harbor	Dredging Frequency Months	Volume of Last Dredging Project 10^4 m^3	Channel Area 10^4 m^2	Average Accumulation Rate cm/yr
Branford	100	7.1	11.3	7.6
Bridgeport	150	13.5	95.0	1.0
Clinton	100	2.4	5.4	5.2
Five Mile River	120	3.6	5.6	6.4
Greenwich	110	3.0	5.4	1.5
Guilford	120	5.6	7.3	7.7
Mianus River	150	1.4	5.9	1.9
Milford	170	3.0	11.8	1.8
Norwalk	70	4.8	43.0	1.9
Average Accumulation Rate for all Sites				3.9

PART III: METHODS

5. An estimate of the stability of a disposal site depends upon a prediction of the amount of dredged material that will be mobilized and dispersed. The currents in coastal waters are affected by the tides and winds. As a result, both currents and the amount of sediment in motion in the water column are quite variable in time and space. Since significant sediment dispersion can occur at very low rates over long periods of time, direct measurements of sediment transport are difficult and costly. It is more efficient, therefore, to estimate the rates of resuspension, erosion, and deposition by indirect measurements of such quantities as bottom currents, wind velocity, water level, and the thickness of accumulated sediment in the disposal area. From these observations, some of which are collected routinely by the Coast Guard or National Oceanic and Atmospheric Administration (NOAA), the amount of sediment transport and deposition may be estimated either empirically or theoretically.

6. To supplement the information available on the circulation and deposition in Long Island Sound discussed earlier, the methods used in the field were designed to yield three types of information. The first is the characterization of the response of the water in Long Island Sound to storms. Data were obtained principally from a wave recorder, arrays of current meters, and from water level (tide gage) records. Wind data were obtained from all National Weather Service and Coast Guard stations on the Sound and from local power companies; some additional continuous records of our own were also made. Second, to determine the response of the bottom of the Sound near the disposal sites to storms, observations of resuspension of bottom sediment were made. The integrated sediment content of the water column was used for this purpose. Additional data were obtained from examination of bottom photographs and cores. The final set of observations comprise determinations of changes in the deposited material at disposal sites after the passage of storms. Precision

bathymetric surveys of the New Haven disposal site are the principal source of information.

Water Level

7. Most of the water level data used in this study were obtained from the National Ocean Survey's tide gage installations around Long Island Sound. Additional data were obtained from a gage operated by the New York District, U. S. Army Corps of Engineers, at the Eatons Neck Coast Guard Station and from a gage maintained in New Haven Harbor by the United Illuminating Company. Water level measurements at the New Haven disposal site were made with a Bass model WG100 wave recorder placed on the bottom for a period of 15 days. This instrument records the water pressure for 2 min each hr. The average pressure for each interval is converted to water depth using the density of Long Island Sound water and graphed to generate the tidal curve. The errors at all gages are small compared to the water level changes in Long Island Sound caused by storms.

8. In order to detect storm-induced changes in water level, it is helpful to separate the observed height into tidal and nontidal components. There are a number of methods by which this can be done ranging from the semi-graphic tidal analysis, which requires no access to computation facilities, to numerical harmonic analysis. The method used for most of the data obtained in this study is a least-square regression of 18 sinusoids with tidal periods over 15 or 29 days (Bokuniewicz et al., 1976 ; Dronkers, 1964).

Currents

9. Two types of current meters have been used to record the water flow in Long Island Sound. The Braincon histogram meter type 381 records the average flow and average direction over 20-min intervals, while the General Oceanics model 2010 records instantaneous current velocities at a fixed sampling interval that can be set between

15 sec and 30 min. Each type of meter can operate for up to six weeks unattended. They are suspended on taut-line moorings, usually 6 ft above the bottom, in water sufficiently deep so as to be unaffected by surface waves, normally 60 ft below the surface.

10. The dominant water flow in Long Island Sound is the tidal stream. As in the analysis of water level, it is again useful to separate the tidal and nontidal components of the current. The tidal constituent may be removed from the record by the same procedure as is used in the analysis of water level. The nontidal part of the current can be further subdivided into an average or long-term flow and a fluctuating flow. The separation of an observed current into tidal, long-term, and fluctuating components is illustrated in Figure 2. When only the long-term component of the flow is desired it is easily obtained to a good approximation by summation of the velocity vectors over successive tidal cycles (12.4 hrs). We will call each such sum a "resultant vector." The average flow is associated with the estuarine circulation in the Sound and is usually steady for days or weeks at a time (Gordon and Pilbeam, 1975). The fluctuating part contains all of the irregularities in the flow such as those associated with the turbulence in the tidal stream. We will see later that the fluctuating component of the current is particularly important in the evaluation of the response of the Sound to storms.

11. During the spring of 1975 an intercomparison of five different types of current meters was made at a location near the New Haven disposal site (Bokuniewicz et al., 1977). It was found that all the meters tested gave generally comparable results for the tidal and fluctuating components of the flow; difference between the meters was greatest for the long-term flow. In the results reported here, inadequacies in the data due to meter characteristics are small compared to those due to gaps in the continuity of the data and to the limited number of locations at which measurements could be made.

Waves

12. Data on the height and period of waves on Long Island Sound

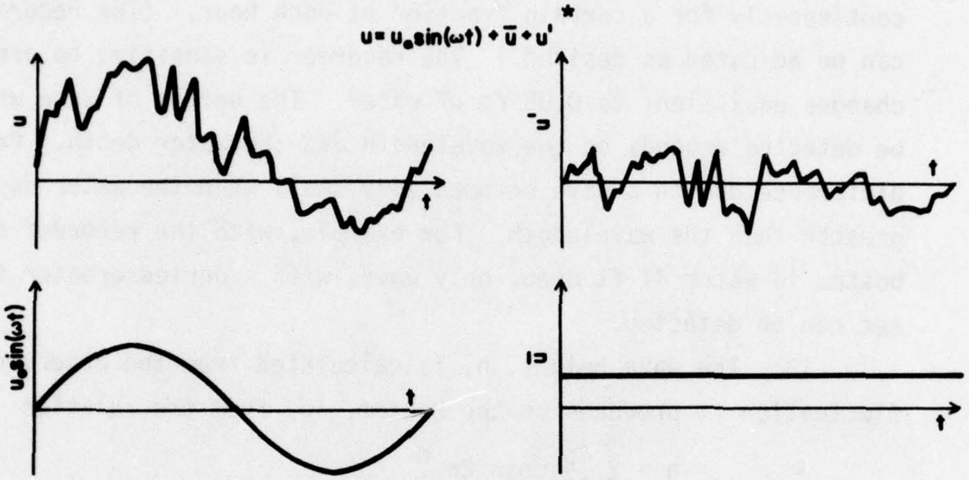

Figure 2. Mathematical separation of a velocity, u, into a periodic component, $u_0\sin(\omega t)$; a mean component, $\bar{u}$; and a random, fluctuating component, u'.

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* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix A).

generated during storms were obtained with a Bass model WG100 wave recorder. This device, placed on the bottom, records water pressure continuously for a certain fraction of each hour. (The recording time can be adjusted as desired.) The recorder is sensitive to pressure changes equivalent to 0.05 ft of water. The height of wave which can be detected depends on the wavelength and the water depth. Pressure difference due to a wave becomes very small when the water depth is greater than the wavelength. For example, with the recorder on the bottom in water 41 ft deep, only waves with a period greater than 3.5 sec can be detected.

13. The wave height, h, is calculated from the observed pressure fluctuation it produces on the bottom, δp, from the relation

$$h = 2 \frac{\delta p}{tg} \cosh 2\pi \frac{d}{\lambda}$$

where t is the wave period, g is the acceleration due to gravity, d is the water depth and λ is the wavelength. The latter is found by graphical solution of the equation

$$\frac{gt^2}{2\pi} = \frac{\lambda}{\tanh 2\pi \, (d/\lambda)}$$

For a given locality, this solution need be done only once.

Wind

14. To supplement wind data available from various observing stations around the Sound, a continuous record of wind speed and direction was made with a wind recorder placed at the Falkner Island lighthouse. This site is particularly useful because it is exposed in all directions; offshore wind speeds are substantially reduced at shoreside stations because of the relatively large ground friction. Unfortunately, the recording equipment and much of the data were lost when the keeper's dwelling at Falkner Island was destroyed by fire in March 1976.

Suspended Sediment

15. The amount of suspended sediment at a fixed place and time in the water column can be determined accurately by filtration of a water sample. However, the number of such samples that can be examined is limited and without some kind of continuous analog indicator of sediment concentration, there is no way of knowing if the sampling is adequate. This is particularly important when the integrated sediment content in the water column is desired. In this application rapidity and continuity of measurement are more important than absolute accuracy. For this reason, sediment concentrations are measured with a white-light transmissometer. The method works well in Long Island Sound because the optical attenuation due to sediment appears to be large compared to that from other sources, such as substances in solution.

16. The transmissometer path length appropriate for the sediment concentrations found in Long Island Sound is 10 cm. The instrument used is fitted with a pressure sensor so that transmittance as a function of depth can be plotted directly on an X-Y recorder. The transmissometer is calibrated with weighed amounts of bottom sediment from the study area resuspended in a tank of sea water. The calibration curve is shown in Figure 3. With this system, instrument errors are small compared to uncertainties associated with the adequacy of sampling in space and time.

Sediment Properties

17. Sediment samples in the study area have been collected as short cores. The size distribution of the mineral constituents was determined by standard soil mechanics laboratory procedures by Haley and Aldrich, consulting soil engineers of Cambridge, Massachusetts. The actual structure of the sediment-water interface has been examined with both diver-made and profile photographs, as described by Bokuniewicz et al. (1975). The acoustic reflectivity technique reported by

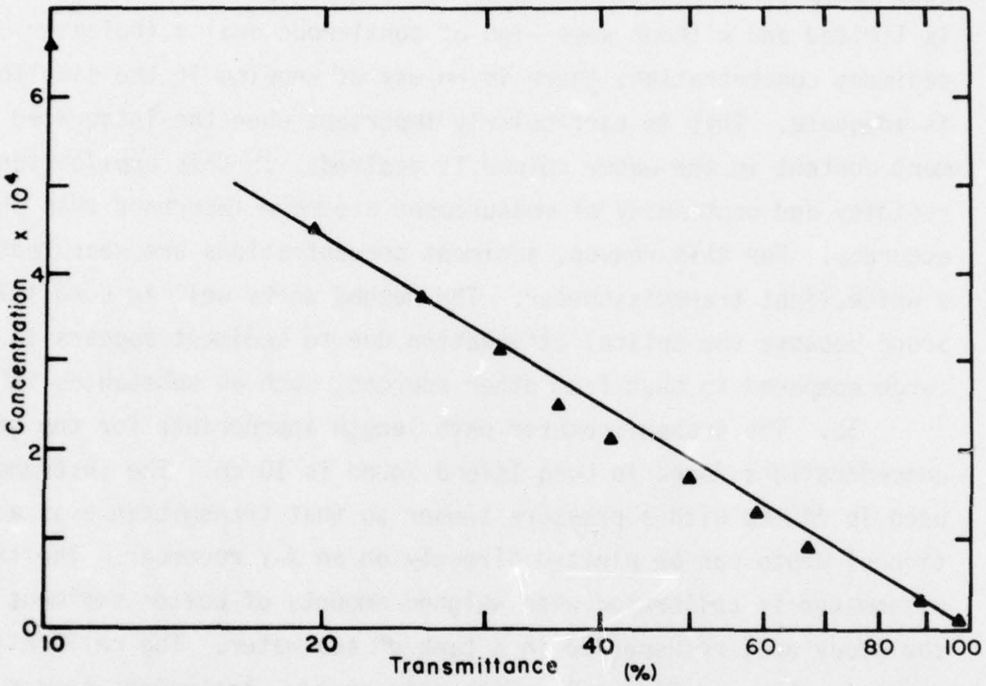


Figure 3. Calibration curve for the optical transmissometer used in this study relating percent transmittance to the suspended sediment concentration in grams of sediment per gram of water.

Bokuniewicz, Gebert, and Gordon (1976) has been used to observe the distribution of sand (characteristic of dredged material) over the natural mud bottom at the New Haven disposal site.

Bathymetric Surveys

18. The best method available at this time for determining the form and distribution of deposited material at a disposal site is by precision bathymetric surveys. Since dredged material at the New Haven site is present in an area of only a few hundred yd radius and the site is 8 miles offshore, great care must be taken with the navigation procedures. This problem is discussed in the following section.

19. All soundings were made with Raytheon model DE-719 survey fathometers operating at 200 kHz. Absolute measurement of water depth relative to a geodetic datum is not required to detect changes in bottom topography at a disposal site if individual survey lines are long enough to extend beyond the disposal area to an area having a stable bottom. However, if several fathometer tracks made over a period of hours are to be combined in the construction of a contour map, correction for the change in tide height that occurs between successive tracks is required. Two procedures have been used to effect this correction. In one, all survey tracks are begun or terminated at one fixed reference point outside the disposal area, which then serves as a local datum. Alternatively, a water level recorder may be placed on the bottom near the disposal site and its record used to correct all surveys to such a reference water level. The initial bathymetric survey of the New Haven disposal site was made by the New England Division, U. S. Army Corps of Engineers, and tidal corrections were based on tide staff observations in New Haven Harbor. Comparison of tide gage records from the Harbor with water pressure records from the disposal site shows a very close correspondence in the water level changes. It is estimated that the errors due to tide height corrections are less than 1 ft (1.7 percent) in all the surveys reported here.

20. The overall configuration of the deposited material is shown by a contour map. When it is desired to show the thickness of the deposit, height differences relative to the initial (predisposal) survey are mapped and a correction applied for the deflection of the bottom under the superimposed load of dredged material (see Bokuniewicz et al., 1975 for a full discussion of this procedure). Small differences in bottom topography, such as would be expected near the outer limits of the area on which dredged material has been placed, are not easily detected by comparison of contour charts. The most sensitive method is a direct comparison of successive fathometer records made along identical tracks. This has proved to be a very useful technique at the New Haven disposal area.

Navigation

21. Three basic methods of positioning are capable of yielding the accuracy required to detect changes in the configuration of disposed material in Long Island Sound. These are:

- a. Measuring the horizontal angles between shoreside landmarks from the sounding vessel with a surveying quintant.
- b. Measuring two angles to the vessel from theodolite observing stations ashore.
- c. Measuring the ranges to two shore stations from the boat with microwave interferometer equipment.

22. Various combinations of these three methods, such as measuring one range and one theodolite angle, are possible. Best precision is obtained with the optical methods but their use is confined to periods of good visibility. The electronic ranging systems suffer from problems of reliability, signal attenuation under unfavorable atmospheric conditions and the difficulty of obtaining sufficient averaging time in readings taken from a moving vessel. All of the above methods have been used at various times during surveys of the New Haven disposal site, depending primarily on equipment availability. A full account is given in two reports to the New England Division, U. S. Army

Corps of Engineers (Bokuniewicz et al., 1975, 1976). Some of the survey results were not of satisfactory quality because of the poor performance of a chartered microwave ranging system. The radius of the probable error circle due to random errors in nearly all of the data presented in this report is less than 20 ft. Larger systematic errors may be present because there was no opportunity to intercompare the different navigation systems used.

PART IV: RESULTS

23. The passage of a storm results in the generation of waves on the water surface and, usually, a change in water level. These are manifestations of the transfer of energy to the waters of the Sound, energy which may result in disturbance of the sediments on the bottom. First, data must be presented that establish the response of the water of the Sound to storms and the magnitude of the resultant disturbance of the bottom compared to the normal tidal disturbance. In order to be able to describe the importance of any given storm as a source of disturbance of the bottom, it is necessary to have a measure of the frequency of occurrence of storms of different magnitudes. An analysis of water level variations over the past 38 years is used to provide this information.

24. When a large amount of dredged material is placed at a disposal site, its susceptibility to dispersion by storms or other natural causes is increased. Consequently, an upper bound on the amount of material that can be accommodated at any given site can be set in terms of the degree of dispersion that is acceptable. This limit is determined for the New Haven site. The optimum configuration of disposed material to make the most effective use possible of the site is also examined.

Response of the Waters of Long Island Sound to Storms

Waves

25. The generation of waves and surf is the most obvious response of a coastal body of water to the passage of a storm. Resultant shoreside erosion, longshore drift, and resuspension of the bottom sediments in the surf zone are easily observed; the effect of storm-generated seas on the bottom in deeper water has to be determined. The horizontal component of the orbital water particle velocity due to the passage of waves on the surface may exceed the critical erosion velocity of the sediment. Material so activated by wave-induced oscillating currents

is susceptible to transport by whatever net bottom water flow may accompany the waves.

26. Because Long Island Sound is almost completely surrounded by land, estimates of the sea state resulting from various wind conditions can be made by the methods developed to evaluate the waves generated in large reservoirs. According to Saville, McClendon, and Cochran, as quoted by Linsley and Franzini (1972), the period, t (sec), length, λ (ft), and height, h (ft), of fully developed waves on an enclosed body of water are given by

$$t = 0.46\ V^{0.44}F^{0.28}$$

$$\lambda = 5.12\ t^2$$

$$h = 0.034\ V^{1.06}F^{0.47}$$

where V is the wind speed in mph measured at a height of 30 ft, and F is the effective fetch in miles. The effective fetch is the average fetch projected on the wind direction over a 90^o arc centered on the wind arrow. At the center of Long Island Sound near the New Haven disposal site, F = 26 miles and the greatest value of F in the Sound is about 30 miles.

27. In the simplest theory of gravity waves the maximum horizontal component of the water particle velocity at the bottom is

$$u_m = \frac{\pi h}{t \sinh (2\pi d/\lambda)}$$

where d is the water depth and h, t and λ are, respectively, the wave height, period and length. The relations above can be used to estimate the range of water depths in Long Island Sound in which u_m can be large enough to cause significant disturbance of sediment. In central and western Long Island Sound the amplitude of the tidal stream is $\sim$ 25 cm/sec and, as shown later, the sediment on the muddy bottom is regularly resuspended by the tide. If $u_m \gtrsim 25$ cm/sec, waves will significantly increase the amount of resuspension but if $u_m << 25$ cm/sec, the net effect of waves on the bottom will be small compared to that of the tide.

28. Figure 4 shows the depths at which u_m = 1, 10, and 25 cm/sec for different wind speeds, as calculated from the equations above. When an estimate of the greatest depth to which waves will disturb the bottom under extreme storm conditions is made, it is necessary to allow for the time required to raise a fully developed sea. This time, T, is shown in Figure 4; it decreases slowly as V increases. On Long Island Sound high wind speeds are associated with intense, fast moving storm systems and so are of short duration. The length of time that the wind may be expected to blow in different ranges of speed was estimated from the continuous wind record made in December 1975 and January 1976 at the Falkner Island Light House. This is shown as curve "D" in Figure 4 and is a conservative estimate because the anemometer was at a height of 100 ft whereas the calculations of u_m are based on winds at a height of 30 ft above the water surface. Comparison of the "D" and "T" curves in Figure 4 shows that when the wind speed exceeds 29 mph it is unlikely to blow long enough to raise a fully developed sea; u_m will then be less than that predicted. The data presented in Figure 4 indicate, then, that u_m is expected to be large enough to significantly disturb the bottom only when the water depth is less than $\sim$ 60 ft.

29. To test the above estimate of bottom disturbance by waves the wave recorder was placed on Cable and Anchor Reef near the Eatons Neck disposal site from 19 February to 27 March 1975. (There is no shoal near the New Haven disposal site on which the wave recorder could be placed.) The water at the reef is 41 ft deep so waves with periods as low as 3 sec can be recorded. Several major storms occurred, but pressure fluctuations were detected only when the wind was blowing from between northeast and southeast, the only direction with a relatively large fetch. Gale force winds from other directions do not cause detectable pressure fluctuations; although they raise a steep sea, the wavelength remains relatively short. Water particle speeds at the bottom calculated for the wave record are shown in Figure 5 for the duration of one winter gale. The square of the wind speed, proportional to the wind stress, and the average value of u_m over each

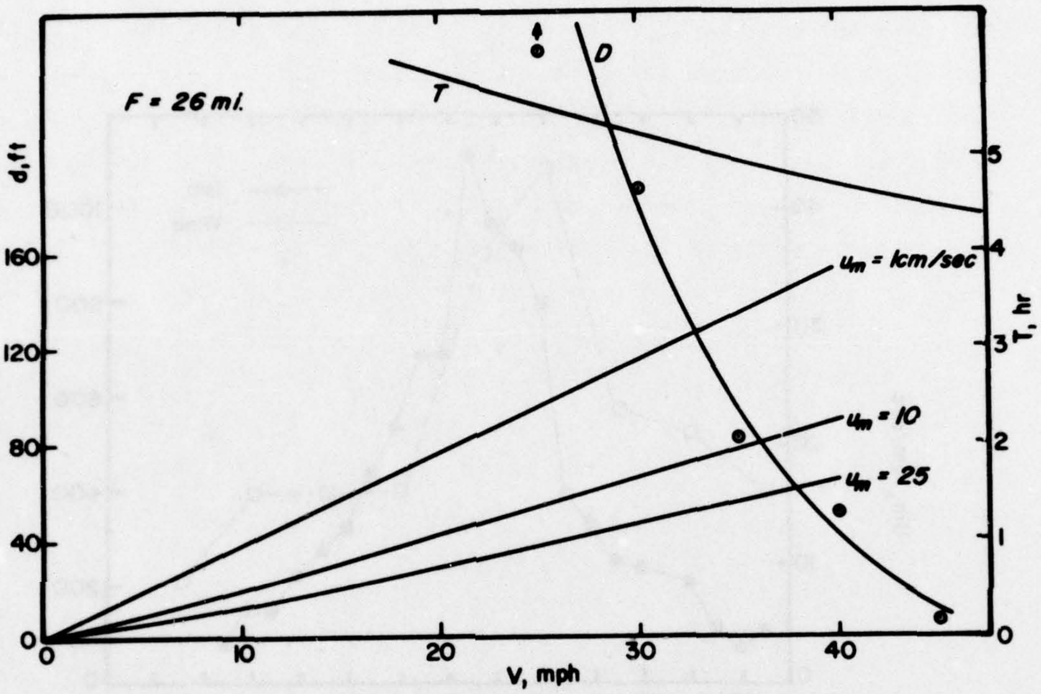


Figure 4. Plot of the maximum orbital wave velocity at the bottom, u_m, as a function of water depth, d, and wind speed, V, for the largest fetch available in Long Island Sound, F = 26 miles. Also shown is the time, T, required to generate fully developed seas and the duration of measured wind speeds in the Sound (curve D). Both curves D and T are scaled by the right axis in hours.

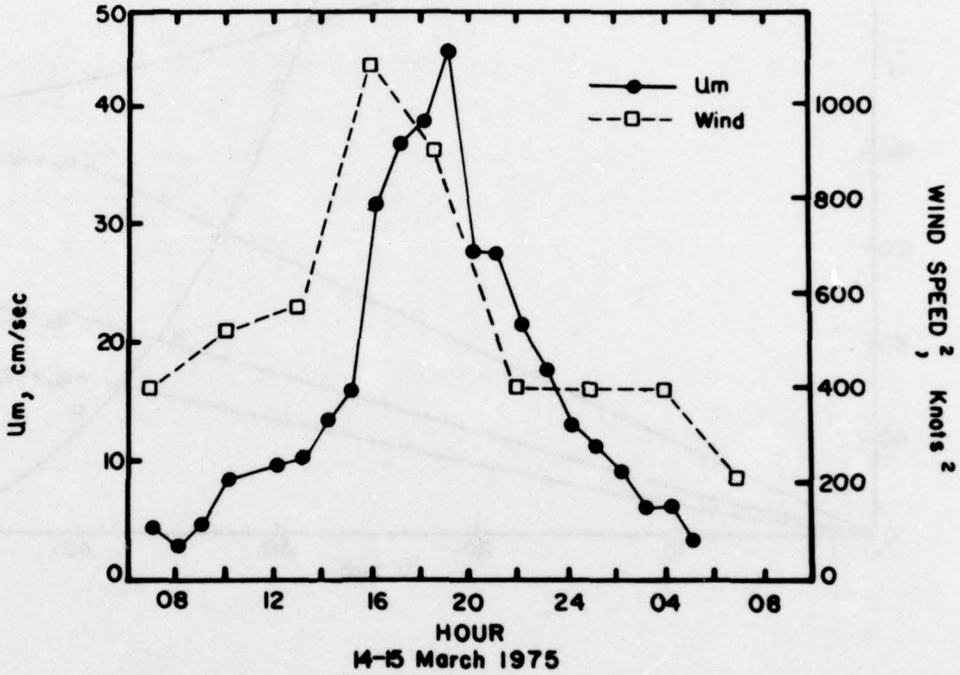


Figure 5. The maximum orbital wave velocity at the bottom, u_m, and the wind speed squared. Water velocities were measured at the Eatons Neck disposal site in 41 ft of water.

3-min recording interval are shown for the time that the wind was blowing from the quadrant between northeast and southeast. The horizontal water velocities at the bottom due to waves are in accord with the predictions for this storm made with the data in Figure 4.

30. Additional evidence that wave-induced water motions are relatively unimportant in Long Island Sound below a depth of 60 ft is found in the records made with the General Oceanics current meters. The photographs of the tilt indicator made by the camera in this meter are blurred when the meter is subject to the accelerations caused by waves. In over 40 records of up to 6 weeks duration made throughout the Sound, blurred images of this kind are found only for meters operating in depths of less than 60 ft.

Currents

31. Current meter records extending over a period of several years have been obtained at the New Haven disposal site. These show that the flow of water over the bottom of Long Island Sound is variable over a wide range of length and time scales. These data can be used to define the hydraulic characteristics of disposal sites in the Sound; they are also helpful in establishing procedures for the design of a current-measuring program for other estuaries.

32. The method of separating an observed record of currents into a long-term flow, a tidal stream, and a fluctuating component is presented in Part III of this report. In Long Island Sound, the tidal stream is the largest constituent. It may be adequately predicted from current meter data taken over 29 days. In the wide, central part of the Sound the current is rotary but the major axis of the tidal ellipse is long compared to the minor and is oriented nearly in the east-west direction. Hence, for many purposes, attention can be focussed on the east-west component of the current, u_x. The harmonic constants for both u_x and the water level have been calculated from current and depth records made simultaneously at the New Haven disposal site. These are listed in Table 2. Inspection of the table shows that the semidiurnal constituent, M_2, is the largest. For an ideal, resonant, co-oscillating

Table 2

Harmonic Constants for Tides and Tidal Streams, New Haven Disposal Site

	Tide		Stream	
Component	Phase, deg	Amplitude, ft	Phase, deg	Amplitude, cm/sec
K1	99	0.36	197	2.1
O1	145	0.24	285	1.2
Q1	225	0.03	265	1.3
L2	349	0.27	328	8.3
M2	323	2.86	46	22.9
MU2	10	0.05	189	1.3
N2	292	0.64	28	10.8
S2	322	0.47	359	4.2
MK3	318	0.02	62	0.2
MO3	53	0.01	201	0.7
M4	150	0.00	234	1.0
MN4	114	0.01	271	0.5
MS4	122	0.01	259	0.6
M6	263	0.10	179	2.6
2MN6	247	0.06	359	0.8
2MS6	270	0.04	210	0.9
MSN6	5	0.03	334	2.4
2SM6	353	0.01	56	0.4

tide the phase difference between the water level and the velocity is 90°; the observed phase difference is 83°. The difference of 7° is due to the effects of friction and can be used to estimate the amount of tidal power dissipated in the Sound (Ippen and Harleman, 1966). It will be shown later that this quantity is useful in evaluation of the relative importance of different energy sources in the resuspension of sediment in the Sound. The harmonic constants listed in Table 2 can be used to make predictions of both the tidal height and the tidal current at the New Haven disposal site.

33. There are no well-defined periodicities in the flow over the bottom of Long Island Sound other than the tidal ones. Therefore, the division of the nontidal component of the observed flow into a fluctuating part and a long-term, net flow has to be made at an arbitrary point. It has been suggested that a useful division point is a time scale of about 15 days (Gordon and Pilbeam, 1975) because the net flow shown by resultant vectors usually remains nearly steady for times ranging between several days and several weeks.

34. During much of the year 1973, current meters were maintained at the New Haven disposal site and at a "control" site 1 mile south. The net flow at the two sites is similar. This is shown by the similarity of the time variation of the north-south and east-west components of the fluctuating velocities displayed in Figure 6. The correspondence of the two sets of resultant vector components shows that the length scale of many of the fluctuations in the resultant flow is larger than 1 mile, the spacing between the two current meters.

35. The longest series of data are available for the control site (a meter could not be kept at the disposal site while dredged material was being placed). The resultant flow vectors for the year 1973 are shown in Figure 7. The net flow is to the west and south throughout the year with the range of direction being about 60°. However, even data over a year are of insufficient duration to characterize the net flow at this locality. This is shown by the resultant flow vectors for the first half of 1975 (see Figure 8). While still

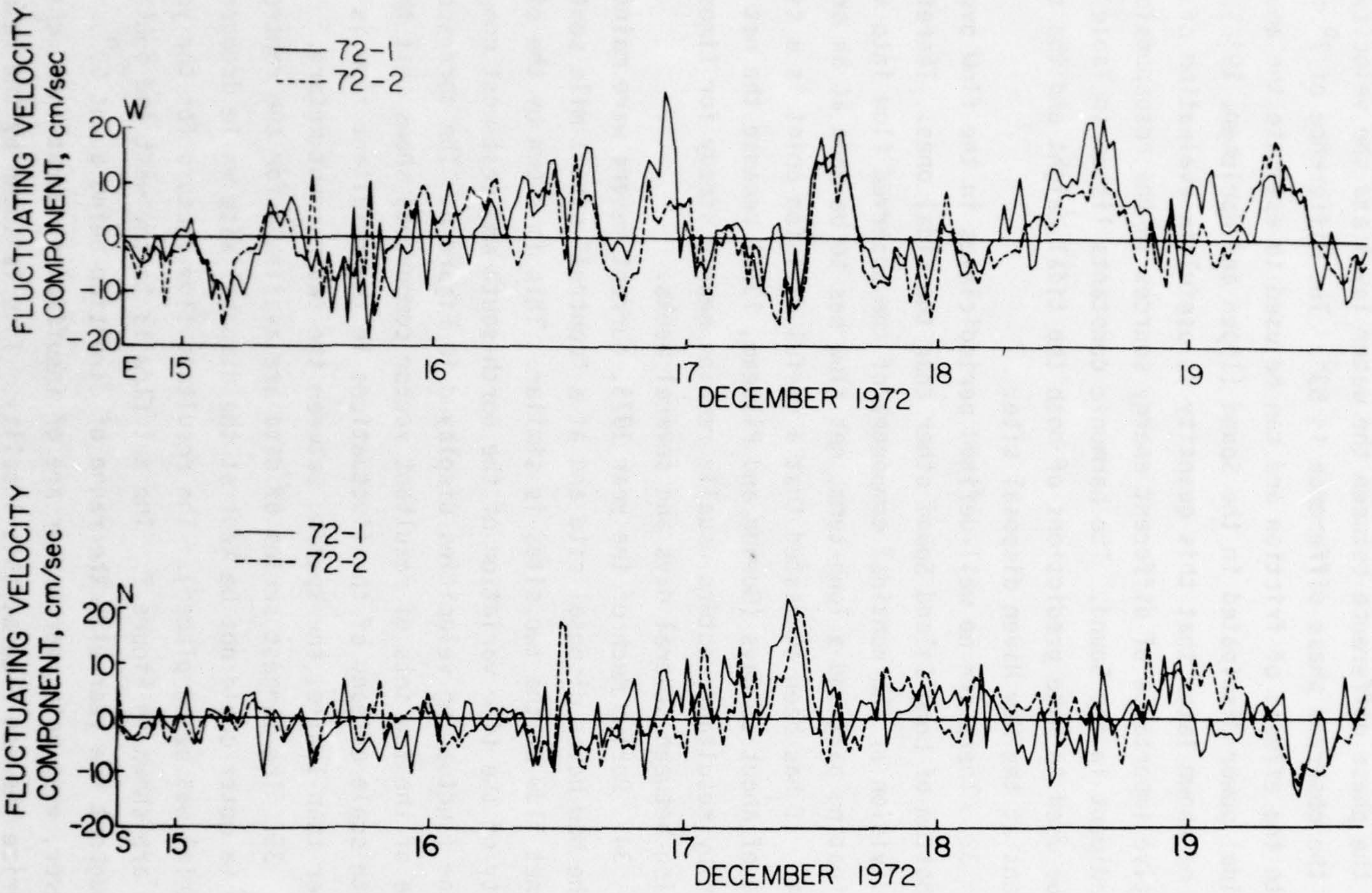


Figure 6. Comparison of the east-west and north-south components of the fluctuating velocity components at two stations in the central Sound. The flow was sampled every 30 minutes at a height of 6 ft above the bottom. The stations are about 1 mile apart (72-1 is the New Haven Disposal Site, 41°08.7'N, 72°52.9'W; 72-2 is the South Control Site, 41°07.4'N, 72°52.9'W).

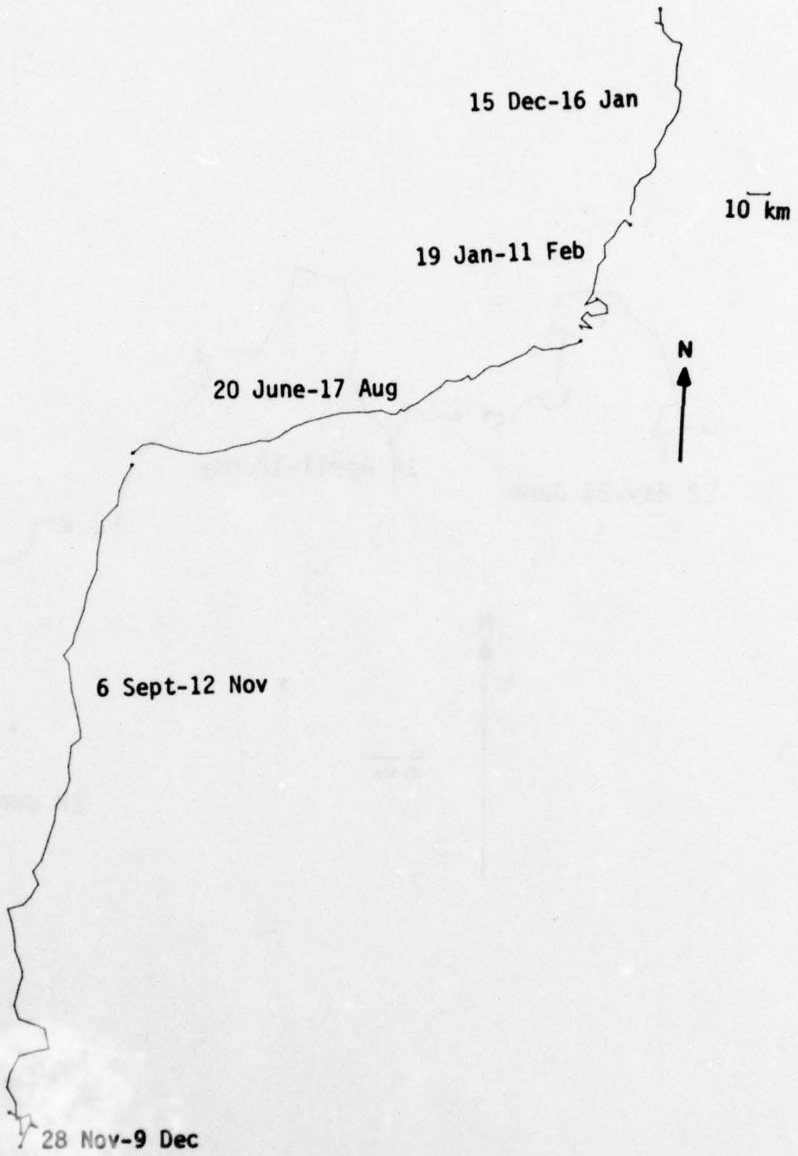


Figure 7. Resultant flow vectors measured 6 ft above the bottom in the central Sound (41°07.4'N, 72°52.9'W) between 15 December 1972 and 9 December 1973.

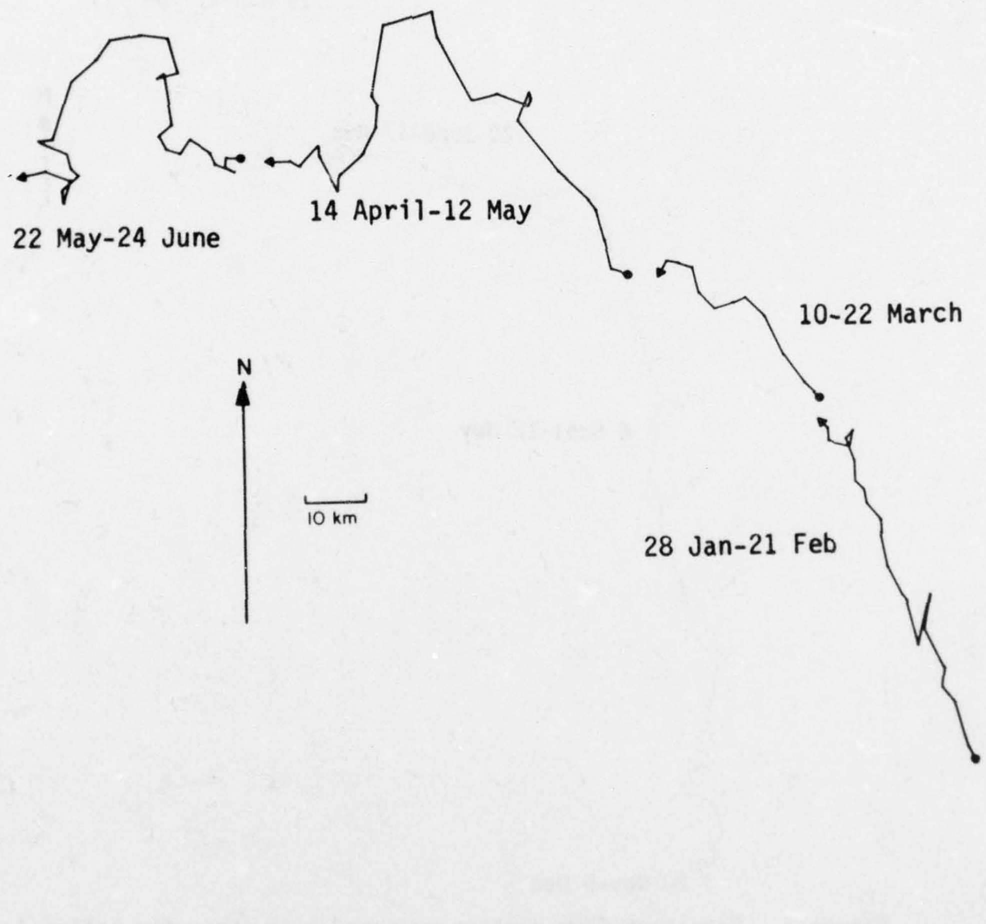


Figure 8. Resultant flow vectors measured 6 ft above the bottom in the central Sound (41°07.4'N, 72°52.9'W) between 28 January and 24 June 1975.

to the west, the net flow now has a northerly rather than a southerly component over much of the interval. The westward flow over the bottom is identified as the estuarine circulation driven by the density difference between the eastern and western ends of the Sound (Wilson, 1976). The cause of the north-south component of the net flow has not been identified.

36. At the New Haven disposal site Long Island Sound is wide compared to the tidal excursion, and geographical constraints on the net flow are small. At the Eatons Neck disposal site in the western end of the Sound, this is no longer true. There the net flow shows much less spatial variation (Bokuniewicz et al., 1976). Even though the net flow velocity is small compared to the tidal velocity, it is, nonetheless, important in prediction of the dispersion of dredged sediment. Material mobilized by the tidal currents will, on the average, drift in the direction of the small, long-term flow. At the disposal areas in Long Island Sound the net flow measured over periods longer than three weeks is generally parallel to the shore and proceeds at speeds of less than 10 cm/sec.

37. Tidal flow can be predicted from relatively short spans of data because the agents that cause the tides are well defined. Any geophysical flow, however, also contains unpredictable variations in the flow velocity. Instantaneous velocities may only be predicted statistically and no attempt is made to assign a cause and effect relationship to specific observed velocities. In dealing with the stability of particulate material placed on the bottom of a large estuary like Long Island Sound, it is necessary to define all components of the observed flow other than the tidal and mean over the record interval as fluctuating and to describe these in statistical terms. The importance of the fluctuating component, u', of the bottom water velocity in Long Island Sound is illustrated by the data presented in Figure 9. The magnitudes of the fluctuating component of the observed velocity for a period of a month at the Eatons Neck disposal site are displayed here. The magnitude is expressed as a fraction

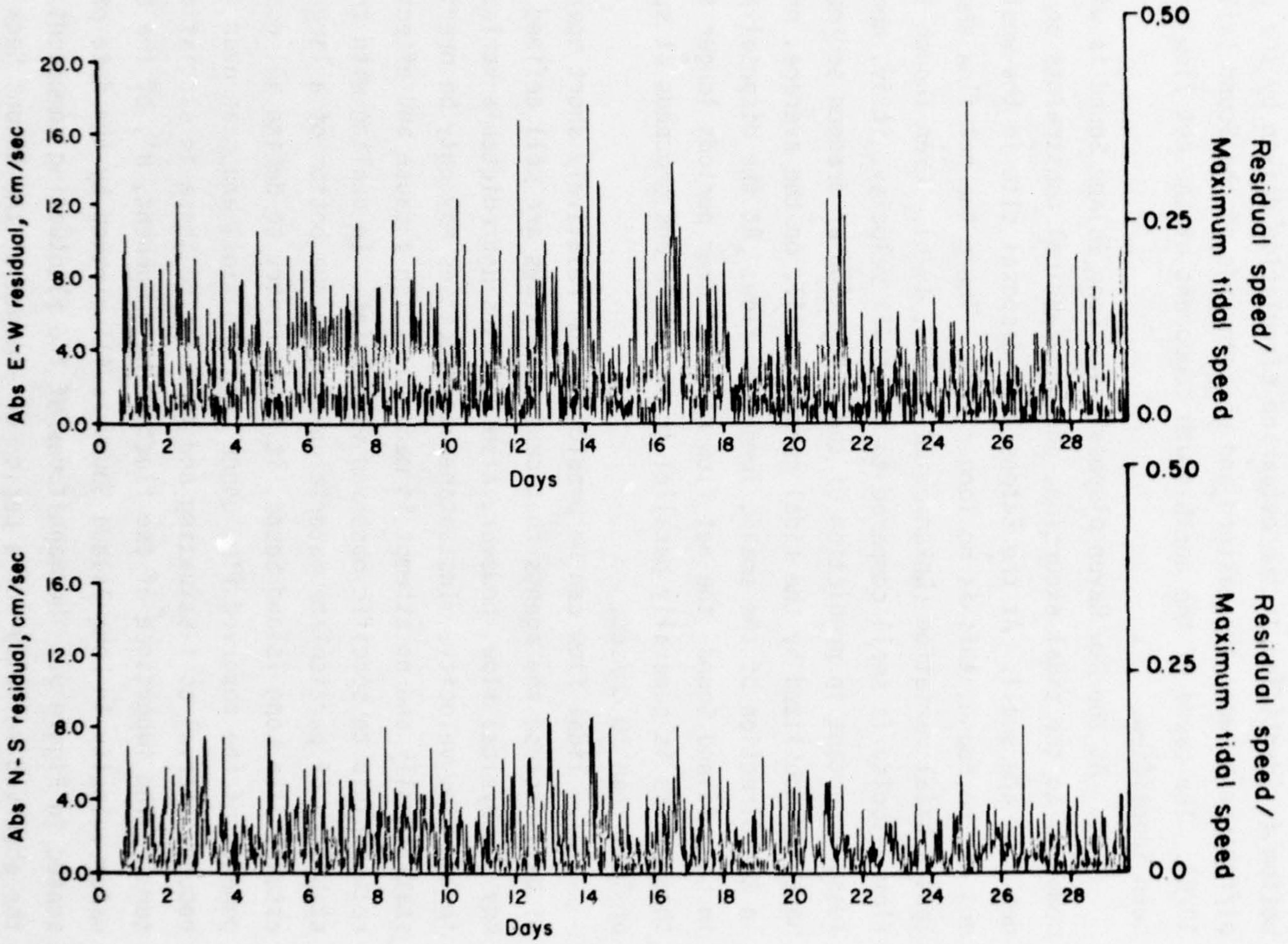
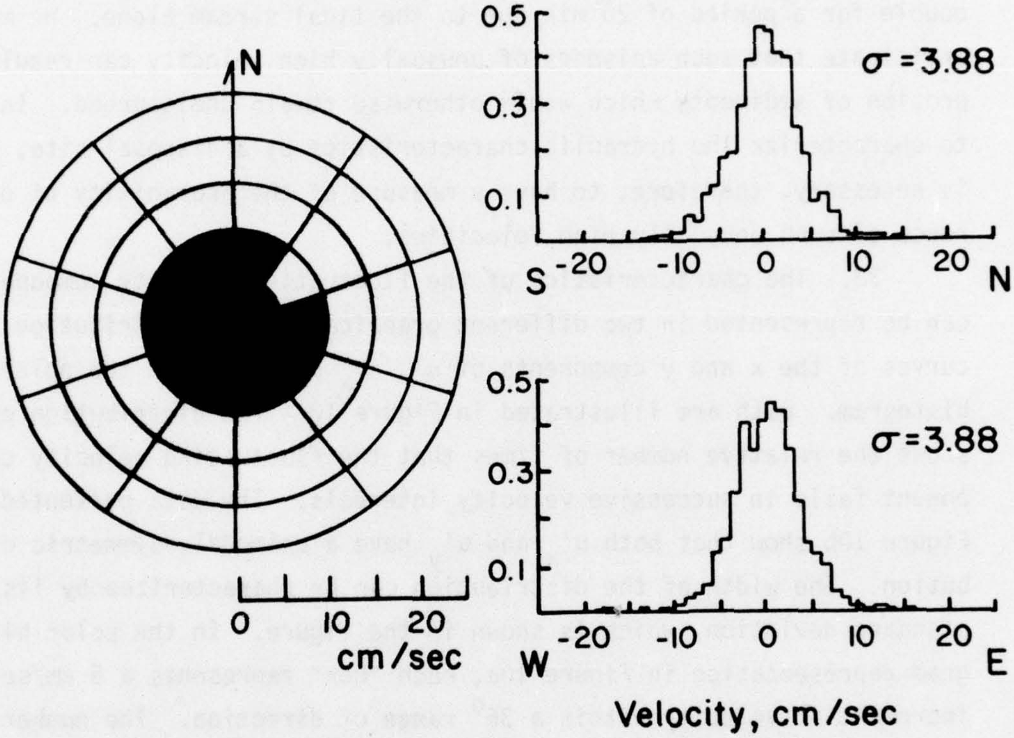


Figure 9. East-west fluctuating current speeds recorded 6 ft above the bottom of the Eatons Neck disposal site (41°00.2'N, 73°26.4'W) between 31 October and 12 December 1974.

of the amplitude of the tidal stream, U, and it is seen that values of u' ranging from 0.5U to U are not uncommon. This means that there will be a number of occasions when velocity over the bottom may be nearly double for a period of 20 min due to the tidal stream alone. We may anticipate that such episodes of unusually high velocity can result in erosion of sediments which would otherwise remain undisturbed. In order to characterize the hydraulic characteristics of a disposal site, it is necessary, therefore, to have a measure of the probability of occurrence of such unusually high velocities.

38. The characteristics of the fluctuating velocity component can be represented in two different graphical forms, distribution curves of the x and y components of u', u'_x and u'_y, and the polar histogram. Both are illustrated in Figure 10. The distribution curve shows the relative number of times that the fluctuating velocity component falls in successive velocity intervals. The data presented in Figure 10b show that both u'_x and u'_y have a unimodal, symmetric distribution. The width of the distribution can be characterized by its standard deviation, which is shown in the figure. In the polar histogram representation in Figure 10a, each "box" represents a 5 cm/sec increment in velocity within a 36^o range of direction. The number of observed values of u' falling in each box is counted and the resultant totals represented by different shading. The polar histogram in Figure 10 shows that the probability of occurrence of a velocity fluctuation is about the same in all directions and decreases steadily for successive greater magnitudes.

39. Some inferences about the fluctuating velocity can be made with the aid of a polar histogram even when the recorded velocities have not been separated into mean, tidal, and fluctuating parts. Polar histograms of the actual recorded velocities and of the fluctuating component calculated from it are shown for comparison with each other in Figure 11. The histogram of the total velocity lacks circular symmetry because of the high east-west velocities of the tidal stream and is not centered on u = 0 because of the net, long-term flow of

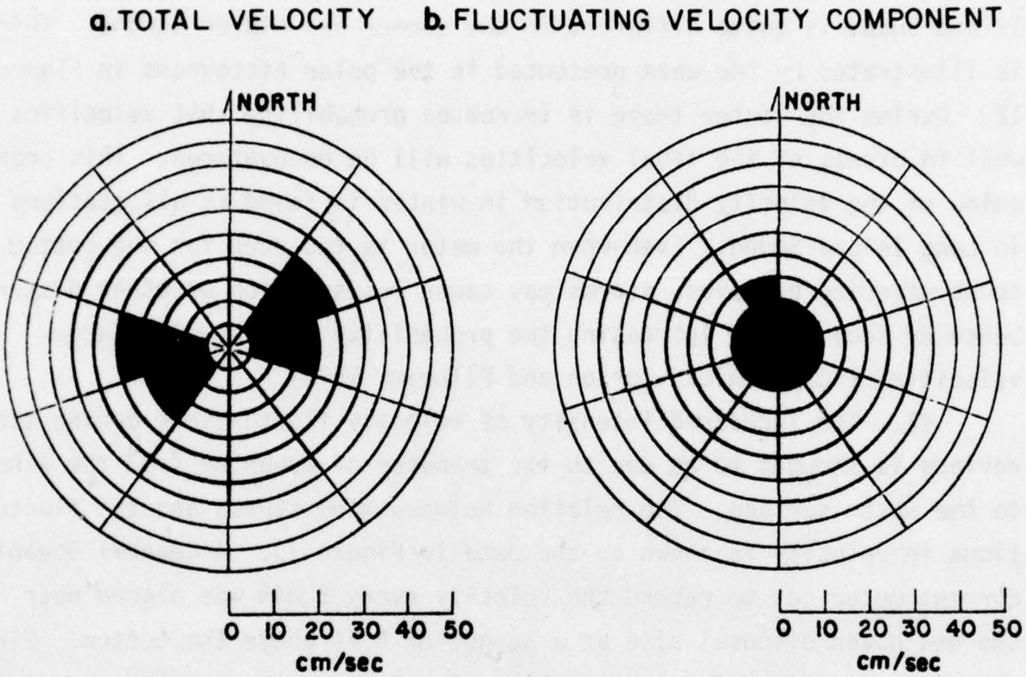


a. Polar histogram

b. Distribution curves of the x and y components

Figure 10. **a.** Polar histogram of 951 observations of the fluctuating velocity component 6 ft above the bottom at a station in the central Sound (41°08.9'N, 72°48.0'W) between October 18 and October 22, 1974. The darkest shading indicates the frequency, P, with which a velocity was observed in a range 36° by 5 cm/sec is $5\% < P < 7.5\%$, intermediate shading, $2.5\% < P \leq 5\%$, and the lightest shading $0 < P \leq 2.5\%$.

b. The distribution of the east-west and north-south constituent of the fluctuating velocity. The thin line superimposed on the distribution is a Gaussian distribution with the same mean and variance as the observations. The standard deviation of each distribution is σ.



a. TOTAL VELOCITY b. FLUCTUATING VELOCITY COMPONENT

3440 observations

Station 72-1

Figure 11. a. Polar histogram of observed current velocity at the New Haven disposal site between 19 January and 26 March, 1973. See Figure 10 for an explanation of the shading.

b. Polar histogram of the fluctuating velocity component of the record shown in Figure 10a.

bottom water to the west. The probability of occurrence of velocities outside the range of the tidal stream and mean flow can still be recognized in this diagram.

40. The distribution of fluctuating velocities recorded in Long Island Sound is quite different in the summer and winter months. This is illustrated by the data presented in the polar histograms in Figure 12. During the winter there is increased probability that velocities well in excess of the tidal velocities will be encountered. This broadening of the velocity distribution in winter is found at all stations in Long Island Sound. Even when the water is too deep for the bottom to be affected by waves, storms may cause resuspension or other disturbance of sediment by increasing the probability of unusually large velocities (Bokuniewicz, Gordon and Pilbeam, 1975).

41. The increased intensity of velocity fluctuations during stormy periods is thought to be due to the transfer of momentum from the wind to the water surface. The relation between wind stress and the fluctuations in velocity is shown by the data in Figure 13. A General Oceanics current meter set to record the velocity every 5 min was placed near the New Haven disposal site at a height of 6 ft above the bottom. Wind data from Stratford Point consisting of a 3-min average speed and direction recorded every 3 hr are used for comparison with the current record. The square of the wind speed, proportional to the wind stress, is plotted for the observing period in Figure 13. Shown for comparison is the mean square fluctuating current over 3-hr intervals, $\overline{u'^2}$. There is a close correspondence between the wind stress and u' when $\overline{u'^2}$ is plotted with a 3-hr time delay as in Figure 13. Thus, the local wind stress appears to increase the level of the velocity fluctuations but it takes about 3 hr for this effect to be transmitted to the water near the bottom. If this is true, there should be a good correlation between the level of u' and the wind speed throughout the year. A test of this for a four-week winter period is shown in Figure 14. The average of fluctuating velocity component for each day and a corresponding measure of the wind stress is shown. The windy period at the start of the test interval corresponds closely with the increase of $\overline{u'}$

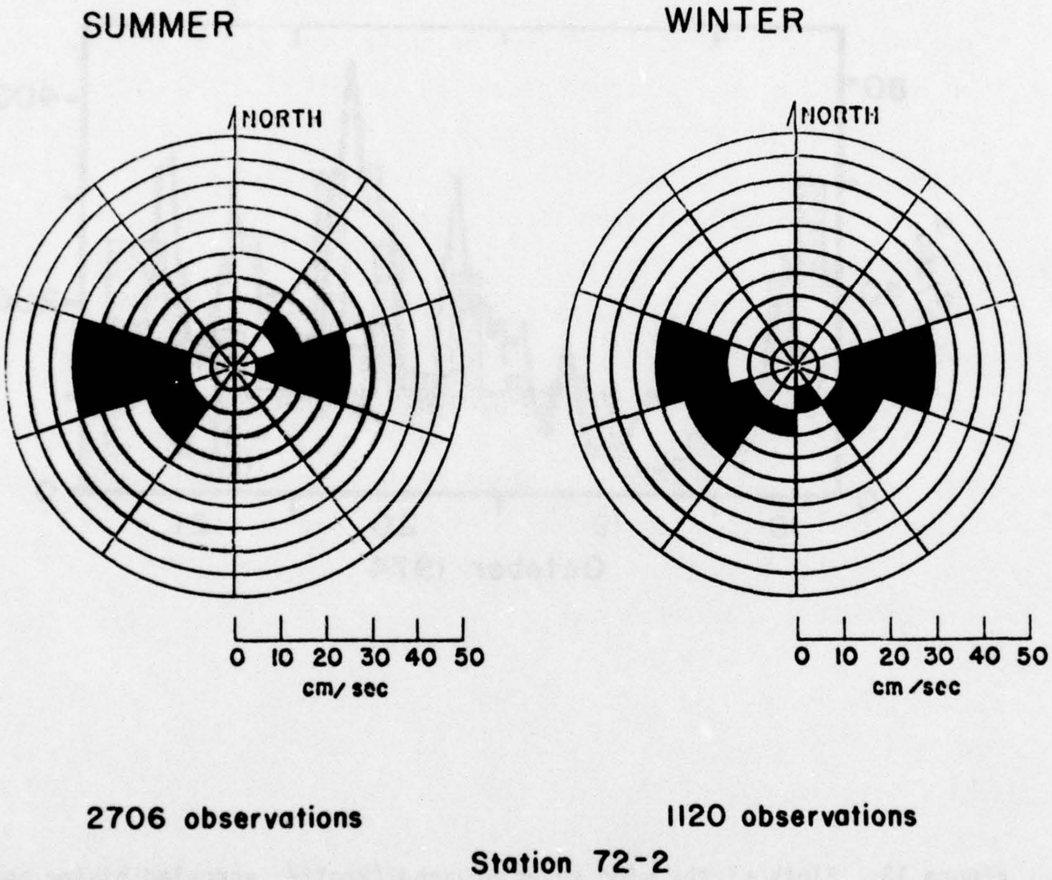


Figure 12. A comparison of the current velocity distributions 6 ft above the bottom during the summer (20 June to 17 August, 1973) and winter (19 January to 11 February, 1973) at station 72-2 (41°07.4'N, 72°52.9'W). See Figure 10 for an explanation of the shading.

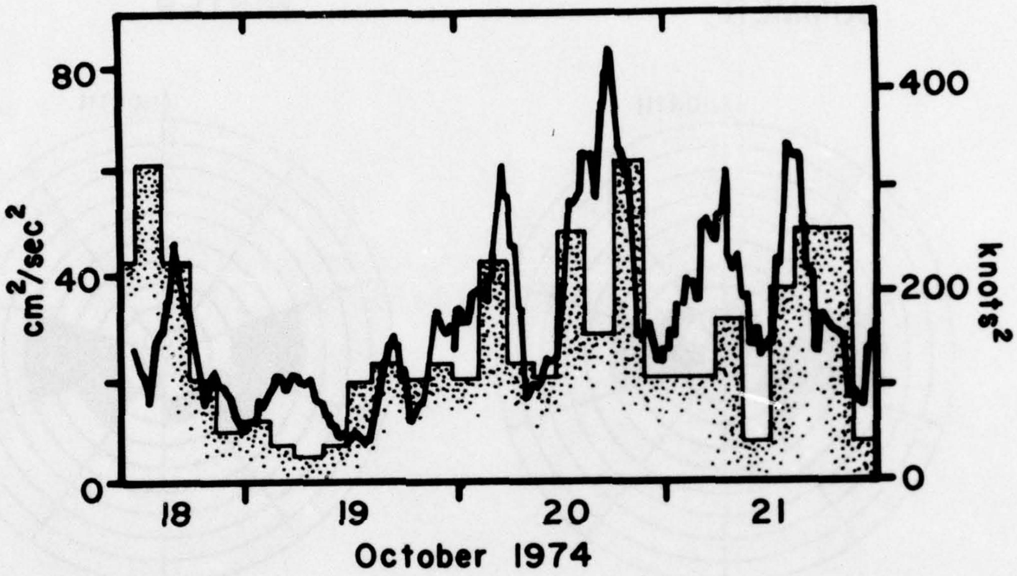


Figure 13. Plots of the wind speed squared (knots^2, speckled histogram) measured on the Connecticut shore (Stratford Point) and the mean squared fluctuating velocity 6 ft above the bottom over 3-hr intervals (cm^2/sec^2, heavy solid line) recorded at 41°08.9'N, 72°48.0'W. Wind speed histogram is shifted to lead the current by 3 hr.

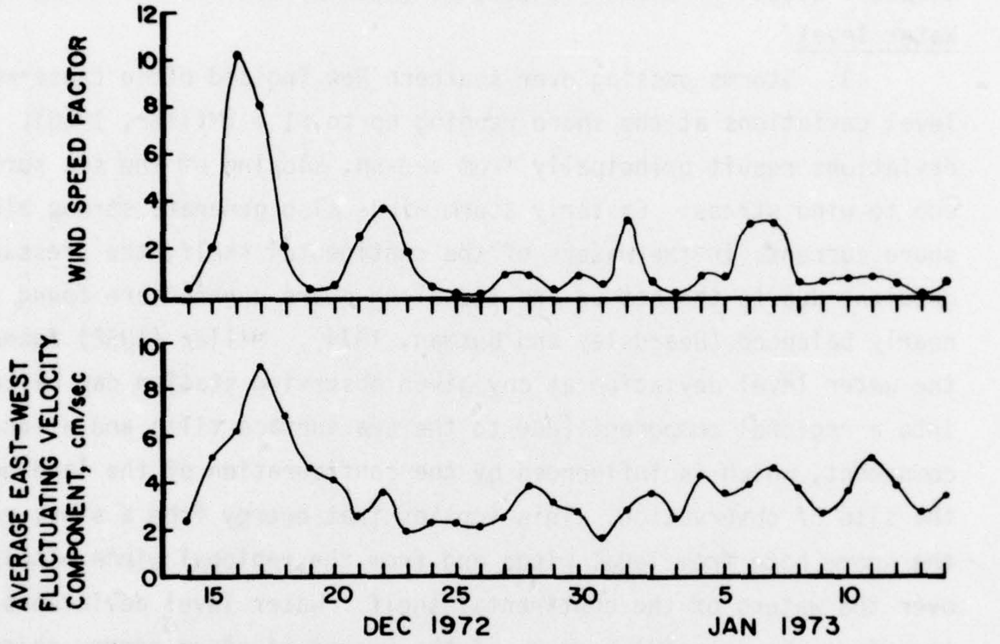


Figure 14. Comparison of the east-west component of the fluctuating current velocity measured 6 ft above the bottom in the central Sound (41°08.7'N, 72°52.9'W) with the wind factor at this time. The wind speed factor used here was

$$\frac{n(u < 20) + 4n(u > 20) + 6.2n(u > 25) + 9n(u > 30)}{24} + \frac{\text{fetch}}{18\ \text{miles}}$$

where n is the number of wind speed observations in the specified range per unit time.

from the value of $\sim$2 cm/sec characteristic of calm periods to 9 cm/sec.

42. Since it is evident that storms can significantly increase water velocities over the bottom throughout Long Island Sound, some measure of storm frequency and intensity is needed in an evaluation of disposal sites. One such measure is presented in the following section.

Water level

43. Storms passing over southern New England often cause water level deviations at the shore ranging up to $\sim$1 m (Miller, 1958). These deviations result principally from set-up, sloping of the sea surface due to wind stress. Easterly storm winds also generate strong along-shore currents in the waters of the continental shelf; the pressure gradient due to the set-up and the along-shore current are found to be nearly balanced (Beardsley and Butman, 1974). Miller (1958) found that the water level deviation at any given observing station can be separated into a regional component (due to the sea surface tilt) and a local component, which is influenced by the configuration of the land near the site of observation. This implies that energy from a storm reaches the shore both from local winds and from the regional winds blowing over the waters of the continental shelf. Water level deviations may, therefore, be a useful measure of the amount of storm energy released in Long Island Sound. To investigate this possibility it is helpful to examine the tide gage records from stations within the Sound for a major winter storm. The "northeaster" of 15-16 December 1972 is chosen because simultaneously recorded water height, current meter and wind velocity data are available for it.

44. Deviations of observed water levels from predicted tidal heights ("residuals", δh) at New Haven and New London, Connecticut, and Newport, Rhode Island, were calculated for an eight-week period starting in mid-December 1972. Additional residuals were also used (personal communication, 1975, J. Ianiello, U. S. Naval Underwater Systems Center, New London) for the days of the major storm of 15-16 December. Two current meters set 6 ft above the bottom and located 1.5 miles apart were in operation near the New Haven disposal site throughout the study period. These meters are in water sufficiently

deep to be unaffected by waves at the water surface. The recorded velocity is resolved into east-west (u_x) and north-south (u_y) components. Tidal and nontidal components of the flow were separated as described in Part III.

45. The residual water levels at New Haven, New London, and Newport, the residual currents (i.e., the sum of the mean and fluctuating components), and the square of the east-west and north-south components of the wind speed measured near Bridgeport, Connecticut, at Stratford Point (assumed proportional to the components of the wind stress on the water surface, σ_x and σ_y) are shown for the duration of the storm in Figure 15. Under strong easterly winds the water level at New Haven, New London, and Newport rises; the subsequent fall in level begins when σ_x reverses. The times of the maximum and zero δh for these three water level stations are nearly coincident but the magnitude of δh increases to the westward. Since the greatest δh occurs earlier at New Haven than at New London, the rise in water level in Long Island Sound is not a surge advancing as a progressive wave from the sea. Evidence of a storm surge in Long Island Sound is found only for very intense, rapidly moving storm systems such as the 1938 hurricane (Redfield and Miller, 1957).

46. The water level residuals observed at successive times during the 15-16 December 1972 storm are shown in Figure 16 for all observing stations. Station locations are projected onto a line running along the axis of Long Island Sound (075° True from Throgs Neck) to construct the abscissa of the graphs. Wind speeds and directions are shown on an adjacent set of maps. The residual water levels at Bridgeport and Port Jefferson, nearly opposite each other across the Sound, are almost the same throughout the storm event. Hence, there is little change in water level across the Sound and the levels shown in Figure 16 define the longitudinal slope of the water surface throughout the study area.

47. The water level and the wind data suggest that the following sequence of events occurred during the December 1972 storm: easterly winds set water on the continental shelf in motion towards the west,

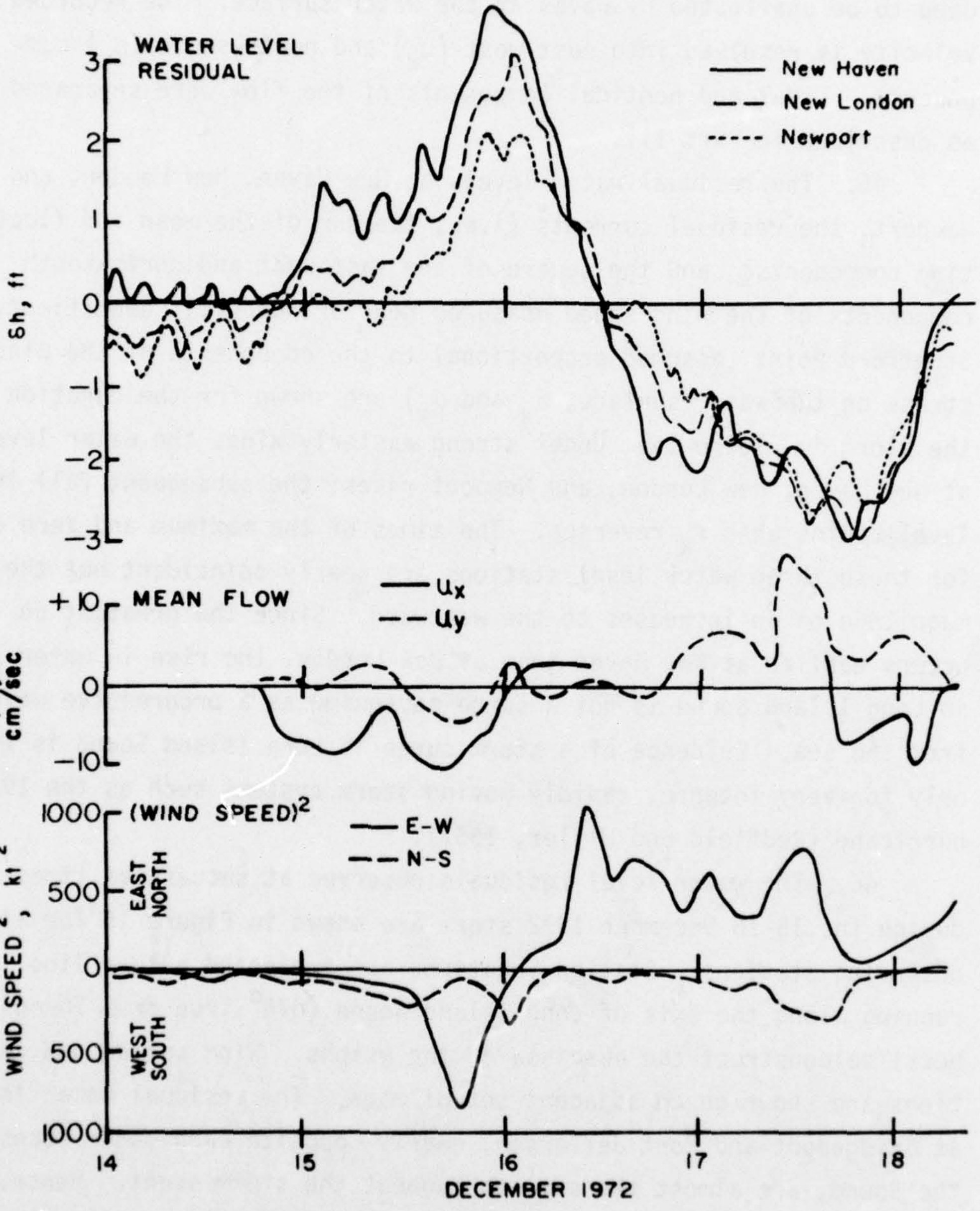


Figure 15. Nontidal water level deviation recorded at New Haven and New London, Connecticut, and at Newport, Rhode Island; the mean flow recorded 6 ft above the bottom in central Long Island Sound; and the wind stress during a winter storm, 1972.

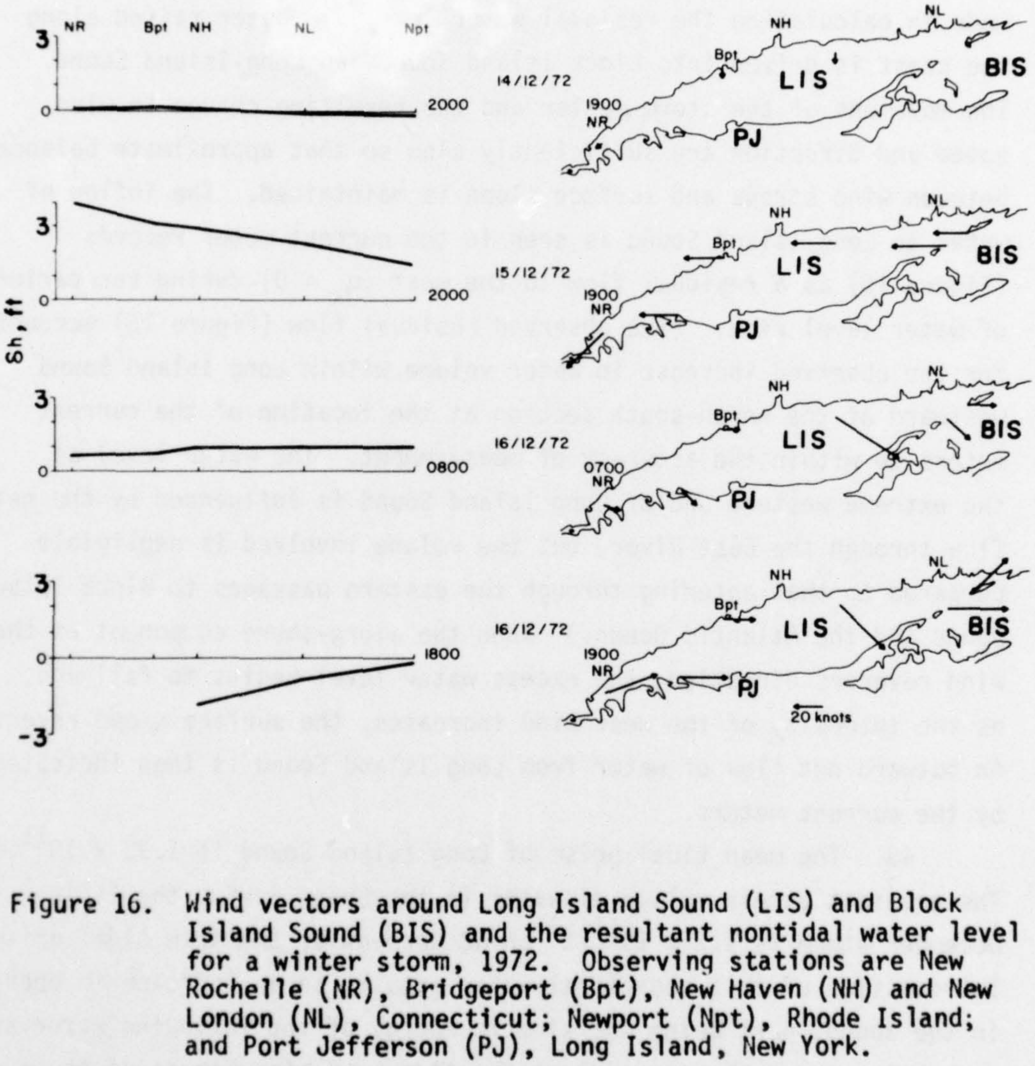


Figure 16. Wind vectors around Long Island Sound (LIS) and Block Island Sound (BIS) and the resultant nontidal water level for a winter storm, 1972. Observing stations are New Rochelle (NR), Bridgeport (Bpt), New Haven (NH) and New London (NL), Connecticut; Newport (Npt), Rhode Island; and Port Jefferson (PJ), Long Island, New York.

increasing water levels along the coast and tilting the sea surface upward, as observed for similar storms by Beardsley and Butman (1974). (There is also an increase in water level along the coast due to the reduced barometric pressure, but this is small compared to the change due to wind stress; no correction for local barometric pressure is made in calculating the residual water levels.) Water raised along the coast is driven into Block Island Sound and Long Island Sound. The movement of the storm center and the resulting change in wind speed and direction are sufficiently slow so that approximate balance between wind stress and surface slope is maintained. The inflow of water to Long Island Sound is seen in the current meter records (Figure 15) as a residual flow to the west ($u_x < 0$) during the period of water level rise. (The observed residual flow (Figure 15) accounts for the observed increase in water volume within Long Island Sound westward of the north-south section at the location of the current meters to within the accuracy of measurement. The water level at the extreme western end of Long Island Sound is influenced by the net flow through the East River, but the volume involved is negligible compared to that entering through the eastern passages to Block Island Sound and the Atlantic Ocean.) When the along-shore component of the wind reverses direction, the excess water level begins to fall and, as the intensity of the west wind increases, the surface slope reverses. An outward net flow of water from Long Island Sound is then indicated by the current meters.

48. The mean tidal prism of Long Island Sound is 1.93×10^{11} ft^3. The greatest excess volume of water in the Sound during the 15-16 December storm is 1.2×10^{11}ft^3 or 62 percent of the mean tidal prism. Introduction of this additional water results in an increase in energy in the Sound, part being the kinetic energy of the inflowing water and part being the work done against the tide-producing forces of the sun and moon. Both of these are small, however, compared to the work done against the hydrostatic pressure of the accumulated water in the Sound. A convenient way to estimate the storm energy flux is to find the potential energy of the excess water at the maximum δh, when the residual velocity is zero. This is 13.3×10^{12}ft-lb; the potential energy

at the top of a tidal oscillation of mean range is 9.07×10^{12} ft-lb. Thus, the storm-driven influx of water more than doubles the energy content of the Sound above the mean tidal energy. This energy is available to drive processes of sediment erosion and transport.

49. Since δh is a measure of storm energy in Long Island Sound, records of tidal deviations over a long period of time can be used to evaluate the relative intensity of individual storms or the total amount of storm energy released in a given season. Water level deviations were calculated for the 38-year period that tide gage records are available for New London in order to make this evaluation of storminess in Long Island Sound. The water level residuals were displayed graphically so that individual storms could be identified. The results are illustrated by the data in Figure 17, which shows the calculated water level residuals for a winter month and a summer month; the succession of winter storms is clearly shown as is the great difference in storm energy release between winter and summer. The seasonal variation in storm energy released to the Sound can be seen by comparing the average standard deviation of the water level residuals for each month of the 38-year period, which is shown in Figure 18. These results indicate that disturbance of the bottom by storms is most likely to occur in the months of December, January, and February when it is most difficult to obtain data on the Sound.

50. The water level residuals can also be used to evaluate the relative amount of storminess in successive years. This information is particularly valuable in establishment of how representative any one year is of conditions on the Sound. The standard deviation of the water level residuals for each month of the 38-year record was computed and used to calculate an averaged standard deviation for the five winter and the five summer months. The results are shown in Figure 19. The standard deviation is plotted because, as was shown above, this is a measure of storm energy. During the summer months the standard deviation is low and shows little variation from year to year. Not only is the seasonal standard deviation high in the winter months, it varies

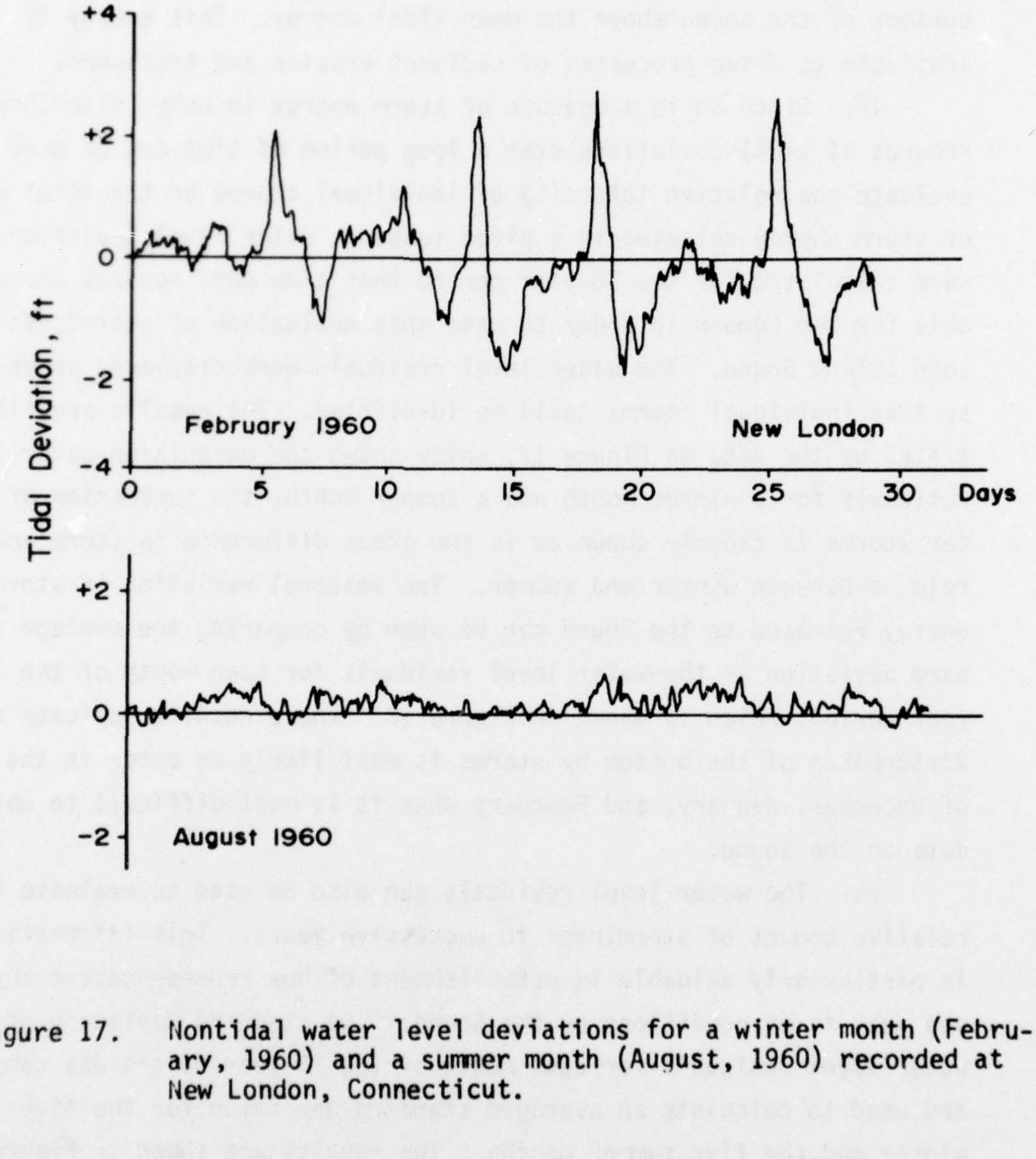


Figure 17. Nontidal water level deviations for a winter month (February, 1960) and a summer month (August, 1960) recorded at New London, Connecticut.

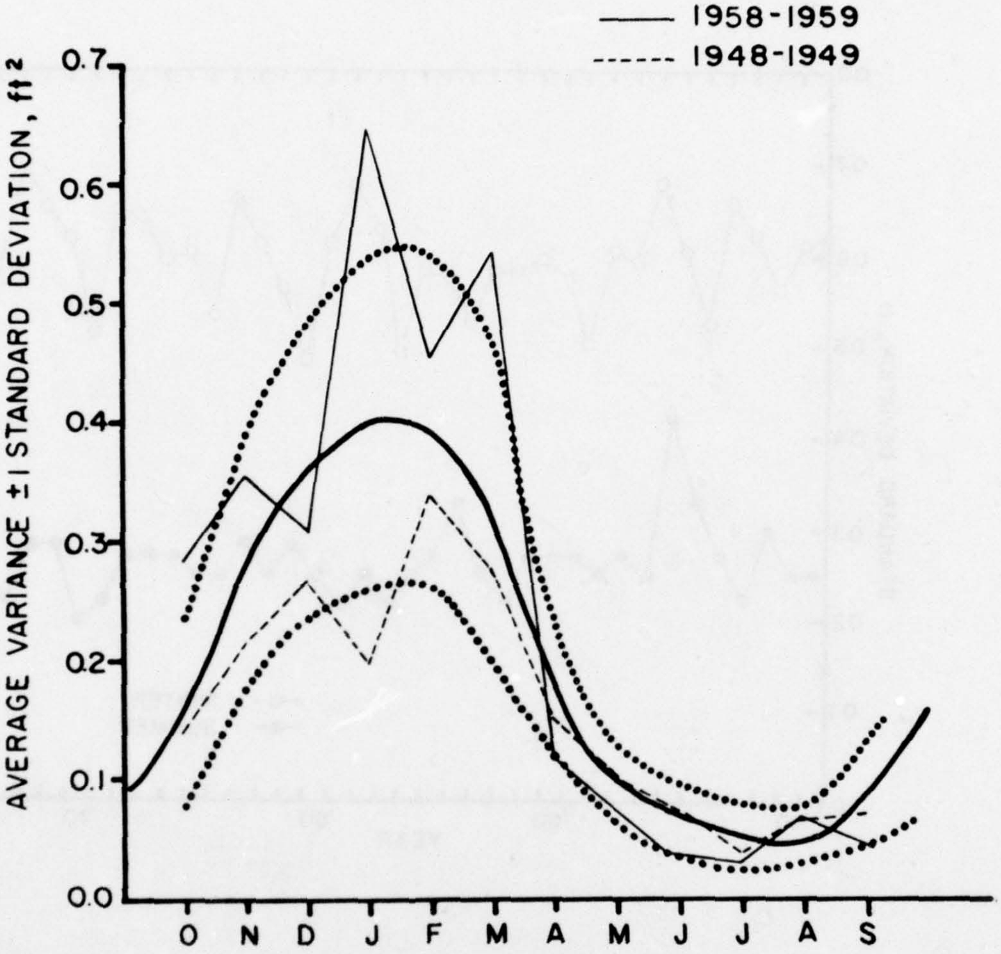


Figure 18. Variance of the nontidal water level during each month of the year, averaged over 38 years of data at New London, Connecticut (heavy solid line). The heavy dotted lines mark ±1 standard deviation of the monthly variances for the 38-year record. The variances for two years are shown for comparison.

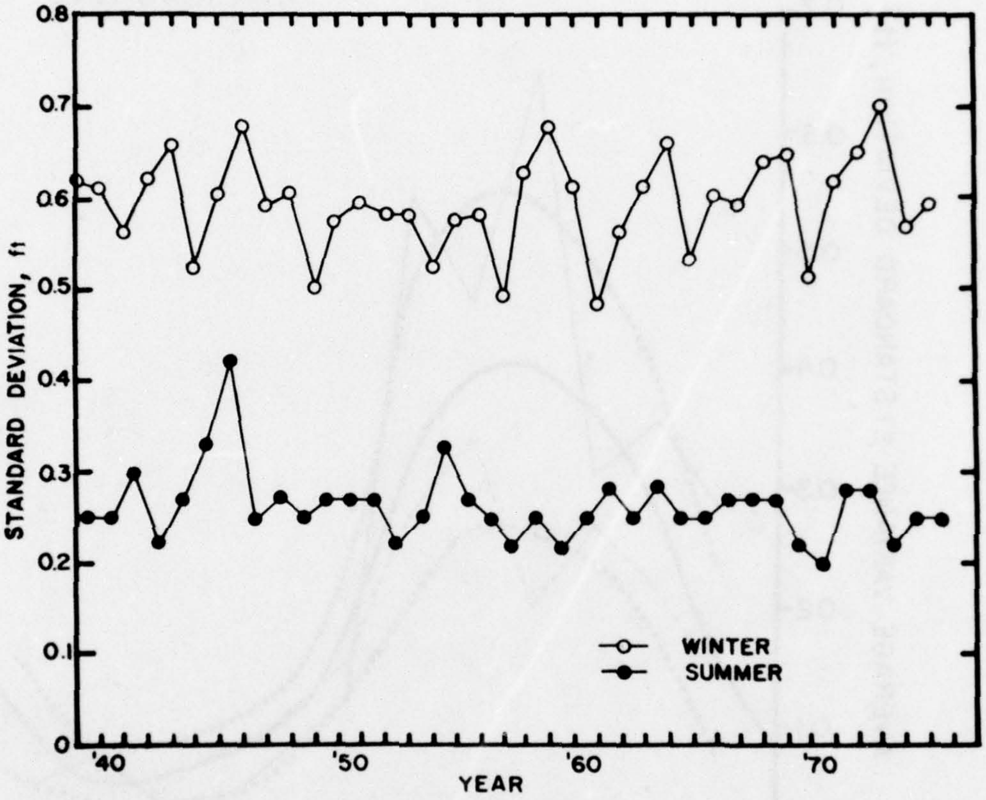


Figure 19. Standard deviation of the nontidal water level deviations measured at New London, Connecticut, for five winter months and five summer months since 1938.

by as much as a factor of 1.5 between different years. For example, the storm energy release for the 1972-3 winter was unusually high. Therefore it is believed that data for storm effects obtained during this winter may be considered representative of the most severe season likely to be encountered on the Sound.

Storm Effects on the Bottom of Long Island Sound

51. A useful measure of the intensity of any given storm is the magnitude of the tidal deviation that it produces at New London. It may be supposed that large storms will occur in an extreme value distribution in much the same way as floods on a river and that storms of a given magnitude can then be assigned a recurrence interval. In order to investigate the distribution of major storms on Long Island Sound a list of all tidal deviations of 2 ft or greater for a 38-year period was prepared. This contained 60 events of which three were hurricanes. These were graphed as a partial duration series after the method described by Linsley and Franzini (1972) with the result shown in Figure 20. It can be seen that aside from the hurricanes, the storms follow the curve of the extreme value distribution. This graph can then be used to define a recurrence interval for any given storm. The data are not extensive enough to permit assignment of recurrence intervals to the hurricanes.

Sediment resuspension

52. Both the New Haven and Eatons Neck dredged material disposal sites are located on muddy bottoms in water depths greater than 60 ft. Bottom sediments are subject to regular resuspension by the tidal stream and up to 200 mgm/cm^2 of resuspended sediment is found in the water column (Gordon and Pilbeam, 1974). It has been shown that waves are unlikely to have much effect on the mud bottom but that velocity fluctuations associated with stormy periods may cause unusually strong currents to flow. Hence, increased resuspension of the bottom and

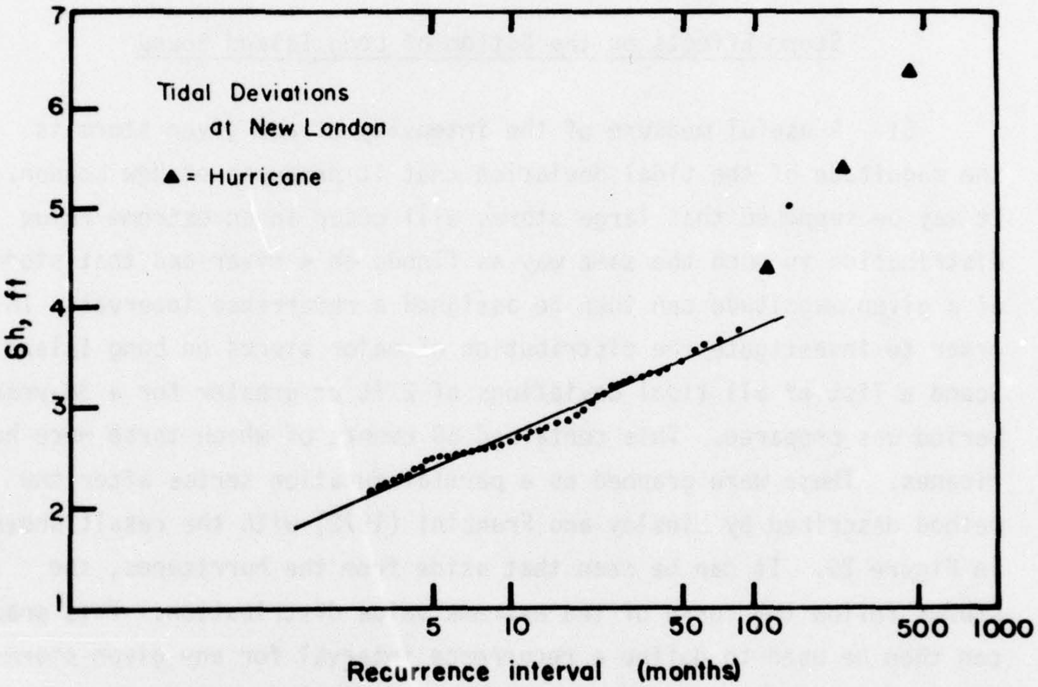


Figure 20. Recurrence period of nontidal water level deviations at New London, Connecticut.

possibly erosion of deposited material may be expected during stormy periods. Observations of suspended sediment in the water column during two stormy periods show the amount of bottom disturbance which occurs.

53. One set of resuspension data was taken at the time the current meter observations presented in Figure 13 were recorded. The total amount of suspended sediment was determined from optical transmittance profiles made each 30 min over a 24-hr period from a boat anchored 3 miles east of the New Haven disposal site. The bottom in this area is a featureless plane of muddy sediment; both the sediment composition and the hydraulic regime are uniform for at least 4 miles around this site while the tidal excursion is only about 1.5 miles. Therefore, it is reasonable to assume that all sedimentary processes within the tidal excursion are simultaneous and equivalent. Transmittance profiles made throughout the area confirm this. Changes in the sediment content of the water column must result, then, from erosion or deposition at the bottom.

54. The total suspended sediment, the observed current speed 6 ft above the bottom, and the mean square of the fluctuating component of the current speed averaged over a 3-hr time period are shown in Figure 21. The increase of the fluctuating velocity component over the observing period is due to increasing wind speed. The total amount of resuspended sediment, S, depends on the strength of the tidal current and on the level of the velocity fluctuations. Thus, S is large at, or slightly before, the time of maximum flood or ebb current. Superimposed on this variation is an overall increase in S as the magnitude of $\overline{u'^2}$ increases. This set of data is not long enough to permit separation of total variation in S into components that can be identified with the tidal and fluctuating components of the velocity, although the general trends noted above are reasonably well defined. The greatest amount of sediment in the water column at any time during this observing period is equivalent to resuspension of a layer of bottom material about 1 mm thick. The greatest observed flux of sediment particles out of the bottom is 1.7×10^{5} gm/(cm^{2}sec).

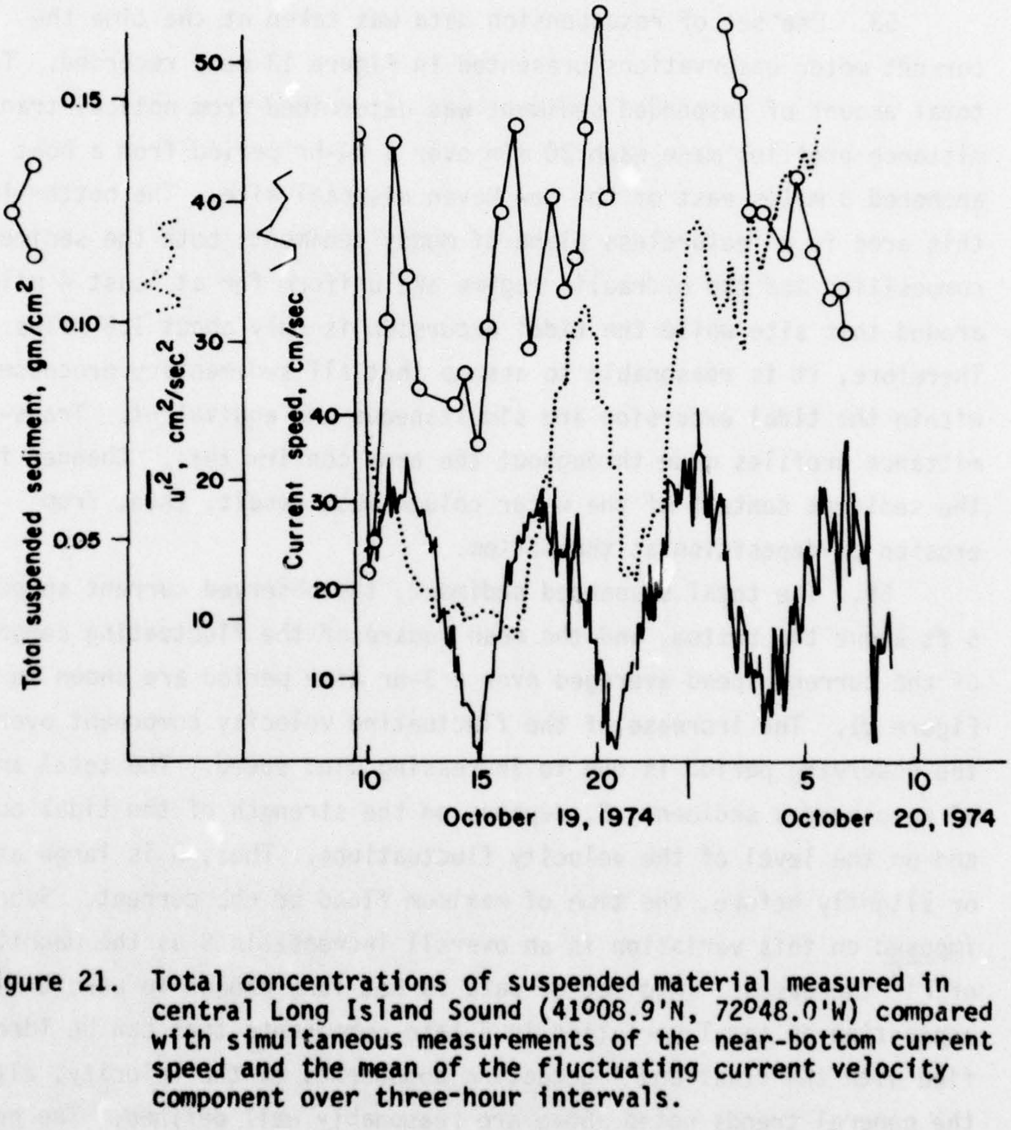


Figure 21. Total concentrations of suspended material measured in central Long Island Sound (41°08.9'N, 72°48.0'W) compared with simultaneous measurements of the near-bottom current speed and the mean of the fluctuating current velocity component over three-hour intervals.

55. The suspended sediment data in Figure 21 show that sediment particles can drop out of the water column in about 3 hours. This requires that the settling velocity be $\sim$1 cm/sec. The mean diameter of mineral grains of the sediment in this part of Long Island Sound is $\sim$0.02 mm; quartz grains of this diameter have a settling velocity of only 0.03 cm/sec. Examination of sediment collected in net tows in this part of the Sound shows that nearly all mineral particles are bound into aggregates by organic matter, mostly in the form of fecal pellets produced by benthic animals (Benninger, 1976). Nuclea annulata, a dominant bivalve deposit feeder in the Sound, produces pellets with a settling velocity of $\sim$0.7 cm/sec (Young, 1971). Thus, the suspended sediment data support the idea that all of the material on the mud bottom available for resuspension consists of organically bound mineral aggregates. The presence of this material is confirmed by bottom photography (Bokuniewicz et al., 1975).

56. An experiment similar to that just described was performed in March 1975 under more severe weather conditions. In this case the ship was anchored 1 mile south of the New Haven disposal site. The wind was from the northwest and its speed was measured by the ship's anemometer (height 30 ft) and ranged up to speeds of 40 knots. The integrated sediment content of the water column was calculated from turbidity profiles made each 30 min. Currents 6 ft above the bottom were measured each 30 sec. The total suspended sediment as a function of time is shown in Figure 22. Also plotted is the average u' for 15-min intervals. In this case there appears to be a close correspondence between the time variation of S and $\overline{u'}$ but with a 3-hr delay in S. The greatest amount of sediment in the water column corresponds to resuspension of a layer about 2 mm thick from the sediment-water interface. Since the maximum $\overline{u'}$ observed in the Sound reaches about 10 cm/sec, it is estimated that resuspension of more than a cm of the bottom sediments is unlikely where the water is too deep to be directly affected by waves.

57. Contaminated sediment which has accumulated in the harbors around Long Island Sound is in shallow water where it is regularly

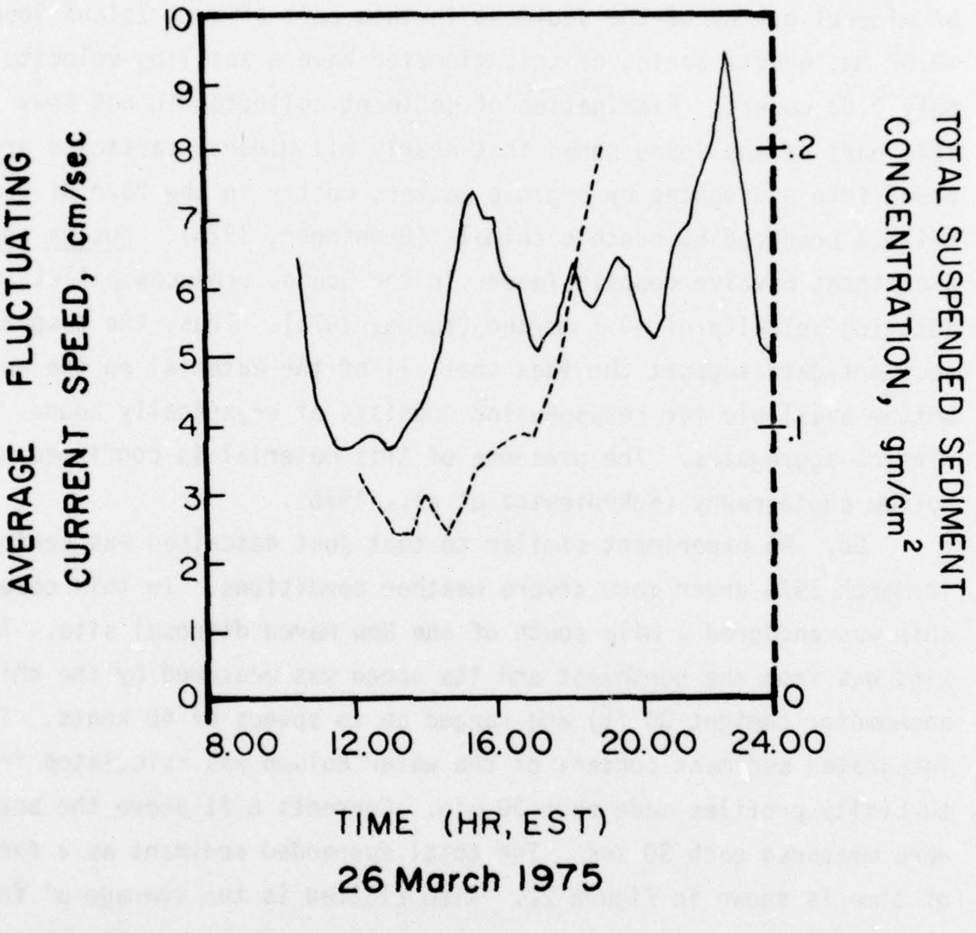


Figure 22. Average fluctuating current speed (shown as solid line) measured 6 ft above the bottom in central Long Island Sound (41°07.4'N, 72°52.9'W) and the total amount of suspended sediment at this location. These measurements were made during a gale, 26 March 1975.

resuspended by waves. During a storm, intense mixing occurs in the water of Long Island Sound; with this in mind, a sample model may be developed to estimate the amount of harbor sediment which is dispersed throughout the Sound. Let us assume that during a storm a layer of bottom sediment of thickness l_H is resuspended in the harbor and a thickness l_S is resuspended in the deeper, main body of the Sound. If the average water depth in the harbor is D_H, then the typical concentration of suspended sediment in the harbor waters as a result of the storm is $C_H = l_H\rho/D_H$, where ρ is the bulk sediment density at the sediment-water interface. Likewise, in the Sound the average suspended sediment concentration is $C_S = l_S\rho/D_S$ where D_S is the water depth. As the tide ebbs from the harbor a volume of water, W, and its suspended material is transferred from the harbor to the main body of the Sound. If the mixing is very rapid, the harbor sediment will be mixed into the waters of the Sound until a uniform concentration of C_S is everywhere attained. The amount of sediment removed from the harbor on ebb tide is

$$\rho W\, l_H/D_H$$

On the flood tide an amount, $\rho W\, l_S/D_S$, is returned to the harbor, so that the net flux of material to the Sound per tidal cycle is

$$\rho W\, \frac{l_H - l_S}{D_H - D_S}$$

In Long Island Sound, l_S is about 2 mm (0.08 inch). Because the water is shallower in the harbor and more storm energy can reach the bottom, l_H is probably greater than l_S; however, to minimize the flux estimate, assume $l_S = l_H$. The typical water depth in the harbor is about one-fifth the depth in the main body of the Sound so that the net volume flux of material carried soundward per tidal cycle is

$$Wl_S\,(\tfrac{4}{5})\ /\ D_H$$

For New Haven Harbor, $W \sim 6.6 \times 10^7$ yd^3 and $D_H \sim 10$ ft so that the net soundward flux per tidal cycle is about 3.3×10^4 yd^3 during a storm.

Bathymetric surveys

58. The New Haven disposal site is located on the mud bottom of central Long Island Sound in a water depth of 60 ft. The data on waves, currents, and sediment resuspension in this area indicate that regular resuspension of silt-clay size dredged material at this site should occur. This would produce an intermixing of deposited material with sediments on the surrounding sea floor, but this intermixing should be limited to a few cm depth on the deposited material. Larger changes in the surface configuration of a pile of material placed on the bottom could occur only if there were local erosion or deposition on the pile. Sand-size deposited material is expected to be moved only very slowly at this site. Repeated bathymetric surveys of the New Haven disposal site after deposition of dredged material can be used to test these predictions about the stability of the material placed on the bottom.

59. A detailed bathymetric survey of the New Haven disposal site was made in May-July 1972 by the New England Division of the Corps of Engineers. At that time the site was essentially a featureless, nearly piane surface. Between October 1973 and March 1974 1.5353×10^6 "scow yards" of dredged material, mostly silt from New Haven Harbor, was placed on this site by "point dumping." A survey of the site in March 1974 was used to prepare the contour map shown in Figure 23. A roughly conical, 22-ft-high mound of deposited material is present. (A small subsidiary mound to the west is present because the disposal site was moved shortly after dumping began.) The slopes of the pile faces are low enough that mass instability within the pile is not expected to occur. Cores collected after completion of disposal show that the central core of the pile is covered by sand (because the outer, sandy part of the harbor was dredged last) while the flanks are silt-type material. The critical erosion velocity of the sand is about 35 cm/sec and of the silt is about 20 cm/sec (personal communications, 1976, D. C. Rhoads, Department of Geology, Yale University). Regular resuspension of the silt by the tidal stream is expected. The thickness of deposited material was determined by comparison of the initial survey

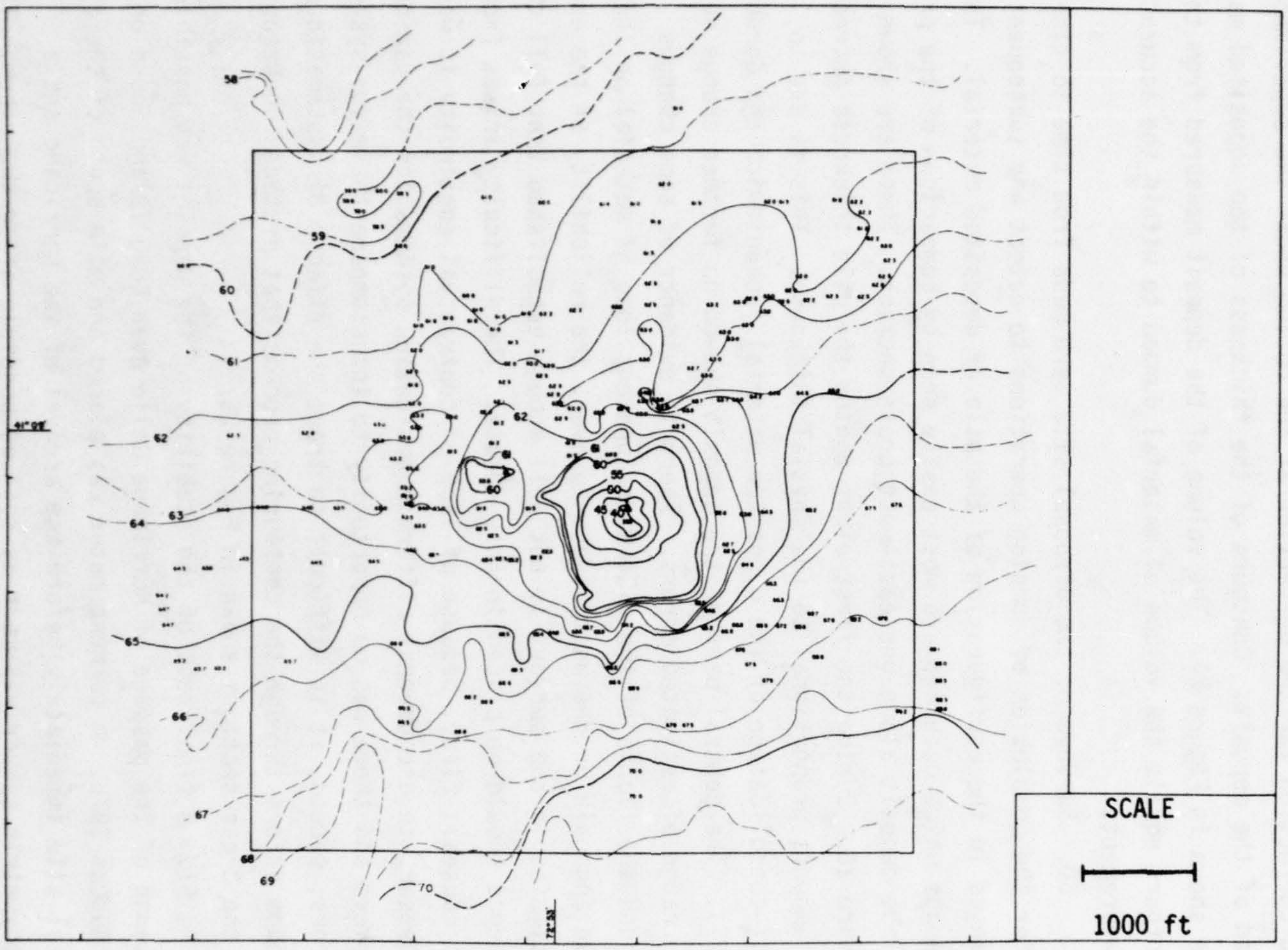


Figure 23. Bathymetry in feet below mean low water of the New Haven disposal site upon completion of the dredging of the channel in New Haven Harbor.

with that made after completion of placement of the dredged material and correction for the deflection of the bottom under the superimposed load of the deposit. Contours of the thickness of the deposited material are shown in Figure 24. The volume of the deposit measured from these contours equals the volume of material dumped to within the accuracy of measurement.

60. Surveys of the disposal site were made from time to time after the completion of dumping operations to detect any subsequent changes in the configuration of the pile of deposited material. The changes which occurred are most easily seen by comparison of the profiles of the deposit along one east-west cross section. These are shown in Figure 25. During the first eight months the pile thickness decreased by amounts proportional to the initial thickness. This is due to self-consolidation of the deposited material (Bokuniewicz and Gordon, 1977). The central part of the deposit showed no further change outside the range of estimated errors. There is evidence of some changes around the flanks of the pile with apparent loss of material on the east side and gain on the west side. However, the reliability of the error estimates in the surveys is not well enough established that full confidence should be placed in this result. The difficulty arises from two causes: first, because of lack of contractual continuity it was necessary to use several different navigation systems for the various surveys and there was no opportunity to intercompare these for systematic errors; second, it is difficult to trace the effects of systematic and random errors through the contouring process that precedes construction of the cross sections shown in Figure 25.

61. A final test of the stability of the deposit was possible because of the passage of Hurricane Belle over Long Island Sound on 10 August 1976. A current meter was placed one mile south of the disposal site immediately before the arrival of the hurricane and a bathymetric survey was made as soon as possible after the storm. The storm center crossed the Sound about 30 miles west of the New Haven site so there was a sudden shift of the wind from northeast to southwest; wind speeds up to 81 knots were reported by the Traveler's

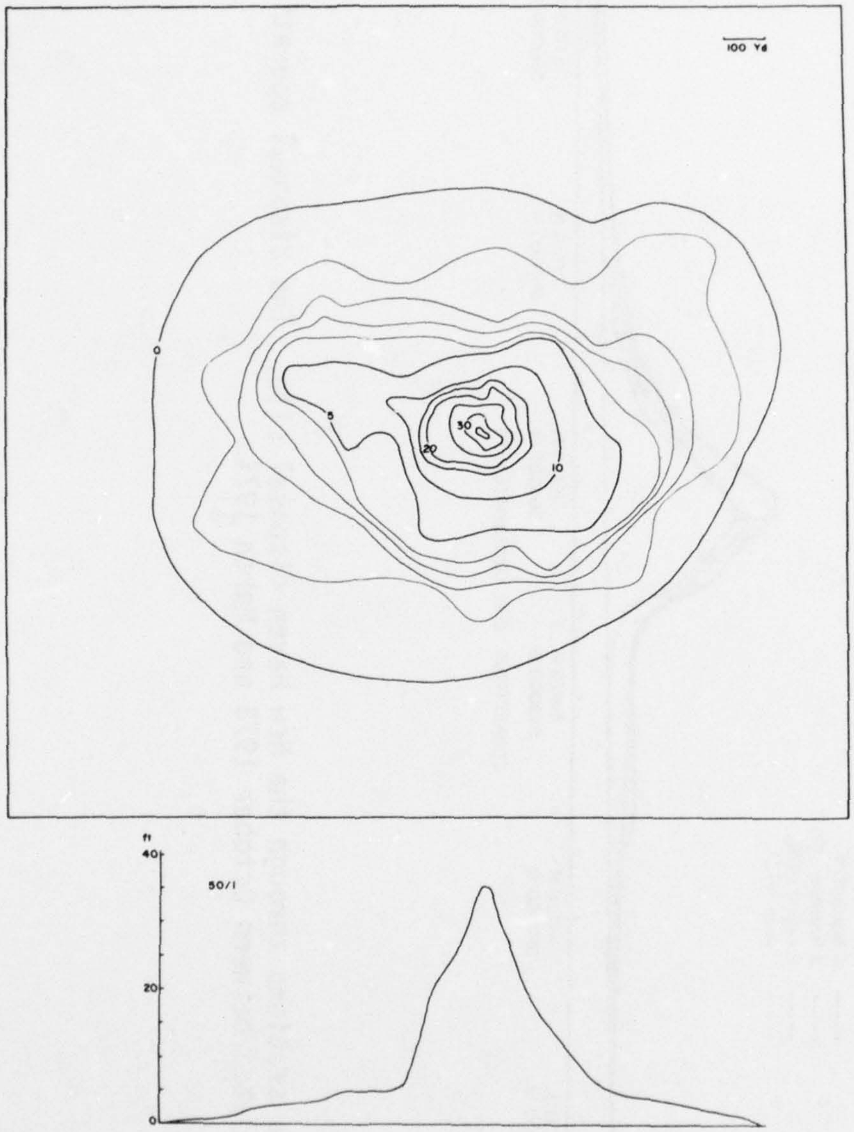


Figure 24. Contours (in ft) of the thickness of the deposit of dredged sediment at the New Haven disposal site and an east-west cross section through the center of the mound.

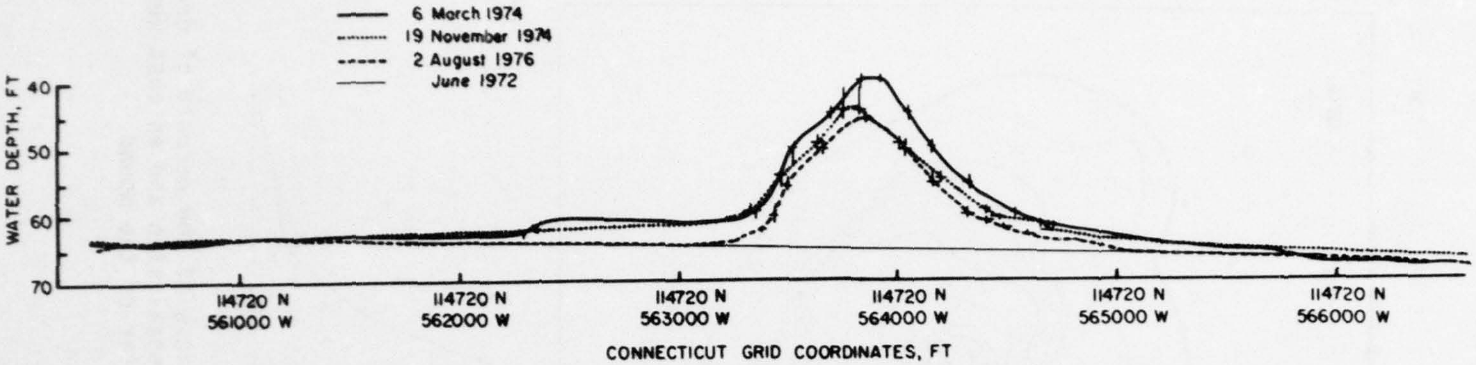


Figure 25. Cross sections through the New Haven disposal site. The disposal operation was completed between October 1973 and March 1974.

Weather Service. Because of the high speed at which the storm center advanced, hurricane winds lasted for only a few hours.

62. Successive 20-min flow vectors recorded during the hurricane are shown in Figure 26 along with wind arrows as reported by the National Weather Service at Stratford Point. Shown for comparison are a set of current vectors from the same meter record but for a period of calm weather. The bottom water response is quite different in the hurricane than in a typical winter storm. In the hurricane the bottom flow is first retarded and then accelerated as the wind direction shifts from against to with the tidal current but no unusually high fluctuating velocities are recorded. In a winter storm the reverse is usually true. The absence of unusually high velocities over the bottom in the deeper parts of the Sound during "Belle" is confirmed by an examination of the diver-collected cores by R. Aller (Personal communications, 1976, Geology Department, Yale University). Cores from sites where the water depth is 40 ft or less show reworking of the bottom to a depth of several cm while cores from deeper water show no evidence of disturbance. Comparison of the bathymetric surveys made before and after the hurricane, Figure 27, shows no disturbance of the pile of disposed material that is significant relative to the errors of measurement.

63. The stability of the peak of the pile of disposed material, which is high enough to penetrate the wave-affected zone, is due to two causes. First, much of the peak is covered with sand, the last material deposited on the site. Second, where silt-clay material is exposed, it is in the form of cohesive clods, which are expected to be erosion resistant. It is the unconsolidated material on the pile flanks that is resuspended by the tidal stream and would be susceptible to disturbance by waves if it were exposed higher on the pile.

Capacity of the Disposal Site

64. The use of an open-water disposal site has a wide range of possible consequences. These may include, for example, alteration of

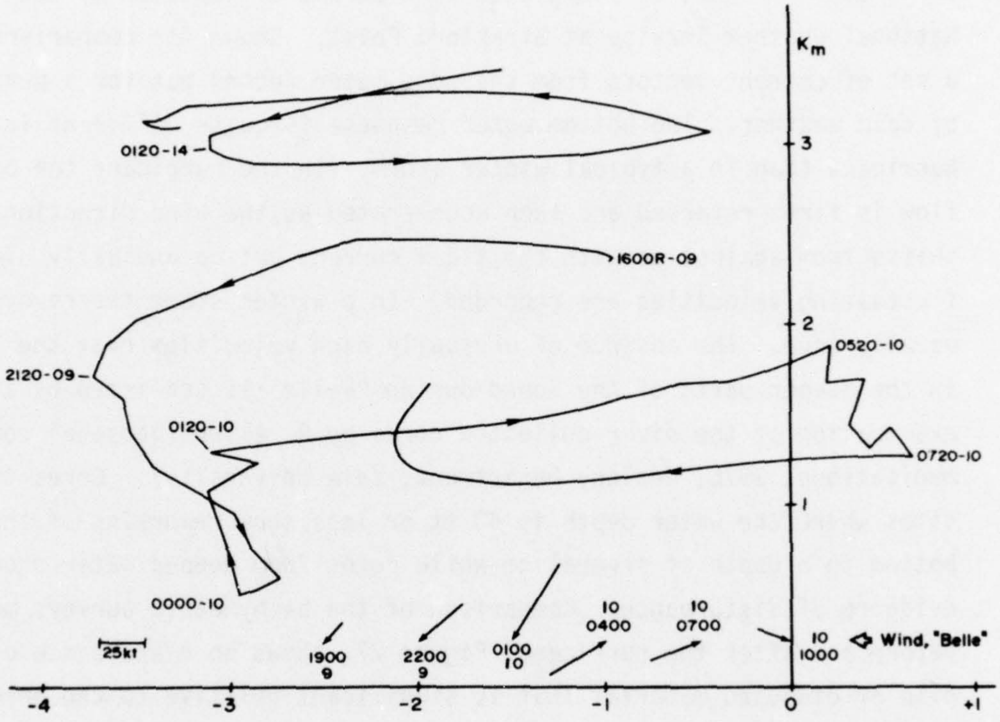


Figure 26. Progressive displacement vectors measured 6 ft above the bottom in central Long Island Sound (41°07.4'N, 72°52.9'W). Hurricane Belle occurred between 1600R on 9 August and 0720R on 10 August, 1976. Wind vectors during this period are shown. Also shown is a typical tidal progressive displacement vector ellipse at this location.

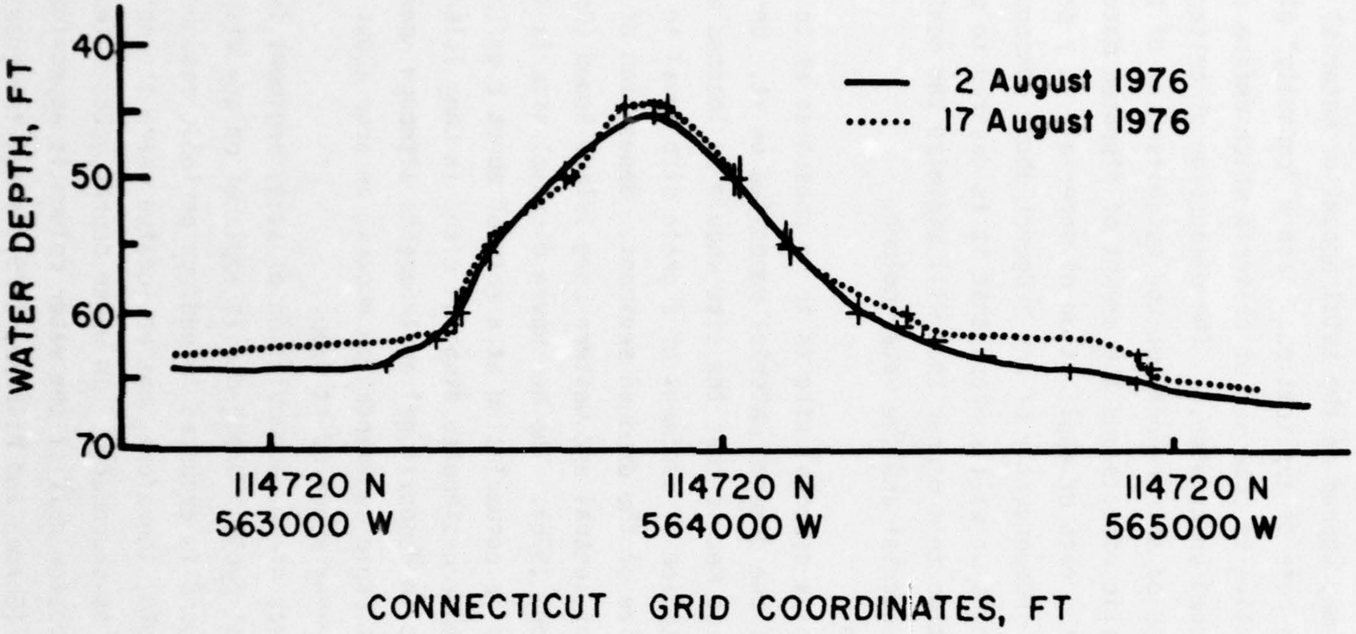


Figure 27. Cross sections through the New Haven disposal site before and after Hurricane Belle, which occurred on 10 August 1976.

animal habitats and animal populations and the release of chemical constituents from the disposed material into the water column. Many of these consequences may depend on the total amount of material placed on the site and on its rate of application. Then a "capacity" of the site can be fixed relative to some set of criteria which define consequences that are judged unacceptable. The discussion of criteria falls outside the scope of this report but the establishment of the relation between specific effects and the amount of disposed material placed on a site, or the rate of application of material, is a problem that can be addressed independently of any judgment about consequences. To give the problem focus we will suppose that it is desired to carry on the disposal operation in a manner that will minimize the contact between the disposed material and the water column.

Disposal site location

65. Suppose that a disposal site is to be chosen so as to minimize dispersion of the dredged material deposited on it. One condition that should be met is that the site should be located where there is natural deposition of sediment of a grain size equal to or less than the grain size of the dredged sediment. Deposition of silt occurs in the basins of central and western Long Island Sound (Bokuniewicz, Gebert and Gordon, 1976). The New Haven disposal site is located in a region where silt is accumulating at a rate of about 8 gm/(m^2yr) (Figure 28); eleven other designated disposal sites in Long Island Sound are also located in depositional environments although none are located where the most rapid sedimentation occurs, an area about 12 mi south of Guilford in water about 60 ft deep.

66. Even in areas of net accumulation of silt, sediment is resuspended every tidal cycle. Dredged silt emplaced on any disposal site in Long Island Sound is expected to undergo periodic resuspension. The disposal site should, therefore, not be located where the net flux of suspended sediment is shoreward . In water depths greater than 60 ft, the net drift in the bottom half of the water column is approximately parallel to the shore (Gordon and Pilbeam, 1975); since the greatest concentrations of suspended sediment are found near the bottom, it is unlikely that the net advection of sediment will be shoreward in water deeper than 60 ft. The water at the disposal site should also be suf-

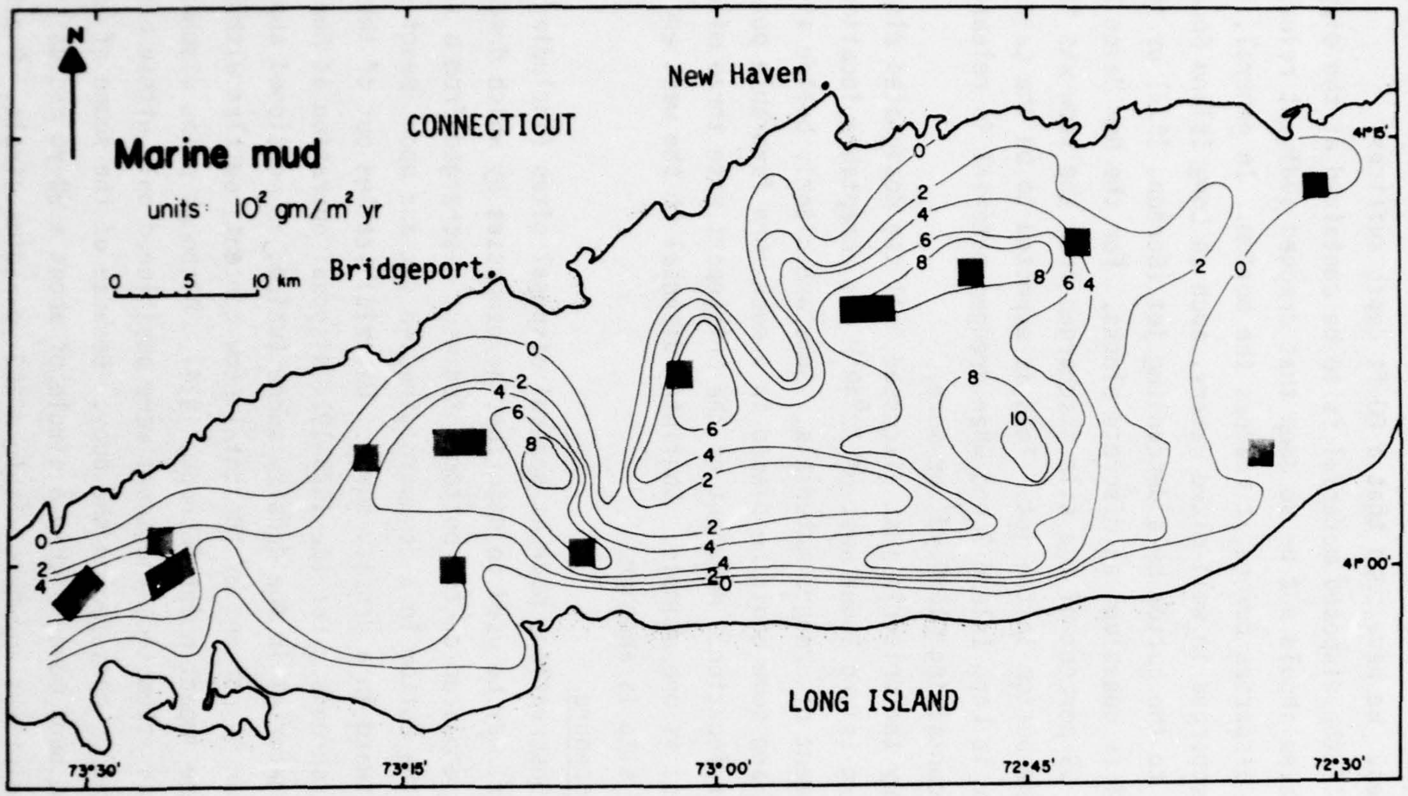


Figure 28. Average rate of silt accumulation in Long Island Sound over the past 8000 years and the locations of designated disposal areas.

ficiently deep that the bottom sediment is not directly disturbed by surface waves. We have seen that a 60-ft depth suffices.

67. If the disposed material is to be contained at the disposal site, the water should not be so deep that dredged sediment released from a scow disperses before it reaches the bottom. In general, dredged sediment discharged in well-mixed waters, such as Long Island Sound, is transported to the bottom by a descending jet (Gordon, 1974) or if the material is cohesive, as discrete blocks. For the New Haven Disposal Project, 99 percent of the silt discharged from the scow was transported to the bottom in the jet. This is expected to be the case for any location in Long Island Sound when dredged material is released from scows containing ~ 1000 yd^3 or more.

68. By the criteria just discussed, all the designated disposal sites in Long Island Sound west of $72^{0}40'$W are acceptable locations for the containment of dredged materials. Some are clearly better situated than others and some could be placed in a much more favorable position by a small relocation. Movement of the Bridgeport site three miles to the southeast is one example. Confining disposal to the west end of the Eatons Neck site is another.

Disposal procedure

69. Observations made at several disposal sites (including New Haven Harbor) may be used to describe the processes by which dredged material is emplaced on the bottom. Sediment discharged from a scow travels to the bottom in a downward directed jet and upon impact spreads radially outward in a density surge. Material settles out of this surge as it spreads. For the 1973-1974 disposal operation at New Haven, all of the material in the density surge (which, as mentioned above, accounted for 99 percent of the total scow content) settled within 170 yd of the impact point (Gordon, 1974). Although point discharge at a buoy was attempted, the scows were positioned only within a circle of 200-yd radius centered on the buoy. Because of the scope of its mooring, the buoy moved within a circle of about a 50-yd radius so the discharge point was anywhere within a 250-yd-radius circle. Discharge

of many scows should then result in the formation of a nearly conical mound of dredged material on the disposal site with a radius of about 400 yd. Bathymetric surveys confirm this configuration (Figure 25). Point-dump disposal operations at any of the designated sites within Long Island Sound are expected to result in a similar configuration of dredged material on the bottom.

70. The method of placement of dredged material on the bottom should be chosen to minimize the surface area of the pile of deposited material. In the central Sound, currents resuspend about a mm of sediment from the natural mud bottom every tidal cycle (and up to several mm in storms). Unless the mound of disposed material is so large as to significantly perturb the water flow, the amount of dredged material mobilized by the currents at the disposal site is proportional to the surface area of the disposed-sediment pile. If the dredged material is silt, as is most likely to be the case for maintenance projects, the top few mm will be dispersed outside the designated disposal site. At the same time, the mound of disposed material will be blanketed by a layer of silt previously resuspended from the surrounding sea floor. This newly deposited sediment will be colonized by benthic animals and bioturbation will carry particles of dredged material from depths as great as 10 cm to the sediment-water interface (Rhoads, Aller, and Goldhaber, 1976). These sediment grains may also be resuspended and dispersed. Thus, it is expected that a layer of disposed sediment approximately 10 cm thick will be mobile in the waters of the Sound; the remaining sediment will be immobilized in the mound.

71. Any disposal of silt-containing sediment in Long Island Sound from barges positioned as at New Haven will cover at least 500,000 yd^2 of the disposal site with dredged material even if only a small amount of material is released. The percentage of the volume of the disposed material which will be mobilized by currents is shown in Figure 29. If more than 500,000 yd^3 are placed on the bottom as a cone (radius = 400 yd) at the disposal site, more than 90 percent of the disposed

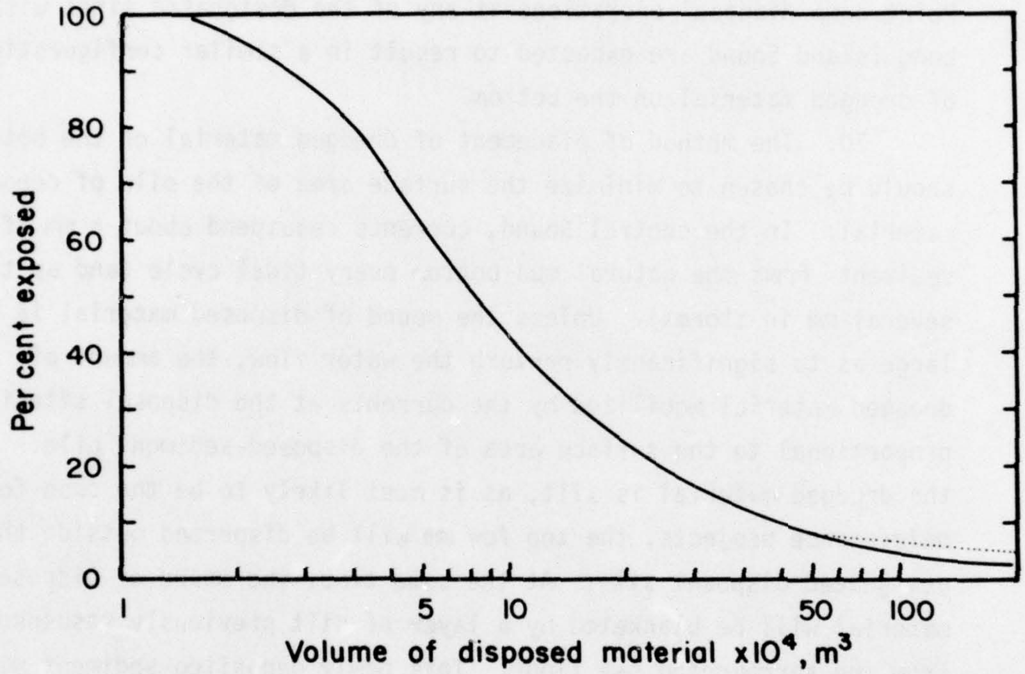


Figure 29. The percentage of disposal material that will undergo dispersion as a function of the size of the disposal project. Calculations are for a conical deposit 400 m in radius assuming a 10-cm bioturbation zone, a 20 percent deflection of the bottom under the deposit and no long-term, net erosion. The dotted curve is for a truncated cone 3 m thick.

sediment will be immobilized by burial. Projects smaller than 800,000 yd^3 will allow more than half of that volume to be dispersed in the Sound, regardless of how the discharge is controlled. To immobilize as much of the discharged sediment as possible, a few large disposal operations are preferable to many small disposal projects.

72. The deposited sediment must not be allowed to become a hazard to navigation; the water depth over the top of the pile of dredged material in Long Island Sound should be at least 40 ft. Additional restrictions may be placed on the height of the deposit of dredged material if long-term dispersion is to be minimized. As the deposit is built higher above the surrounding natural sea floor, it is exposed to higher current velocities. The rate of erosion will increase and the rate of redeposition will decrease, causing a net loss of material from the deposit. The loss may be stopped in either of two ways. The top of the deposit of dredged material may be armored with material having a high critical erosion velocity or the deposit may be kept low enough that the net loss of material due to the greater pile altitude is balanced by the natural sedimentation rate. A useful indicator of the greatest thickness of unarmored sediment that can be placed on a disposal site without subsequent dispersion is the slope of naturally occurring topographic features on the bottom (Bokuniewicz and Gordon, 1977). At the New Haven site this slope is 1:1000. The deposit of waste which was placed there exceeds this slope but it nevertheless is retained because the higher parts of the pile are armored with sand and clods of cohesive sediment.

73. A disposal site for dredged material in Long Island Sound has a capacity which, when exceeded, will result in long-term dispersal of material from the site. The capacity depends on the sedimentary regime at the site and on the mechanical properties of the deposited material. (These properties may be altered by biological activity at the site.) The capacity of the New Haven disposal site for unarmored silt-clay material, such as that likely to be produced by maintenance dredging, is about 1.7×10^6 yd^3 per square mile of site area. Greater

amounts can be retained only if covered by an erosion-resistant cap. If the full capacity of a site is to be utilized, the dredged material must be placed in an optimum configuration. The side slopes of an unarmored deposit must be kept below the greatest naturally occurring slope at the site. This will require placement of the dredged material on the site with a higher standard of accuracy than has been customary in the past. "Point dumping," the release of all material at one discharge point marked by a buoy, will be inappropriate in most cases.

74. Evidence that erosion-resistant dredged material is retained for long periods of time at the New Haven disposal site is found in bathymetric observations of an old mound of disposed material slightly north of the designated New Haven disposal site. A survey track run on 18 January 1973 south from New Haven Harbor shows a large mound of dredged material (Figure 30, from Gordon and Pilbeam, 1974). On this track, the emplaced sediment rises to a height of 9 ft above the ambient sea floor. In 1957, 2.0×10^6 yd^3 of dredged sediment was discharged at this site and 1.3×10^6 yd^3 was added between 1957 and 1972. Much of this material is coarse sand. The observed volume of the disposal mound in 1973 accounts for all of this material. Thus, there is evidence for a mound of sand-size dredged material resisting erosion for at least 20 years.

Disposal schedule

75. Insoluble chemical species which are adsorbed on immobilized sediment grains within the pile of disposed material are effectively isolated. This is thought to be true for heavy metals such as lead (Benninger, Lewis and Turekian, 1976). Dredging the most polluted material first and covering the mound of disposed sediment with less polluted material can isolate contaminants (Pratt and O'Connor, 1973). Soluble chemical species in the disposed material may be released into the Sound water by advection, or diffusion through the pore water as long as the concentration of such species in the pore water is greater than the concentration in the Sound. The flux of such species across the sediment-water interface depends on the thickness of the disposed

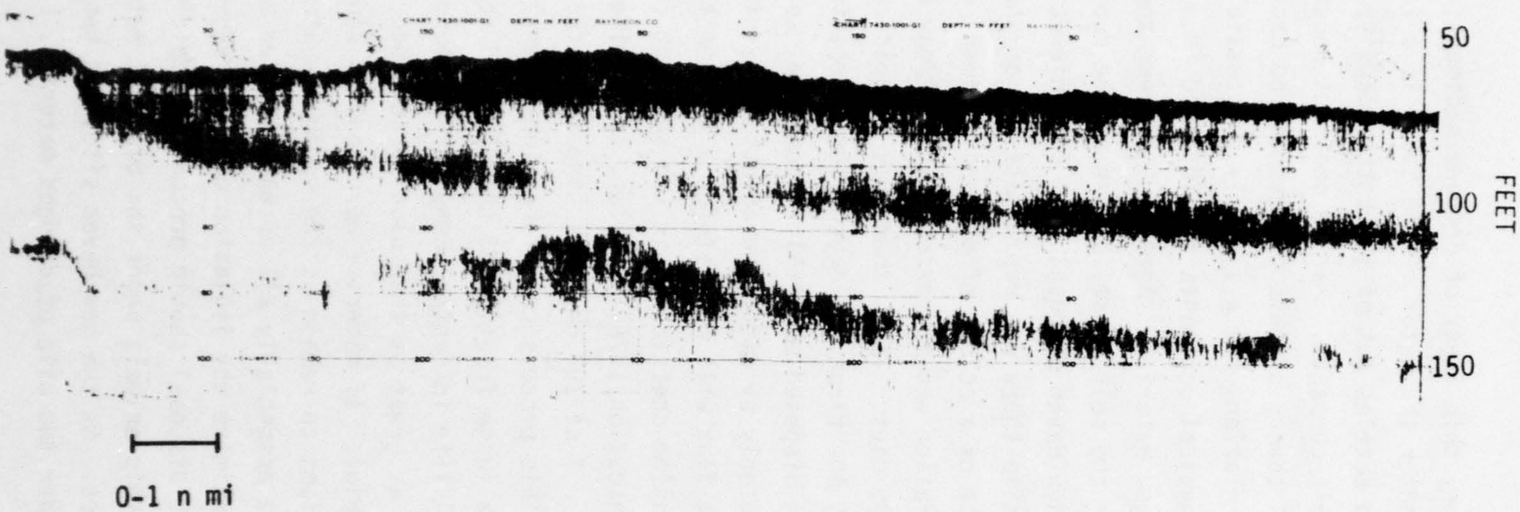


Figure 30. Acoustic reflection profile showing a mound of dredged material south of New Haven Harbor.

sediment cover. For a very thin layer of dredged sediment, all the soluble chemicals could enter the water of the Sound in a few days.

76. Sediment which settles out of the bottom density surge will expel pore water as it self-compacts. Marine sediment under the deposit will also consolidate. A theory of this process may be constructed using the stress-strain relations for a linearly compressible, porous medium. The necessary physical constants are obtained from a consolidation test on the dredged material. Agreement between theory and observations is found for the self-consolidation of the deposit of dredged material on the New Haven disposal site (Bokuniewicz and Gordon, 1977). At this site there was rapid settling of the dredged material. The strain rate of a column of dredged sediment during the first 28 days after completion was approximately 0.002/day and was effectively zero after 200 days. Thus, there was a rapid release of interstitial water during the first 200 days after deposition. When self-consolidation of the disposed material is complete, soluble chemicals can be released only by diffusion across the sediment-water interface. The diffusive flux will persist for a time on the order of T^2/D where D is the diffusion coefficient in the sediment ($D \sim 10^{-6}$ cm^2/sec) (personal communication, 1976, R. Aller, Yale University) and T is thickness. For a T of 10^2 cm, this time is on the order of several hundred years. This process cannot be significantly accelerated without mobilizing a large fraction of the disposed sediment.

77. Benthic animal life in central Long Island Sound cannot survive burial at a rate as great as that usually attained in the disposal of dredged material. If material were applied slowly enough to allow burrowing organisms to remain at the sediment-water interface, bioturbation would expose essentially all of the disposed material to the ambient water. To maximize the isolation of the dredged material placed in the bottom, the disposal should proceed as rapidly as possible with burial of benthic animals under the disposal material as an unavoidable consequence. At the New Haven site, the benthic animal population was buried under the pile of dredged material, but recoloni-

zation from the surrounding sea floor took place quickly; within five months the population density and diversity were comparable to those on areas well removed from the disposal site (Figures 31 and 32 from Rhoads, Aller, and Goldhaber, 1976).

78. The activities of benthic animals also influence the susceptibility of bottom sediments to erosion. Rhoads, Aller, and Goldhaber (1976) have shown that the water velocity necessary to erode muddy bottom sediment in the central Sound is as much as 50 percent higher during the winter than it is during midsummer. During the winter, macro- and micro-faunal populations are low and the bioturbation rate is minimal; at this time, bacterial exudates have opportunity to bind sediment together and hence increase the stability of the bottom. Disposal operations occurring between November and February not only bury the fewest benthic animals but also allow bacteria to stabilize and prepare the disposal site surface for recolonization by larvae when recruitment occurs in the spring.

Summary

79. In order to operate an open-water disposal site for dredged material in Long Island Sound so as to minimize exposure of the deposited sediment to the waters of the Sound, the following procedures may be followed:

a. All material to be disposed in a given year should be placed on one site (or a small number of sites). Because release of deposited material into the water by resuspension is as great for a small as for a large deposit of disposed material, numerous small releases of dredged material are most undesirable.

b. Contaminated material should be placed on the site first, followed by the cleanest material last.

c. The rate of application of material should be as large as possible.

d. Disposal operations should be conducted between the months of October and March.

e. Great care is required in all navigational procedures and in the supervision of the placement of dredged mate-

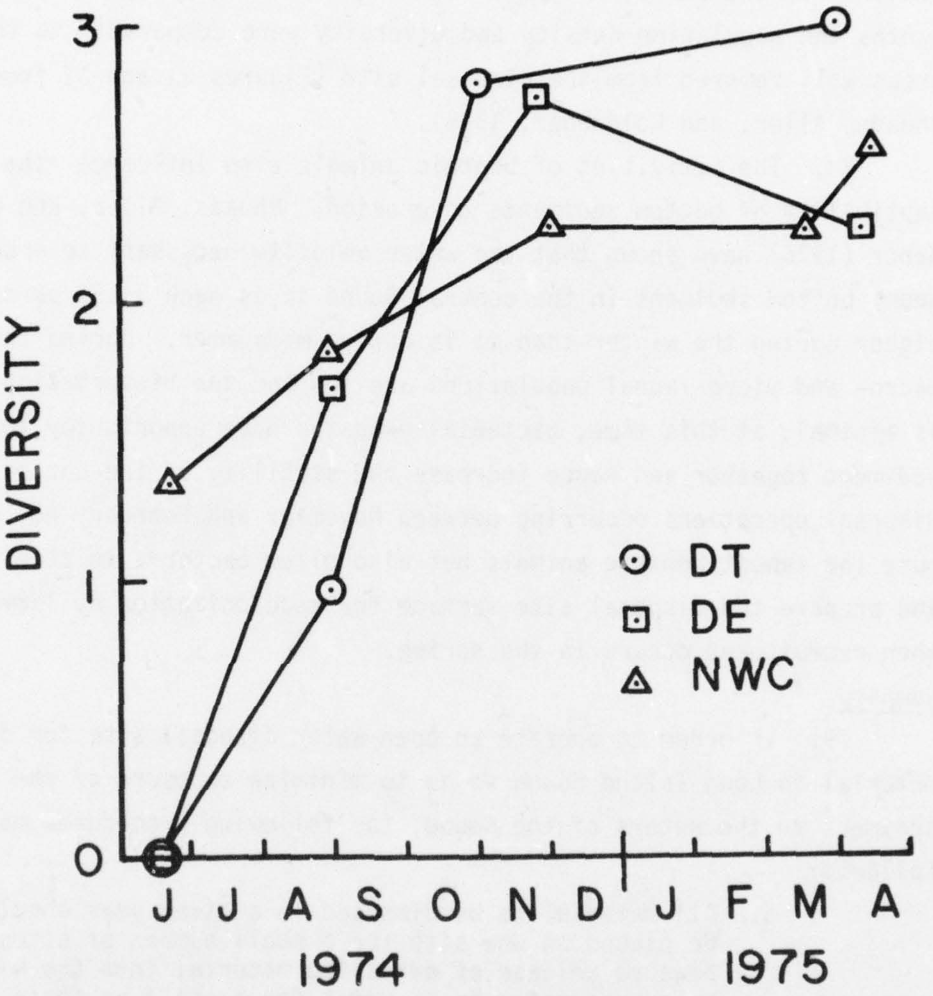


Figure 31. Diversity of the benthic population recolonizing the New Haven disposal site. "DT" indicates samples taken on the peak of the conical deposit of waste material; "DE", on the edge of the mound; and "NWC", at a control site 3 miles to the northwest of the disposal site (from Rhoads, Aller, and Goldhaber, 1976).

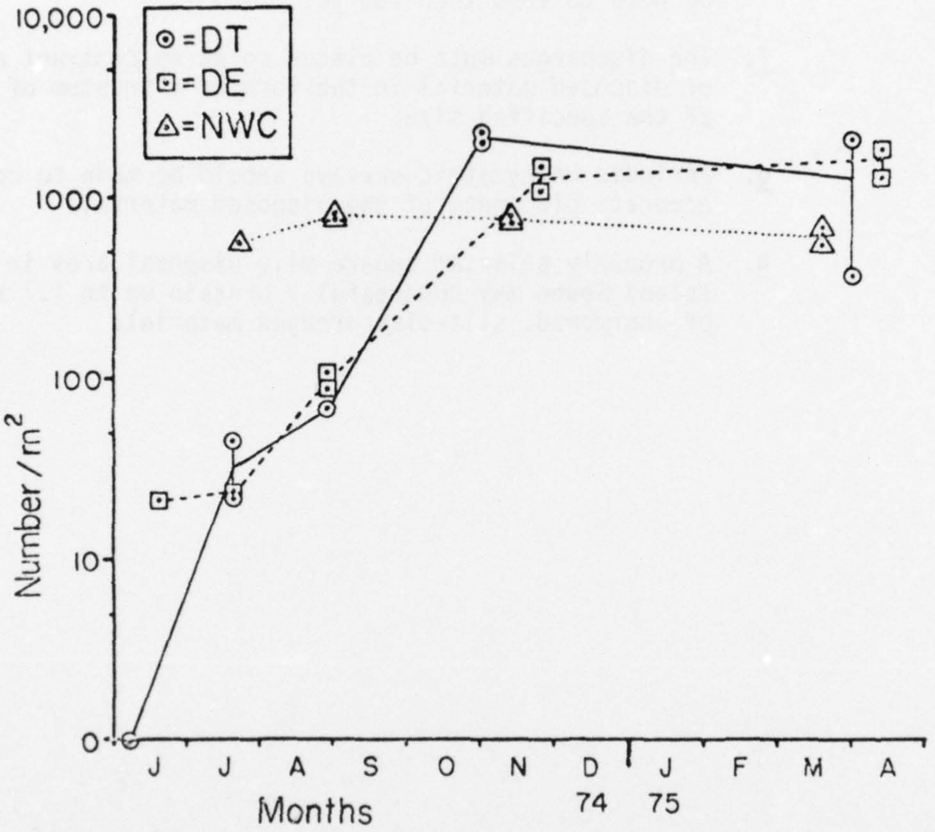


Figure 32. Size of the populations recolonizing the New Haven disposal site on the peak of the disposal mound (DT) and the edge of the waste deposit (DE). These populations are compared to the benthic population at a control site (NWC) located 3 miles to the northwest of the disposal site (from Rhoads, Aller, and Goldhaber, 1976).

rial. This should be regarded as the construction of an underwater structure and not as a "dumping" operation. Errors in the placement of scows for discharge should be held to less than 100 yd.

f. The discharges must be placed so as to contruct a pile of disposed material in the form of a frustum of a cone of the specified size.

g. Periodic bathymetric surveys should be made to confirm accurate placement of the disposed material.

h. A properly selected square mile disposal area in Long Island Sound may successfully contain up to 1.7×10^6 yd^3 of unarmored, silt-clay dredged material.

PART V: CONCLUSIONS

80. Dredged material placed on the bottom of Long Island Sound may be disturbed by waves and by currents. In the Sound the dominant source of energy for the suspension and transport of sediment is the tide. Hence, the relative importance of other energy sources may be evaluated by comparison with the tide. Waves on the surface cause an oscillating water flow at the bottom, but only in shallow water is the current due to waves sufficiently great to contribute to disturbance of sediments. The greatest depth of the wave-affected zone in Long Island Sound is found to be 60 ft from wind observations and empirical relations for calculating wave heights on enclosed bodies of water. This estimate is confirmed by wave-recorder data and by direct observation of the bottom at different depths after passage of Hurricane Belle.

81. Tidal stream amplitudes in Long Island Sound range from 1 to 4 knots. In the wide central part of the Sound, the tidal stream is rotary and no slack water occurs. Superimposed on the tidal stream is a net drift of bottom water westward and surface water seaward . This drift is detected in current meter records of a week or more in duration but is variable in magnitude and direction over long periods of time. Even current meter records of a year's length do not suffice to fully define this flow in the central region of the Sound.

82. The current over the bottom of the Sound is variable in a wide range of lengths and time scales. At times these fluctuations may cause the current speed to be substantially greater than that due to the tidal stream above. The fluctuating component of the current velocity can be described statistically so that the probability of unusually high velocities occurring can be evaluated. It is found that the intensity of the velocity fluctuations is greatly increased by storms to values comparable to the maximum tidal velocity. Even in the deepest parts of the Sound the bottom is, therefore, subject to increased disturbance during stormy periods.

83. Throughout Long Island Sound the tidal currents are suffi-

ciently strong to cause regular resuspension of the muddy bottom to a depth of $\sim$1 mm. During stormy periods the amount of resuspension is increased and may be double that or more during calm periods. This storm-induced resuspension is due to the fluctuating component of the current. The total amount of resuspension is determined by both the strength of the tidal current and the mean fluctuation amplitude.

84. Deviations from predicted water levels as recorded by tide gages are a useful measure of the amount of storm energy in the waters of Long Island Sound. Examination of water level deviations at New London over a 38-year period defines the seasonal variation in storminess in the Sound and also shows the relative amount of storm energy released in successive winters. These results may be used to evaluate the extent to which data taken in one winter are representative of conditions over a much longer period of time.

85. It is expected on the basis of the above results that silt-clay dredged material placed on a site in Long Island Sound where the water depth is greater than 60 ft and where natural muddy bottom is accreting will remain undisturbed by currents except for a layer a few mm thick, provided the deposit slopes are less than 1:1000. Steeper deposits are stable if armored. This expectation was tested at the New Haven disposal site after the placement of 1.5×10^6 yd^3 of dredged material. During the first six months after placement, dewatering and self-compaction caused shrinkage of the pile of deposited material. After that, no further significant changes in the pile configuration occurred. In particular, the pile was found to be undisturbed by the passage of Hurricane Belle in August 1976. The results obtained would be more convincing, however, if the contractual arrangements made for studies at this site had provided for continuity of observations: the quality of the data were degraded by the need to use several different navigation systems and by gaps between study periods.

86. The examination of the physical causes of disturbance of particulate material placed on the bottom of Long Island Sound may be used to establish criteria for the selection of a disposal site and a disposal procedure that will result in maximum containment of the

deposited material. The capacity of a site to contain deposited material may also be set.

87. A site intended to contain silt-clay material is best placed in an area of rapid, natural accumulation of muddy sediment. The natural sedimentation rate has been mapped for Long Island Sound and it is found that while all disposal sites in the central and western Sound are in areas of mud accretion, better locations could be chosen for several of the disposal sites now in use. Silt-clay material placed on one of these sites is subject to resuspension and intermixing with sediment from the surrounding sea floor to depths of a few mm. Bioturbation increases the thickness of deposited material in communication with the water column to about 10 cm. Material deeper than this may be effectively isolated. To minimize contact of disposed material with the ambient water, the rate of deposition should be as great as possible. The relative amount of disposed material in communication with the water column decreases rapidly as the total amount of material placed on a disposal site by controlled discharge is increased. It is, therefore, desirable to combine as many small projects into one large disposal operation as possible. The capacity of a site to contain deposited material is limited by the maximum acceptable height of the pile of material placed on the bottom. Optimum use of site capacity is attained when the disposed material is placed in the shape of a frustum of a cone or pyramid. A square mile site in Long Island Sound may contain up to 1.7×10^6 yd^3 of unarmored, dredged material.

88. Optimum use of a disposal site requires precise placement of the material to be disposed so that the desired form of the resultant deposit is attained. Adequate placement can be attained with the equipment now in common use in the dredging industry, but much closer control over the placement operation than has been customary in dredging projects will be required.

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APPENDIX A: NOTATION

C_H = suspended sediment concentration in the harbor waters
C_S = suspended sediment concentration in the Sound (LIS)
d = water depth
D_H = average water depth in harbor
D_S = average water depth in the Sound
F = fetch
g = acceleration due to gravity
h = wave height
l_H = thickness of bottom sediment resuspended in harbor
l_S = thickness of bottom sediment resuspended in the Sound
P = frequency with which a velocity was observed
S = total amount of resuspended sediment
t = wave period
T = time
u = velocity
$\overline{u}$ = mean velocity component
u' = fluctuating velocity component
u_m = maximum orbital wave velocity at the bottom
u_x = east-west component of current velocity
u_y = north-south component of current velocity
U = amplitude of the tidal stream
V = wind speed
W = volume
δh = nontidal water level
δp = pressure fluctuation of waves at the bottom
λ = wavelength
ρ = sediment density
σ = standard deviation
σ_x = east-west component of wind stress
σ_y = north-south component of wind stress

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Bokuniewicz, Henry J
Field study of the effects of storms on the stability and fate of dredged material in subaqueous disposal areas / by Henry J. Bokuniewicz ... [et al.], Department of Geology and Geophysics, Yale University, New Haven, Connecticut. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1977.
86, 1 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; D-77-22)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW51-75-C-0008 (DMRP Work Unit No. 1B08)
References: p. 84-86.

1. Disposal areas. 2. Dredged material. 3. Estuaries. 4. Long Island Sound. 5. Sediment. 6. Storms. I. United States. Army. Corps of Engineers. II. Yale University. Dept. of Geology and Geophysics. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; D-77-22.
TA7.W34 no.D-77-22