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REMOTS® Sediment-Profile Photography Survey of Boston Harbor, Dorchester, Quincy, Hingham, and Hull Bays

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REMOTS®
SEDIMENT-PROFILE PHOTOGRAPHY SURVEY OF BOSTON HARBOR, DORCHESTER, QUINCY, HINGHAM, AND HULL BAYS

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1.0 INTRODUCTION

Under the mandate of the Clean Water Act, the Massachusetts Water Resources Authority (MWRA) has developed a plan to provide the proper treatment and disposal of sewage in an effort to make the waters of the Boston Harbor area "swimmable" and "fishable". To characterize the existing benthic habitat conditions, the MWRA contracted Science Applications International Corporation (SAIC) to conduct two REMOTS® Sediment-Profile surveys in June 1989 and May 1990 (SAIC, 1990a). The June 1989 survey consisted of 64 stations located in the outer Boston Harbor area, including President Roads, Governor's Island Flats, Dorchester Bay, and the Winthrop Channel. The 53 stations occupied during the 1990 survey were located throughout Quincy, Hingham, and Hull Bays, the Boston Inner Harbor, and western regions of Dorchester Bay. Benthic habitat parameters, including sediment grain size, surface boundary roughness, apparent redox potential discontinuity (RPD), infaunal successional stage, and organism-sediment indices (OSI), were characterized.

In December 1991, sewage sludge dumping in Boston Harbor was terminated. In conjunction with the planned construction of a sewage treatment facility and the extension of the Deer Island effluent discharge pipe to the deep waters of Massachusetts Bay, the termination of sludge dumping was an initial step toward the recovery of the harbor. The activities of benthic organisms play a critical part in the recovery process. Biogenic activities (bioturbation resulting from active feeding and burrowing) mix surface and subsurface sediments with the overlying water column and effectively decrease sediment concentrations of certain organic and metal contaminants. A natural slowing down of these biological processes occurs during the winter months when water temperatures decrease.

As part of an ongoing effort to monitor the conditions of the benthic environment, the MWRA commissioned SAIC to conduct a REMOTS® survey of the Boston Harbor area. The 1992 survey was conducted on May 14 and 15, 1992 and consisted of 69 stations located in the Boston Harbor area, including Dorchester, Quincy, Hingham, and Hull Bays (Figure 1). Fifty-six (56) stations of the 1992 REMOTS® survey had been occupied during the May 1990 survey, while 5 of the 1992 REMOTS® stations had been occupied during the June 1989 survey. Eight "T" stations (MWRA Traditional grab stations) were also incorporated into the 1992 survey plan. Prominent landmarks, shoals, islands, and channels are shown in Figure 2.

The objectives of the May 1992 survey were twofold: 1) to provide additional baseline data of benthic habitat conditions prior to the recovery from sludge discharge and 2) to provide a spring-summer comparison in conjunction with a planned Summer 1992 REMOTS® survey of the area. Since water temperatures had not increased significantly from the time sludge disposal ceased until the time of the 1992 survey, biological activity will have been very low. The 1992 survey was considered to represent a reconnaissance of pre-recovery habitat conditions. Therefore, the results of the May 1992 survey could be compared with results of the 1989/1990 surveys to assess the inter-annual variations which characterize the harbor area. An understanding of these natural fluctuations in habitat content and condition is an important requisite to assessing improvements of the benthic habitat resulting from changes in anthropogenic activity (e.g., cessation of sludge disposal).

2.0 METHODS

2.1 Navigation

SAIC utilized the International Wildlife Coalition's research vessel, NAVAHO, for the May 1992 field effort. Navigation was provided by the SAIC Portable Integrated Navigation and Survey System (PINSS). This system consists of Northstar 800 LORAN-C and MX4200 Global Positioning System (GPS) receivers interfaced to an IBM PC/AT computer and Hewlett-Packard Thinkjet printer. The system provided positive vessel control through steering commands and a visual plot of the ship's position in relation to the station location. This information was relayed to the helmsman through a remote CRT display. Position fixes showing date, local time, latitude and longitude were recorded on magnetic disk and sent to the printer as a hard copy back-up. Position fixes were recorded manually for each replicate REMOTS® photograph as well as automatically at a user-specified time interval (5 minutes for this survey).

The LORAN-C was calibrated to the GPS signal prior to initiation of the survey. Calibration factors derived from this procedure were entered into the PINSS navigation system. Navigation by calibrated LORAN-C allowed stations to be reoccupied to within ± 25 meters. These same calibration factors were used during the second day of the 1992 survey.

2.2 REMOTS® Field Procedures

REMOTS® (Remote Ecological Monitoring Of The Seafloor) is a formal and standardized technique for sediment-profile imaging and analysis (Rhoads and Germano, 1982). A Benthos Model 3731 Sediment Profile Camera was used in this study (Benthos, Inc., North Falmouth, MA; Figure 3). The camera is designed to obtain profile images of the top 15-20 cm of sediment. Functioning like an inverted periscope, the camera consists of a wedge-shaped prism with a front face plate and a back mirror mounted at a 45 degree angle to reflect the profile of the sediment-water interface up to the camera. The camera is mounted horizontally on top of the prism. The prism assembly is moved up and down by producing tension or slack on the winch wire. Tension on the wire keeps the prism in the up position. The camera frame normally is lowered to the seafloor at a rate of about 1 m/sec. When the frame settles onto the bottom, slack on the winch wire allows the prism to vertically penetrate the seafloor. A passive hydraulic piston ensures that the prism enters the bottom slowly (ca. 6 cm/sec) and does not disturb the sediment-water interface. On impact with the bottom, a trigger activates a 13-second time delay on the shutter release; once the prism comes to rest in the sediment, a photo is taken. Because the sediment photographed is directly against the face plate, turbidity of the ambient seawater does not affect image quality. When the camera is raised, a wiper blade cleans off the faceplate; the film is advanced by a motor drive, the strobe is recharged, and the camera can be lowered for another image.

During the May, 1992 survey, three (3) replicate photographs were taken at each station. SAIC used Ektachrome 100 ASA color slide film for all photographs. All film was developed at the end of each sampling day using a JOBO E6 rotary processor to ascertain the success of the REMOTS® sampling for that day.

2.3 REMOTS® Image Analysis

Replicate REMOTS® photographs were analyzed with the SAIC REMOTS® image analysis system. This system utilizes a SPARCstation 1+ Sun WorkStation integrated with a PULNIX TMC-50 video camera and frame grabber. Color slides are digitally recorded as color image files on computer disk. The image analysis software is a menu-driven program which incorporates user commands via keyboard and trackball (computer mouse). This system displays each color slide on the CRT while measurements of all physical and biological parameters are obtained. Up to 21 different variables can be obtained for each REMOTS® image. All REMOTS® parameters are stored on computer disk and printed out on data sheets for editing by a senior-level scientist before being approved for final data synthesis, statistical analyses, and interpretation. A separate data sheet is generated for each REMOTS® image (Figure 4). Automatic disk storage of all parameters measured allows data from any variables of interest to be compiled, sorted, displayed graphically, contoured, or compared statistically. A summary of the 1992 REMOTS® data is provided in Table 1.

2.3.1 Sediment Type Determination

The sediment grain-size major mode and range are visually estimated from the photographs by overlaying a grain-size comparator which is at the same scale. This comparator was prepared by photographing a series of Udden-Wentworth size classes (equal to or less than coarse silt up to granule and larger sizes) through the REMOTS® camera. Seven grain-size classes are on this comparator: > 4 phi, 4-3 phi, 3-2 phi, 2-1 phi, 1-0 phi, 0-(-)1 phi, and < -1 phi. The accuracy of this method has been documented by comparing REMOTS® estimates with grain-size statistics determined from laboratory sieve analyses. In most cases where the REMOTS® grain-size estimate is different from the granulometric analysis, the major and minor grain-size modes have been found in adjacent size classes. The REMOTS® visual estimates in some cases cannot resolve the major mode when adjacent class peaks are comparable.

2.3.2 Surface Boundary Roughness

Surface boundary roughness is determined by measuring the vertical distance (parallel to the film border) between the highest and lowest points of the sediment-water interface. The presumed origin (biological vs. physical) of this small scale topographical feature is recorded so that inferences can be made as to the physical characteristics (wave, current, and bottom energy) of a site or magnitude of macrofaunal activity at the site.

2.3.3 Mud Clasts

When fine-grained, cohesive sediments are disturbed either by physical bottom scour or faunal activity (e.g., decapod foraging), intact clumps of sediment are often scattered about the seafloor and detected in REMOTS® photographs. These mud clasts are counted, the diameter of a typical clast is measured, and their oxidation state assessed. The abundance, distribution, oxidation state, and shape of mud clasts are used to make inferences about the recent pattern of seafloor disturbances in an area. Mud clasts which occur as sampling artifacts (i.e., resulting from the physical bottom disturbance by the camera prism) usually have an anomalous shape or appearance which allows them to be distinguished from those which occur naturally.

2.3.4 Apparent Redox Potential Discontinuity (RPD) Depth

Typically, aerobic near-surface marine sediments have a higher reflectance value relative to underlying hypoxic or anoxic sediments. This is readily apparent in REMOTS® images and is due to the fact that oxidized surface sediment contains particles coated with ferric hydroxide (an olive color when associated with particles), while the reduced sediments below this oxygenated layer are darker, generally grey to black. The boundary between the colored ferric hydroxide surface sediment and underlying grey to black sediment is called the apparent redox potential discontinuity (RPD).

The depth of the apparent RPD in the sediment column is an important time-integrator of dissolved oxygen conditions within sediment pore waters. In the absence of bioturbating organisms, this high reflectance layer (in muds) will typically reach a thickness of maximally 2 mm (Rhoads, 1974). This depth is related to the supply rate of molecular oxygen by diffusion into the bottom, and the consumption of that oxygen by the sediment and associated microflora. In sediments that have very high sediment-oxygen demand (SOD), the sediment may lack a high reflectance layer even when the overlying water column is aerobic.

In the presence of bioturbating macrofauna, the thickness of the high reflectance layer may be several centimeters thick. The relationship between the thickness of this high reflectance layer and the presence or absence of free molecular oxygen in the associated pore waters must be made with caution. The boundary which separates the positive Eh region of the sediment column from the underlying negative Eh region is called the Redox Potential Discontinuity or RPD. The exact location of this Eh=0 potential can only be accurately determined with microelectrodes; hence the relationship between the change in optical reflectance, as imaged with the REMOTS® camera, and the actual RPD can only be determined by making the appropriate *in-situ* Eh measurements. For this reason, we describe the optical reflectance boundary, as imaged, as the "apparent" RPD and it is mapped as a mean value. In general, the depth of the actual Eh=0 horizon will be either equal to, or slightly shallower than, the depth of the optical reflectance boundary. This is because bioturbating organisms can mix ferric hydroxide-coated particles downward into the bottom below the Eh=0 horizon. As a result, the apparent mean RPD depth can be used as a conservative estimate of the depth of pore water exchange, usually through pore water irrigation (bioturbation).

The rate of depth increase of the apparent RPD within the sediment is relatively slow in organic-rich muds (on the order of 200 to 300 micrometers per day), therefore this parameter has a long time constant (Germano and Rhoads, 1984). The rebound in the apparent RPD is also slow (Germano, 1983). Measurable changes in the apparent RPD depth using the REMOTS® optical technique can be detected over periods of one or two months. This parameter is effectively used to document changes (or gradients) which develop over a seasonal or yearly cycle related to water temperature effects on bioturbation rates, seasonal hypoxia, sediment oxygen demand, and infaunal recruitment. In repeated sediment-profile surveys of ocean disposal sites throughout the New England region performed under the DAMOS program for the U.S. Army Corps of Engineers, New England Division, SAIC has repeatedly documented a drastic reduction in apparent RPD depths at disposal sites immediately after dredged material disposal, followed by a progressive post-disposal apparent RPD deepening (barring further disposal activity). Consequently, time series RPD measurements can be a critical diagnostic element in monitoring the degree of recolonization in an area by the ambient benthos.

Another important characteristic of the apparent RPD is the contrast in reflectance values at this boundary. This contrast is related to the interactions among the degree of organic-loading and bioturbational activity in the sediment, and the levels of bottom-water dissolved oxygen in an area. High inputs of labile organic material increase sediment oxygen demand, and subsequently sulfate reduction rates (and the abundance of sulfide end-products). This results in more highly reduced (lower-reflectance) sediments at depth and higher RPD contrasts. In a region of generally low RPD contrasts, images with high RPD contrasts indicate localized sites of relatively high past inputs of organic-rich material (e.g., dredged material or sewage sludge).

2.3.5 Sedimentary Methane

At extreme levels of organic loading, pore-water sulfate is depleted, and methanogenesis can occur within the sediments column. The process of methanogenesis is detected by the appearance of methane bubbles in the sediment column. These gas-filled voids are readily discernable in REMOTS® images because of their irregular, generally circular aspect and glassy texture (due to the reflection of the strobe off the gas). If present, the number and total areal coverage of all methane gas pockets is measured.

2.3.6 Infaunal Successional Stages

The mapping of successional stages is based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor perturbation (e.g., passage of a storm, dredged material deposition, hypoxia). This theory states that primary succession results in "the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance. Because functional types are the biological units of interest..., our definition does not demand a sequential appearance of particular invertebrate species or genera" (Rhoads and Boyer, 1982). The term disturbance can refer to a natural process such as seafloor erosion, changes in seafloor chemistry, macrofaunal foraging disturbances which cause major reorganization of the resident benthos, or anthropogenic impacts such as dredged material or sewage sludge disposal, trawling, thermal effluent from power plants, industrial discharge, etc. This theory is formally developed in Rhoads and Germano (1982) and Rhoads and Boyer (1982).

An important aspect of using this successional approach to interpret benthic monitoring results is relating organism-sediment relationships to the dynamical aspects of end-member seres (i.e., Stage I, II or III seres as defined in the following paragraphs). This involves deducing dynamics from structure, a technique pioneered by R. G. Johnson (1972) for marine soft-bottom habitats. The application of this approach to benthic monitoring requires *in-situ* measurements of salient structural features of organism-sediment relationships as imaged through REMOTS® technology.

Pioneering assemblages (Stage I assemblages) usually consist of dense aggregations of near-surface living, tube-dwelling polychaetes; alternately, the opportunistic mactrid bivalve *Mulinia* may colonize initially in dense aggregations after a disturbance (Rhoads and Germano, 1982, Santos and Simon, 1980a). These functional types are usually associated with a shallow depth of bioturbation which results in a shallow apparent RPD boundary. In the absence of further disturbance, these early successional assemblages are eventually replaced by infaunal deposit feeders; the start of this "infaunalization" process is designated arbitrarily as a Stage II sere. Typical Stage II species are shallow dwelling bivalves or, as is common in New England waters, tubicolous amphipods. In studies of hypoxia-induced benthic defaunation events in Tampa Bay, Florida, ampeliscid amphipods appeared as the second temporal dominant in two of the four recolonization cycles (Santos and Simon, 1980a, b).

Stage III taxa represent high-order successional stages typically found in relatively low disturbance regimes. These invertebrates are infaunal, and many feed at depth in a head-down orientation. The localized feeding activity results in distinctive excavations called feeding voids. Diagnostic features of these feeding structures include: a generally semicircular shape with a flat bottom and arched roof, and a distinct granulometric change in the sediment particles overlying the floor of the structure. This granulometric change is caused by the accumulation of coarse particles that are rejected by the animals feeding selectively on fine-grained material. Other subsurface structures, such as burrows or methane gas bubbles, do not exhibit these characteristics. The bioturbational activities of these deposit-feeders are responsible for aerating the sediment and causing the apparent redox horizon to be located several centimeters below the sediment-water interface. In the retrograde transition of Stage III to Stage I, it is sometimes possible to recognize the presence of relict (i.e., collapsed and/or inactive) feeding voids.

The end-member stages (Stages I and III) are easily recognized in REMOTS® images by the presence of dense assemblages of near-surface polychaetes and the presence of subsurface feeding voids, respectively; both types of assemblages may be present in the same image. Additional information on REMOTS® image interpretation can be found in Rhoads and Germano (1982, 1986).

As noted during previous REMOTS® surveys of the Boston Harbor area, capitellid polychaetes were apparent in several REMOTS® photographs from the 1992 survey. The abundance of these organisms can be inferred in a report by Fleming (1989) who found that up to 78% of total sediment weight of Boston Harbor sediment samples consisted of resistent pellets. These pellets presumably result from these polychaetes feeding at depth and irrigating the sediment column. Similar abundances of this polychaete have been observed in nutrient-rich sediments in Black Rock Harbor in Long Island Sound. We have no explanation for why this taxon feeds at depth in the sediment while most other enrichment species feed on labile organic matter near the sediment surface. This anomalous feeding behavior deserves special study because, in our experience, it represents a notable exception to the organism-sediment model outlined above. For purposes of our Boston Harbor analysis we have classified the capitellids as Stage I seres.

2.3.7 REMOTS® Organism-Sediment Index

The multi-parameter REMOTS® Organism-Sediment Index (OSI) has been constructed to characterize habitat quality. Habitat quality is defined relative to two end-member standards. The lowest value is given to those bottoms which have low or no dissolved oxygen in the overlying bottom water, no apparent macrofaunal life, and methane gas present in the sediment (see Rhoads and Germano (1982, 1986) for REMOTS® criteria for these conditions). The REMOTS® Organism-Sediment Index for such a condition is minus 10. At the other end of the scale, an aerobic bottom with a deep apparent RPD, evidence of a mature macrofaunal assemblage, and no apparent methane gas bubbles at depth will have a REMOTS® Organism-Sediment Index value of plus 11. The OSI is calculated automatically by SAIC image analysis software after completion of all measurements from each slide and represents the sum of weighted values assigned to specific REMOTS® parameters (Table 2). The index has proven to be an excellent parameter for mapping disturbance gradients in an area and documenting ecosystem recovery after disturbance (Germano and Rhoads, 1984; Revelas et al., 1987).

The OSI may be subject to seasonal changes because the mean apparent RPD depths vary as a result of temperature-controlled changes of bioturbation rates and sediment oxygen demand. Furthermore, the successional status of a station may change over the course of a season related to recruitment and mortality patterns or the disturbance history of the bottom. The sub-annual change in successional status is generally limited to Stage I (polychaete-dominated) and Stage II (amphipod-dominated) seres. Stage III seres tend to be maintained over periods of several years unless they are eliminated by increased organic loading, extended periods of hypoxia, or burial by thick layers of dredged material or other sediment depositional events. The recovery of Stage III seres following abatement of such events may take several years (Rhoads and Germano, 1982). Stations that have low OSI values (≤ +6) tend to have greater temporal and spatial variation in benthic habitat quality than stations that have higher OSI values.

3.0 RESULTS

3.1 Distribution of Sediment Types

The mapped distribution of grain size (Figure 5) revealed the patchy, relatively heterogeneous sedimentary pattern which characterizes the Boston Harbor, Quincy, Hingham, and Hull Bay areas (Knebel et al., 1991). Processes of sediment deposition, reworking, and active erosion are ongoing throughout the harbor area due to variations in current regimes, source inputs of organic-rich silt/clay material, water depth, and kinetic energy potential due to wind-driven waves.

REMOTS® stations exhibiting fine sand surface sediments (2-3 Phi) were located primarily in regions considered vulnerable to significant wave and tidal activity. This includes stations in the Nantasket Roads area (stations 44, 47 and 52), the President Roads area (stations 9 and 72), and along the Nubble Channel at the eastern tip of Long Island (stations T5 and 50). These findings are supported by previous studies of Boston Harbor which mapped the distribution of erosional and depositional areas (Knebel et al., 1991). The cobble observed in REMOTS® photographs from station 21 is most likely the result of the high current velocities characteristic of Hull Gut. Additionally, several nearby stations within Hull Bay (stations 15, 18, 22, and T8) exhibited thin layers of fine sand overlying silt/clay muds.

Stations 16, 27, and 65 exhibited exclusively silt/clay sediments (>4 phi). The predominance of these silt/clay sediments is characteristic of depositional sites which are generally located above the 20-foot isobath on mud flats (western recesses of Quincy Bay) or in the upper reaches of low kinetic channels (Boston Inner Harbor).

Although silt/clay material was present at stations throughout the sampling area, the majority of stations in Quincy and Hull Bays consisted of mixtures of silt/clay with very fine sand (3-4 phi). Similar grain size distributions were noted during the 1990 REMOTS® survey. This predominance of fine grained, sandy material may reflect the absence of input of silt/clay from rivers or sewage outfalls. Additionally, this sand component may be derived from reworking of morainal material.

Numerous REMOTS® photographs revealed relatively dark, low reflectance sediments located below the sediment-water interface. These profiles are indicative of high sedimentation rates of organic labile material. In instances of extreme organic loading, anaerobic bacterial activity can result in the formation of methane gas bubbles. Evidence of methanogenesis was apparent at two REMOTS® stations (stations 62 and 71).

Station 26 continued to exhibit the distinct sand over mud stratigraphy apparent in the 1990 survey, although it had been repositioned approximately 200 m northwestward from its 1990 location. Similar grain size anomalies were observed at stations 58 and T1 and may be due to a combination of storm runoff and anthropogenic activities (Sewage Treatment Facility construction on Deer Island). Consolidated clay material present in REMOTS® photographs from stations 63 and 64 provided evidence of potential deposits of dredged materials from nearby, ongoing construction projects (Central Artery/Third Harbor Tunnel).

3.2 Mean Apparent RPD Depths

The frequency distribution of apparent RPD depths in 1992 had a major mode in the 0.76 to 1.50 cm depth class interval (Figure 6). Approximately 83 % of all replicate photographs (142 of 170 slides) showed an apparent RPD depth of ≤1.5 cm. REMOTS® surveys conducted in other open embayments along the New

England coast have shown that fine grained, ambient sediments typically exhibit apparent RPD depths of ≥3.0 cm; therefore, the apparent RPD depths recorded during the 1989, 1990, and 1992 surveys represented a significant decrease from expected RPD depth values.

The shallowest apparent RPD depths (≤ 0.5 cm) occurred at stations in and near the Boston Inner Harbor (stations 65, 64, 63, 33, and T2) and in the Winthrop Channel areas (station 74 and T1). Isolated instances of very shallow apparent RPDs were also observed at stations 59 and 60 in Dorchester Bay and station 45 in Quincy Bay (Figure 7).

The deepest apparent RPD boundary layers were located in Quincy Bay where 19 of 27 stations exhibited apparent RPD depths of ≥ 1.0 cm. Also within this region were 3 of 4 stations with apparent RPD depths ≥ 2.0 cm (stations 29, 35, and 46). The fourth station, T3, located at the tip of Long Island, had a mean apparent RPD of 2.0 cm. Sediment profiles from T3 revealed extensive reworking and recolonization by Stage II infauna (tube-dwelling amphipods, Ampelisca sp.) This biogenic activity likely augmented the oxygenation of the upper sediment surface.

At stations located throughout much of the survey area, REMOTS® profiles were characterized by low reflectance sediments; however, several stations exhibited very dark subsurface sediments indicative of a high sulfide content and high sediment oxygen demand (SOD) (Figure 7). Anthropogenic input of organic labile, nutrient-rich material can result in significant increases in microbial activity which can, in turn, decrease dissolved oxygen availability. Stations exhibiting high SOD sediments were located along western portions of Quincy Bay, in the President Roads/Boston North Channel area, in the Boston Inner Harbor, and at isolated stations in Dorchester Bay and on Crow Point Flats. In cases of extreme organic loading, methane gas can be produced. The REMOTS® survey revealed methane gas formation at stations 62 and 71.

3.3 Infaunal Successional Stages

The mapped distribution of infaunal successional stages showed a predominance of Stage III organisms throughout much of 1992 survey area (Figure 8). Evidence of Stage III infaunal activity was based on the presence of active feeding voids resulting from head-down deposit feeding. Active feeding voids can often be distinguished from vacated, inactive voids by the appearance of increased reflectance in the sediments surrounding the void. This increased reflectance results from the organism's continual recirculation of water from the sediment-water interface down to the void and the incorporation of oxygen into the nearby sediments.

Inferences as to the potential health and stability of the benthic habitat can be made from the presence of Stage III infauna. These organisms are sensitive to disturbances such as dredged material and sewage sludge disposal. The effects of these disturbances are manifested in a variety of ways, including the burial of the benthic infauna by layers of dredged material deposits, increases in sediment organic particulate matter, and the onset of anaerobic conditions resulting from increased bacteriological activity. Stage III taxa are adapted primarily for relatively nutrient-poor sediments. These organisms feed in a head-down position on buried refractory detrital organic matter that has undergone microbial "depolymerization" (Rice and Rhoads, 1989). Stage III populations cannot survive, or are commonly absent, in sediments that receive inputs of labile organic matter at rates of ca. 500 mg C/m2/yr or higher, (Valente et al., 1990). An exception to this generalization exists in Boston Harbor where large, head-down deposit feeding Capitellidae are common.

The designation of Stage III successional stages was based on the evidence of Stage III activity in at least one of the three replicate photographs taken at each station. Ten REMOTS® stations revealed only Stage I activity in replicate photographs. Five of these stations were located in the President Roads/Boston North Channel area (stations 9, 70, 71, T1, and T3). In comparing these findings with data collected during the 1989/1990 surveys, one must be careful to note that many of the 1989/1990 stations exhibiting exclusively Stage I infauna were located in the Winthrop Channel area and were not sampled during the 1992 survey.

Tunicate-like organisms (prob. Bostrichobranchus pilularis or Mogula sp.), "stick-building" amphipods (Family Podoceridae), and thin algal mats were observed in REMOTS® photographs from several stations in Quincy and Hull Bays (Figure 9). The presence of these organisms does not represent a progression of infaunal successional stages.

3.4 Organism-Sediment Index

The frequency distribution of median OSI values for all replicate photographs (N = 158) showed major modes at the +2 to +3 and +6 to +8 intervals (Figure 10). Based on the results of past REMOTS® surveys, OSI values of +6 or less indicate chronically-stressed benthic habitats and/or those which have experienced recent disturbance such as erosion, dredged material or sewage sludge disposal, or hypoxia (SAIC, 1990b).

The mapped distribution of median OSI values showed that stations with OSI values of >+6 were confined to Quincy and Hull Bays (Figure 11). This represented approximately 63 % of the Quincy Bay stations (17 of 27 stations) and 37 % of the Hull Bay stations (7 of 19 stations). Low OSI values in Quincy Bay were located along the western portion of this region and were due to the relatively shallow apparent RPD boundary layers measured at those stations. This may provide evidence that Long Island impedes some of the flow and circulation of water from the outer harbor area, while at the same time, permits passage of nutrient-enriched waters from the inner harbor between Moon Head - West Head gap in Long Island.

None of the stations north of Long Island (N = 23) had OSI values of >+6 which indicated that Boston Harbor and Dorchester Bay have poor benthic habitat quality relative to Quincy, Hingham, and Hull Bays. The distribution of stations with low OSI values did not provide any indication as to possible point sources of contamination in the harbor area. Although stations 9, 71, 73 and T1 (OSI values of ≤+3) were located near the sewage sludge disposal areas, low OSI values were also calculated for stations in Dorchester Bay (57, 58, and 59), in the Boston Inner Harbor (T2, 62, and 63), and in the Winthrop Channel (74). Low OSI values at these stations were more likely the result of organic enrichment and/or contaminant inputs from numerous other sources located "upstream" and around the harbor.

4.0 DISCUSSION

4.1 Objectives of the 1992 Survey

The primary objective of the May 1992 REMOTS® survey was to provide baseline data of habitat conditions of the Boston Harbor area for a spring-summer comparison. This data will be used in conjunction with data collected during a REMOTS® survey planned for late summer, 1992 as part of an effort to monitor improvements in the benthic habitat resulting from the cessation of sludge disposal.

The May 1992 data were also collected to further characterize habitat conditions prior to the recovery from sludge disposal. Although sludge disposal ceased in December 1991, cold water temperatures suppressed the burrowing, feeding, and bioturbating activities of the benthic infauna. These biogenic activities play an important part in the recovery of contaminated sediments. Therefore, the May 1992 data should represent pre-recovery conditions and supplemented thspringtime data gathered during the previous June 1989 and May 1990 REMOTS® surveys. Comparison of the May 1992 data with 1989/1990 data assisted in characterizing the seasonal and inter-annual habitat variability of the harbor area. An understanding of this variability will help identify future changes and improvements in the benthic habitat attributable to sludge disposal cessation.

REMOTS® stations in adjacent Quincy and Hull Bays provided farfield reference areas to assist in monitoring habitat changes in the Boston Harbor area. These embayments are not as susceptible to continual nutrient enrichment as stations in Boston Harbor. Having experienced a past history of organic loading (as evident by the presence of low reflectant subsurface sediments and nominal OSI values and RPD depths), sediments in Quincy and Hull Bays are more appropriate as reference stations than sediments with only a minimal history of organic/contaminant loading.

4.2 Results of the 1989 and 1990 Surveys

REMOTS® parameters calculated for the June 1989 and May 1990 surveys showed that Boston Harbor and Dorchester Bay had poor habitat qualities relative to the adjacent, eastern embayments. This disparity in habitat conditions was attributed to the proximity of the Deer Island effluent and the sewage sludge disposal points along the northern tip of Long Island and to the organic enrichment and contaminant inputs from sources along the Neponset River, Winthrop Channel, and Boston Inner Harbor (SAIC, 1990a).

Stations occupied during the June 1989 REMOTS® survey were located in the outer Boston Harbor area (north or east of Long Island) and provided detail of habitat conditions in that region. The distribution of stations occupied during the May 1992 survey encompassed a much broader area. The 1990 survey included stations located in Boston Inner Harbor, Dorchester Bay, and numerous stations throughout Quincy and Hull Bays. The two datasets provided an indication of spring habitat conditions although the distribution of the 1990 stations did not provide the same level of detail for mapping the outer harbor area as the 1989 data.

Dense mats of ampeliscid amphipod tubes were observed at many stations during the 1990 survey (Figure 12). The majority of these stations were located at the entrance of Quincy and Hull Bays. Although these amphipods are filter feeders and do not actively bioturbate subsurface sediments (a feeding behavior characteristic of Stage III infauna), colonization by these organisms resulted in an increase in the apparent RPD depth at several stations. The dense tube mats trapped oxygenated fecal pellets and fine grained material, effectively thickening the apparent RPD. These dense mats of ampeliscid tubes were not observed during the 1989 survey. The 1989 stations exhibiting deep apparent RPD boundary layers (≥ 2.0 cm) were characterized by spionid polychaete tubes originating from Stage I infaunal activity.

The mapped distribution of apparent RPD depths from the 1989 and 1990 survey has been recontoured and is provided in Figure 13. Due to a transcription error at the time of the 1990 data analysis, the apparent RPD depth of 0.63 cm at station 8 in Hingham Bay was incorrectly reported as 6.3 cm.

4.3 *Results of the 1992 Survey*

The results of the 1992 survey showed that the benthic habitats within Quincy and Hull Bays continued to be of higher quality compared to the Boston Harbor/Dorchester Bay areas. The area frequency distribution of apparent RPD depths and OSI values (Figures 14 and 15) showed that stations in the Boston Harbor area had shallower apparent RPD depths and lower OSI values compared to those in Quincy and Hull Bays. The bimodal distribution of OSI values (major modes of +3 and +7) supported these findings as all stations having OSI values >+6 were located south of Long Island (Figure 11). OSI values of ≤+6 are considered indicative of unstable, recently and/or chronically disturbed environments. Although the deepest apparent RPD depths were observed at the stations in Quincy Bay, mapped distributions of apparent RPD depths and OSI values show that conditions even at these stations south of Long Island still fall below sediment habitat quality characteristic of other New England embayments. Sediment conditions in areas of low disturbance typically exhibit apparent RPD depths of ≥3.0 cm and OSI values between of +9 to +11.

REMOTS® photographs from several stations in Quincy and Hull Bays revealed thin algal mats, and populations of tunicate-like organisms and "stick-building" amphipods. Although not considered significant to the infaunal successional stage model, these algae apparently colonized sediment surfaces during the winter months when benthic infaunal activity, and associated bioturbation, decreased. As water temperatures begin to warm during the summer months, increased bioturbation by Stage III infauna could result in the destabilization of these surface sediments and the eventual elimination of these mats. Tunicates are typically associated with hard-bottom substrates including cobble or shell hash. However, some species are known to inhabit soft substrates (e.g. Bostrichobranchus pilularis) and others (e.g. Mogula sp.) are easily dislodged and may collect in large numbers in depositional areas (R. Osman pers. comm.). At 5 of the 7 stations where tunicates were observed, large boundary roughness elements ("stick-building" amphipods and tubes) were apparent. This close association of tunicates and increased boundary roughness suggests that the tunicates may have been transported from other regions and trapped by the roughness of the bottom.

4.4 *Comparison of 1989/1990 and 1992 Survey Results*

Sampling in the late spring-early summer months provided some standardization of environmental conditions during the 1989, 1990, and 1992 REMOTS® surveys. Similarity in certain biological and sediment features was also apparent during each of these surveys. For example, low reflectance subsurface sediments (indicative of high organic content) continued to characterize the sediment-profile photographs from stations throughout the region.. Shallow apparent RPD depths and low OSI values revealed the persistence of poor habitat conditions throughout the harbor compared to other embayments along the New England coast. Additionally, the bimodal distribution of OSI values calculated during each survey showed that benthic conditions north of Long Island were of lower habitat quality than areas to the south.

Differences in habitat conditions observed during these surveys can originate from a number of naturally-occurring sources. The benthic environment consists of a myriad of organisms competing for space and food. One result of this dynamic relationship between organisms and the sediment is the natural variation in species composition which can occur from year to year. Water temperatures increase rapidly during the springtime. In conjunction with rising water temperatures, associated rates of bioturbation increase. Surface-dwelling organisms (i.e., Stage I and II organisms) are particularly vulnerable to fluctuations in bottom boundary layer conditions such as resuspension during storms. Given the number of environmental and biological factors which govern the makeup of the benthic habitat, some variation in the results of the REMOTS® surveys is expected.

One of the more conspicuous changes in benthic habitat noted during the 1992 survey was the disappearance of Stage II tube-dwelling amphipods observed throughout much of Quincy and Hull Bays during the 1990 survey (Figure 12). With the exception of station T3, located at the tip of Long Island, there was no evidence of viable communities of these tube-dwelling amphipods during the 1992 survey. REMOTS® photographs revealed relatively flat surfaces consisting of fine to very-fine sand at several stations in the 1992 survey where dense tube mats had been observed during the 1990 survey (Station 21, Figure 16). At other stations, the 1992 survey showed colonization of surface sediments by "stick-building" amphipods (Family Podoceridae) where tube-dwelling Ampelisca sp. were present during the 1990 survey (Station 49 and 43, Figures 17 and 18, respectively).

Although both of these organisms are filter-feeders and are included in the same functional feeding group, there is a marked difference in how colonization by these organisms affects the conditions of the surface sediments. The colonization by the tube-dwelling amphipods is closely associated with an increase in the apparent RPD depth due largely to accumulation of oxygenated fecal pellets between the tubes. This deepening of the apparent RPD is not observed at stations occupied by the "stick-building" amphipods.

The abundance and broad distribution of tube-dwelling amphipods in Quincy Bay during the 1990 survey likely accounts for some of deeper RPD depths recorded in Quincy Bay during that survey. Likewise, the absence of these tube-dwelling organisms during the 1992 survey may account for the conspicuous loss of deep (> 3.0 cm) apparent RPD depths in Quincy Bay. The frequency distribution of apparent RPD depths at stations occupied during all three surveys showed this shift (Figure 19): approximately 13 replicate photographs from the 1989/1990 surveys revealed apparent RPD depth > 3.0 cm while no apparent RPD depths > 3.0 cm were observed in the 1992 survey. Closer examination of this frequency distribution histogram shows that the majority of apparent RPD depths for each of the surveys fell within the 0.01 - 1.50 cm range. The overall broader distribution of apparent RPD depths noted during the 1990 survey are likely attributable to the presence of the tube-dwelling amphipods.

The disappearance of these tube-dwelling amphipods could be due to several factors including inter-annual variation in species composition or erosional events during storms (Mills,1967). Most of the 1990 stations occupied by these organisms are located in areas susceptible to wave activity generated by easterly winds. Two major storms did occur in Massachusetts Bay between 1990 and 1992. Hurricane Bob passed over Massachusetts Bay on August 19, 1991, and an extreme Atlantic coast northeast storm occurred in October, 1991. Hurricane Bob produced an average maximum wind speed of 45 knots with peak gusts of 59 knots at the Boston Buoy, 42.2°N and 70.8°W (Morris, 1992). The October 1991 Storm (Hallows' Eve Storm), which lasted 114 hours with sustained 40 knot easterly winds, occurred over October 30 and 31, 1991 (Davis and Dolan in press). Wave heights in Massachusetts Bay were over 30 ft. (Dolman pers. comm.). The scouring effects of these storm events may have displaced the tube-dwelling amphipod communities and subsequently allowed recolonization of surface sediments by other, more opportunistic organisms. The presence of small mud clasts at several stations in Quincy and Hull Bays, and outer Boston Harbor provided additional evidence of erosional activity.

Prior to the 1992 survey, the majority of stations exhibiting exclusively Stage I infauna were located in the outer Boston Harbor area. This region was extensively monitored during the June 1989 survey. In an effort to adequately characterize the habitat conditions of greater Boston Harbor area and adjacent embayments, the 1992 survey did not incorporate as many stations in the outer harbor area. As a result, the wide distribution of sediments containing exclusively Stage I organisms appears to have decreased since the time of the 1989/1990 surveys which might suggest that there was an increase in the distribution of Stage II and Stage III infauna. This apparent shift in the distribution of infaunal successional stages is largely the product of modifications in the sampling scheme utilized during each of the surveys. Successional stage data from the three surveys did show that the majority of stations with exclusively Stage I infauna were north of Long Island and in the vicinity of the Deer Island effluent pipe.

The frequency distribution of OSI values at stations occupied during all three surveys revealed the persistence of a bimodal grouping at index values of +2 and +7 (Figure 20). This grouping reflects the overall poor habitat conditions of the area compared to other New England embayments and the continued disparity in habitat conditions north and south of Long Island. The highest OSI values ($\geq$ +9) were limited to the 1989/1990 surveys and are most likely the result of the deep apparent RPD depths noted in conjunction with extensive colonization by tube-dwelling amphipods. Additionally, all negative OSI values were attributable to the 1989/1990 surveys. Negative OSI values can occur where anaerobic sediment conditions resulted in the formation of methane gas bubbles. Station 71 (identical to station 22 of the 1989 survey) provided evidence of methanogenesis in both the 1989/1990 and 1992 surveys.

4.5 General Conditions of Boston Harbor and Neighboring Embayments

The relatively dark subsurface sediments observed in sediment profiles from stations throughout the survey area attest to the history of organic and nutrient-laden sediment loading from a myriad of point sources located in Boston and neighboring communities. The majority of stations with exceptionally dark subsurface sediments, which imply a very high sediment-oxygen demand, were located in the vicinity of Long Island and President Roads/Boston North Channel. The proximity of these stations to the sewage sludge disposal site and to the Deer Island outfall could have contributed significantly to formation of these dark sediments.

REMOTS® photographs from stations throughout the survey area, including stations with a high apparent SOD, showed extensive reworking of the sediment surface by Stage I organisms. Most notable was the progression of successional stage from Stage I polychaetes to Stage II (Ampelisca sp.) amphipods at Station T3, where extensive reworking of surface sediments increased the apparent RPD boundary layer to a 2.0 cm depth. Colonization by Stage I organisms plays a crucial role in the natural processes which can lead to a healthier benthic habitat. In addition to facilitating the oxygenation of surface sediments, Stage I seres are important agents for the breakdown and redistribution of accumulated organic matter (Rice and Rhoads, 1989). Burrowing and feeding activities of the nutrient-tolerant Capitellidae population may have contributed significantly to the diagenesis of the organic-laden sediments (Fleming, 1989).

The expected rate of change in sediment properties due to biogenic processes can be estimated from data on recolonization, bioturbation, and associated changes in sediment chemistry from the EPA/COE Field Verification Program in Long Island Sound. Organic-rich sediment containing high concentrations of both metals and PAHs from Black Rock Harbor (Bridgeport, CT) were dumped in central Long Island Sound and studied over a three-year period. The results of this study showed that major changes in sediment chemistry had taken place after one year of colonization (Scott et al., 1987). In predicting a time frame during which improvements in the benthic habitat of the Boston harbor area can be detected (due to cessation of sludge disposal), several additional factors should to be taken into account. Rates of bioturbation and infaunal activity decrease during the winter months as water temperatures drop. Associated oxygenation of the upper sediment surfaces and increases in the depth of the apparent RPD boundary layer are suppressed and often regress to a less advanced state. Apparent RPD depths continue to be shallower during the late Spring compared to summer months. Because sludge disposal was terminated in early Winter and only 5 months prior to the May 1992 survey, active recolonization of the deposited sludge had not likely occurred. Given the long history of sludge disposal and the tremendous inventory of organic material in these sediments, one might expect that the progression toward advanced recolonization stages will be slower than conventional model predictions.

The low OSI values apparent throughout much of Boston Harbor and Dorchester Bay, particularly at the mouth of the Neponset River, in Boston Inner Harbor, and at the mouth of Winthrop Channel, show that input of nutrient-rich/contaminated sediments from "upstream" sources has a marked, continuing effect on the condition of the benthic habitat. Stations with low OSI values located along the western boundaries of Quincy Bay, adjacent to the Moon Head - West Head gap in Long Island, provided additional evidence of nutrient enrichment originating from the Dorchester Bay area. As a result, evidence and detection of benthic habitat improvements relating to the cessation of sludge disposal could be effectively masked and/or prolonged.

5.0 SUMMARY AND CONCLUSIONS

On May 14 and 15, 1992, SAIC conducted a 69 station REMOTS® survey of the Boston Harbor area, including Dorchester, Quincy, Hingham, and Hull Bays. The 1992 survey stations were selected from various stations occupied during the June 1989 and May 1990 REMOTS® surveys of the area. Eight MWRA traditional grab stations (stations T1 - T8) were also sampled. The objectives of the 1992 survey were 1) to provide a spring-summer comparison in conjunction with a planned summer 1992 REMOTS® survey of the area and 2) to provide additional baseline data of benthic habitat conditions prior to the recovery from sludge discharge.

Selected biological and physical parameters were obtained from REMOTS® photographs (3 replicates per station) to allow mapping of major sediment modes, mean apparent redox potential discontinuity depths (RPDs), distribution of infaunal successional stage, and the presence of methane gas bubbles. An Organism-Sediment Index (OSI) was calculated for each station. OSI values rank benthic habitats as either impacted by organic enrichment or pollution (indices $\leq$+6) or relatively unaffected by enrichment or pollution (indices >+6). REMOTS® stations monitored in Quincy, Hingham, and Hull Bays provided farfield reference data of neighboring embayments which have received reduced amounts of nutrient-enriched materials. The major conclusions that can be drawn from these data include the following:

(1) The distribution of sediment grain size shows that the sedimentary patterns in the survey area are governed by several factors, including water depth, source inputs of organic-rich silt/clay material, and vulnerability to high kinetic energy regimes (i.e., tidal and wave-induced erosion). Stations at the tip of Long Island and at the entrances to Quincy and Hull Bays consisted of coarse grained material resulting from the washing away of fines by current and wave activity. As noted during the 1989 and

1990 surveys, Quincy, Hingham, and Hull Bays were dominated by very fine sand mixed with silt/clay material. This may be the result of relatively limited input of silt/clay material from sewage effluents and streams. Several stations in Hingham and Hull Bay, at the mouth of Quincy Bay, and at the western section of the President Roads Channel had a thin layer of sand overlying fine grained muds. REMOTS® photographs from two stations, at the tip of Deer Island and in the Boston North Channel, showed methane gas production. Production of methane gas is usually associated with intensive organic loading.

(2) The frequency distribution of apparent RPD depths in 1992 (N = 170) had a major mode in the 0.76 to 1.5 cm depth interval. Apparent RPD depths $\geq$ 1.0 cm were located primarily in Quincy Bay with a small clustering of $\geq$ 1.0 cm stations located in President Roads and in Hull Bay. There were no apparent RPD depths > 3.0 cm noted in the 1992 survey. The disparity in apparent RPD depths north and south of Long Island was also observed during the 1989/1990 survey: approximately 13 replicate photographs from the 1989/1990 surveys revealed apparent RPD depths > 3.0 cm, and the majority of these stations were located south of Long Island. These relatively well-developed apparent RPDs were attributed to the abundance and broad distribution of tube-dwelling Ampeliscid amphipods observed throughout much of Quincy Bay in 1990. A comparison of the frequency distributions of apparent RPD depths for all three surveys showed that the majority of apparent RPD depths fell within the 0.1 - 1.5 cm depth range. The absence of the tube-dwelling amphipods in 1992 may account for the relatively shallower apparent RPD depths observed in Quincy Bay during the 1992 survey. This disappearance may be attributable to the October 1991 Hallows' Eve storm or to natural inter-annual variation in species composition. Sediment-profiles in all three surveys were characterized by low reflectance subsurface material. Several stations were considered to have a high sediment-oxygen demand characterized by extremely dark subsurface sediments. Many of these stations were located along Long Island, where past sludge disposal may have had the greatest impact. Methane gas bubbles were apparent in sediment-profiles from station 71 in the 1992 and 1989 surveys.

(3) Photographs from 10 of the 1992 REMOTS® stations revealed exclusively Stage I infaunal activity compared to 21 of the 1989/1990 survey stations. This shift in successional stage distribution is largely due to modifications in the sampling scheme utilized for each of the surveys. Successional stage data from the three surveys showed that the majority of stations with exclusively Stage I infauna were north of Long Island and in the vicinity of the Deer Island effluent pipe. Due to the sensitivity of Stage III organisms to nutrient-rich sediments, the lack of Stage III activity in this area probably reflects the extreme nutrient loading resulting from past sludge disposal and ongoing effluent discharging. Extensive reworking of surface sediments by Stage I pioneering organisms suggested that the initial stages of recolonization were ongoing. These organisms represent a crucial step in the rehabitation of stressed benthic environments.

(4) The bimodal frequency distribution of OSI values for the 1989/1990 and 1992 surveys (major modes of +2 and +7) showed that the benthic habitats of Quincy and Hull Bays are of greater quality that Boston Harbor and Dorchester Bay. For all three surveys, the lowest OSI values in the Boston Harbor and Dorchester Bay areas were located primarily at the entrances of river/tributary systems which feed into Boston Harbor. These findings suggest that poor water quality and resulting poor benthic habitat conditions found in this area are, to a large extent, the result of input of nutrient-rich/contaminated materials from "upstream" sources. Low OSI values observed in 1992 at stations along the western portion of Quincy Bay may be due, in part, to the influx of poor water quality and nutrient-rich fine grained sediments through the Moons Head - West Head gap of Long Island. OSI

values of > +9 were limited to the 1989/1990 surveys and are most likely the result of the relatively deep apparent RPD depths noted in conjunction with extensive colonization by tube-dwelling Ampeliscid amphipods.

(5) Naturally-occurring fluctuations in the composition of the benthic habitat were observed during the 1989/1990 and 1992 surveys. This inter-annual variation is attributable to the numerous environmental and biological factors which affect rates of bioturbation and recolonization. An understanding of this variability will help future monitoring studies identify changes and improvements in the benthic habitat attributable to ongoing pollution abatement efforts by the MWRA.

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Station Designation

REMOTS® Survey of Boston Harbor Area, May, 1992

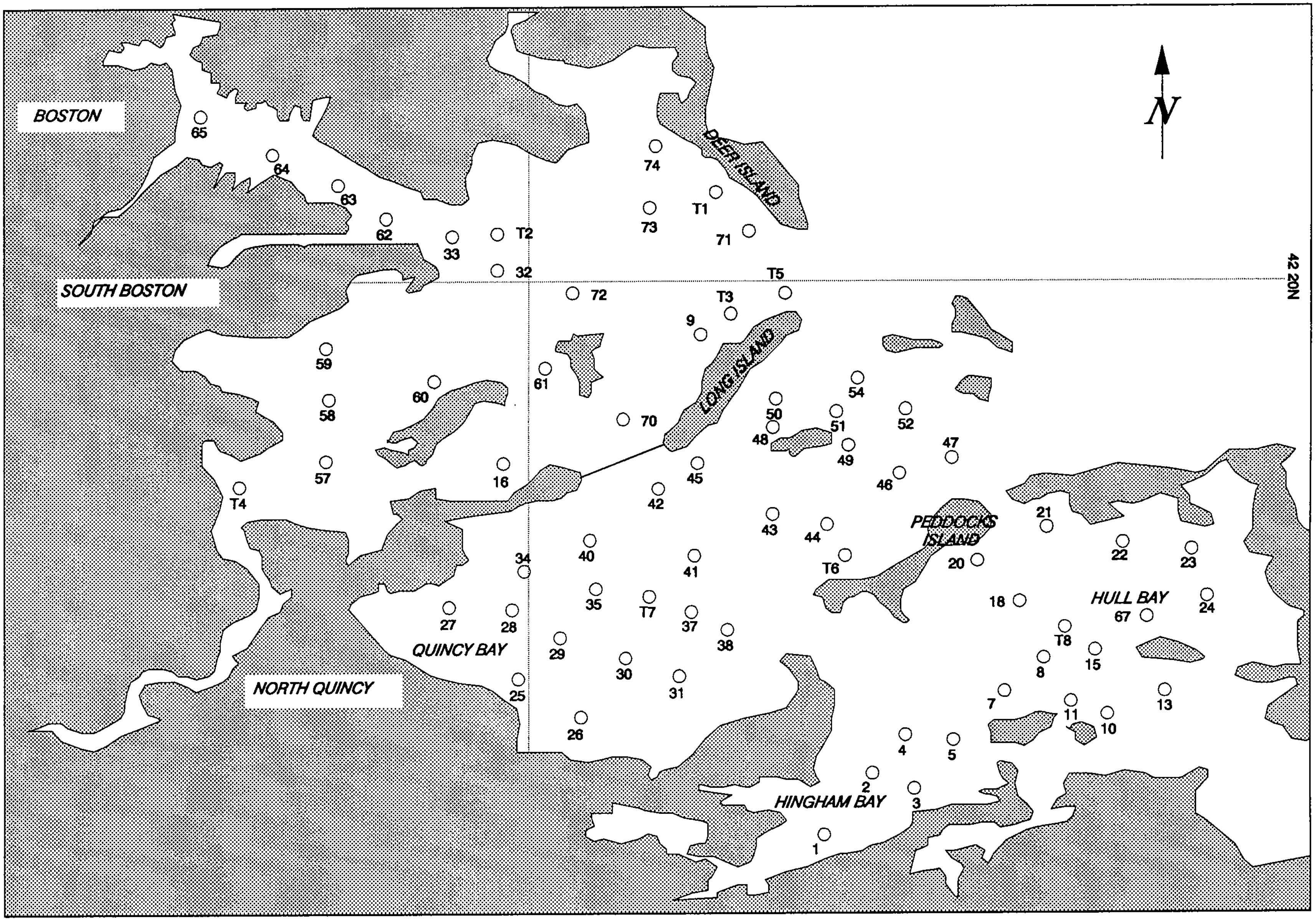


Figure 1. Station Locations for the 1992 REMOTS® Survey of the Boston Harbor Area.

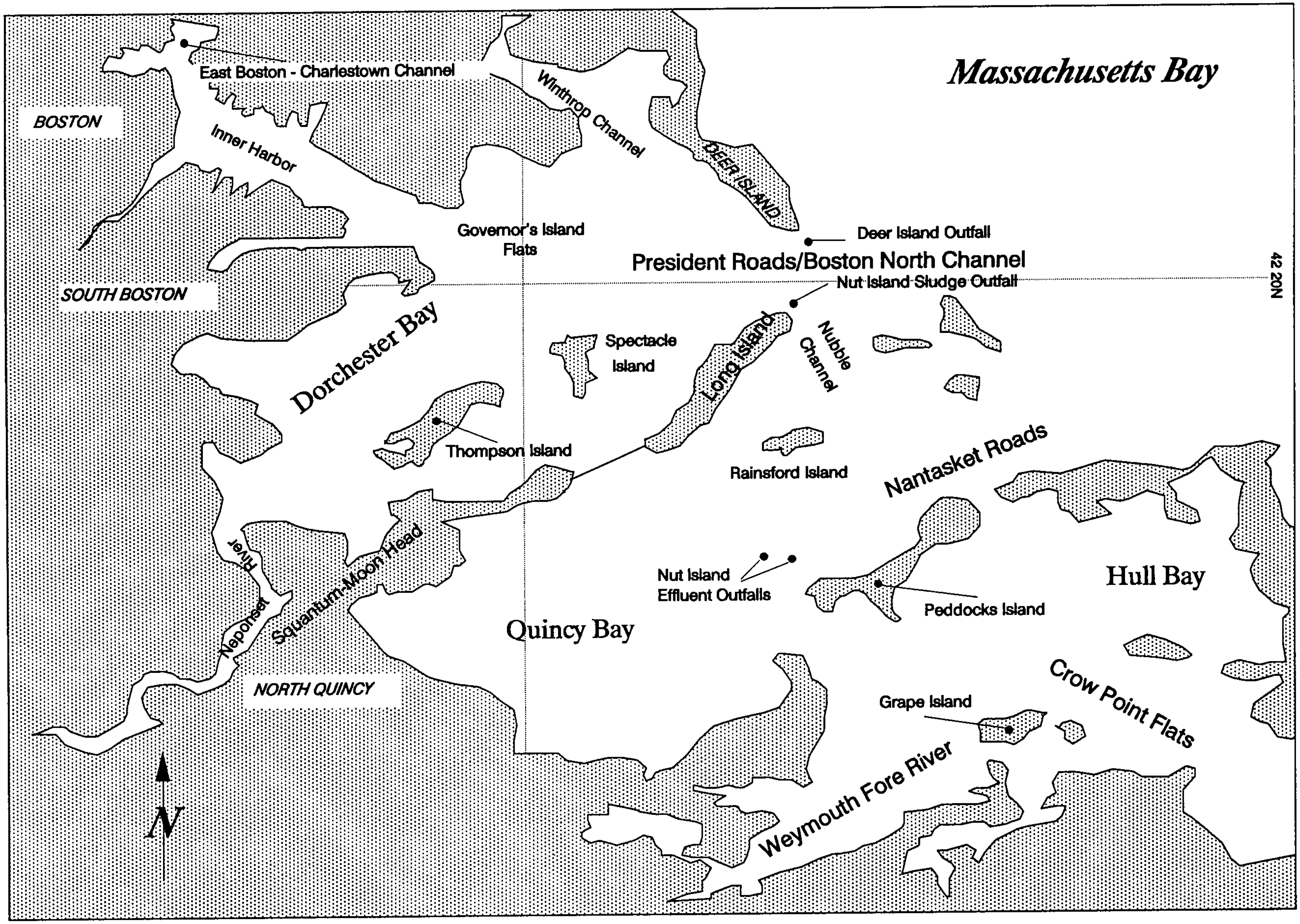
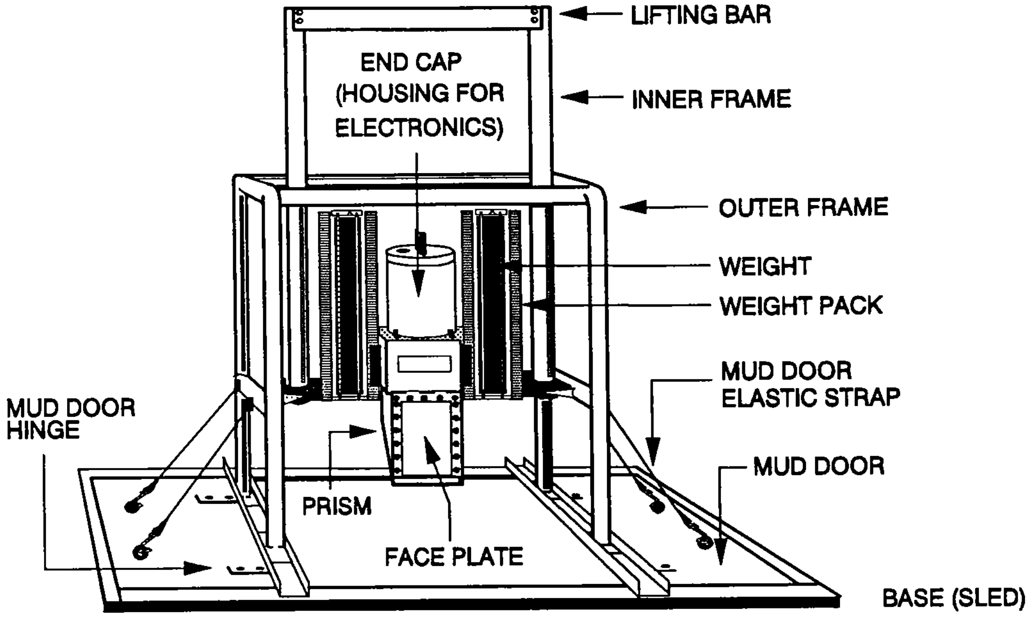
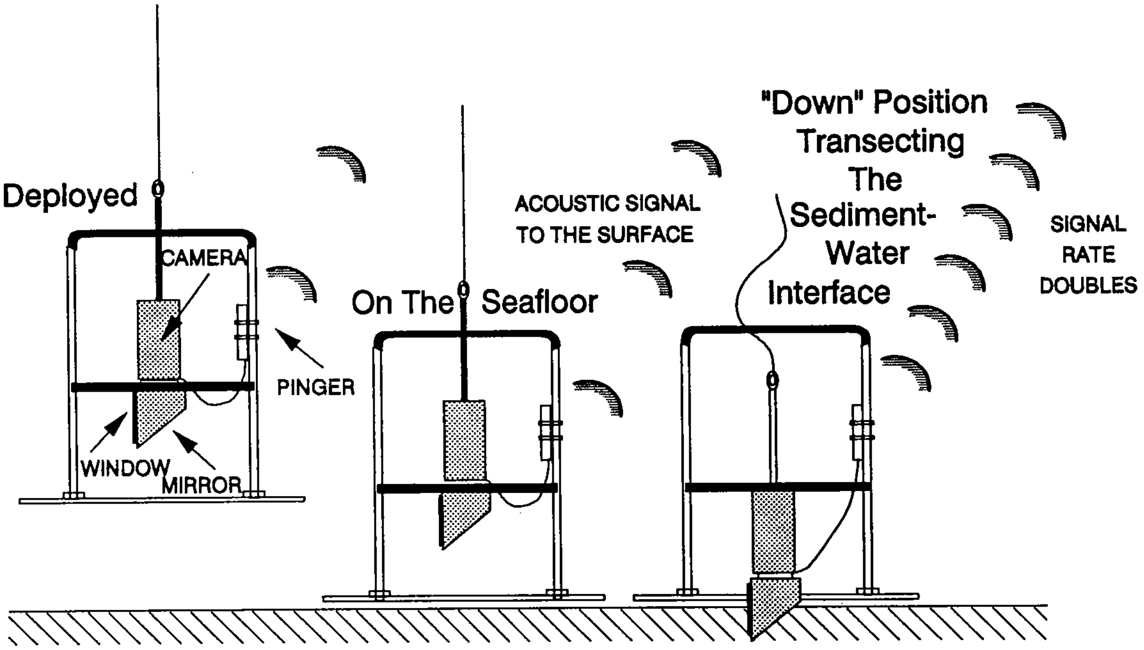


Figure 2. Prominent Landmarks in Boston Harbor, Dorchester, Quincy, Hingham, and Hull Bays.

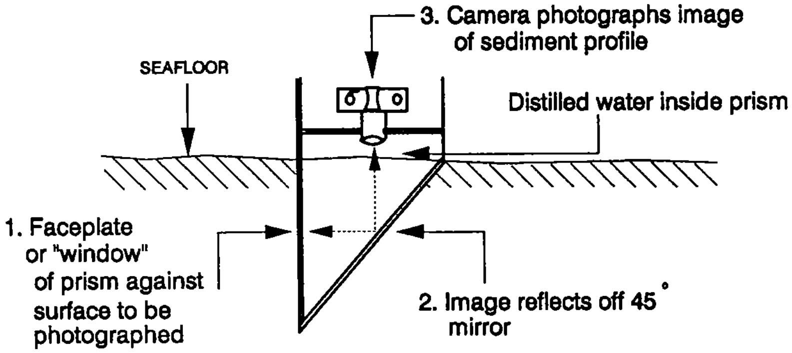
REMOTS Camera



Front View



Side View of REMOTS Camera in Operational Mode



REMOTS Camera Prism Schematic

Figure 3. The Benthos Model 3731 Sediment-Profile Camera used for REMOTS® Data Acquisition.

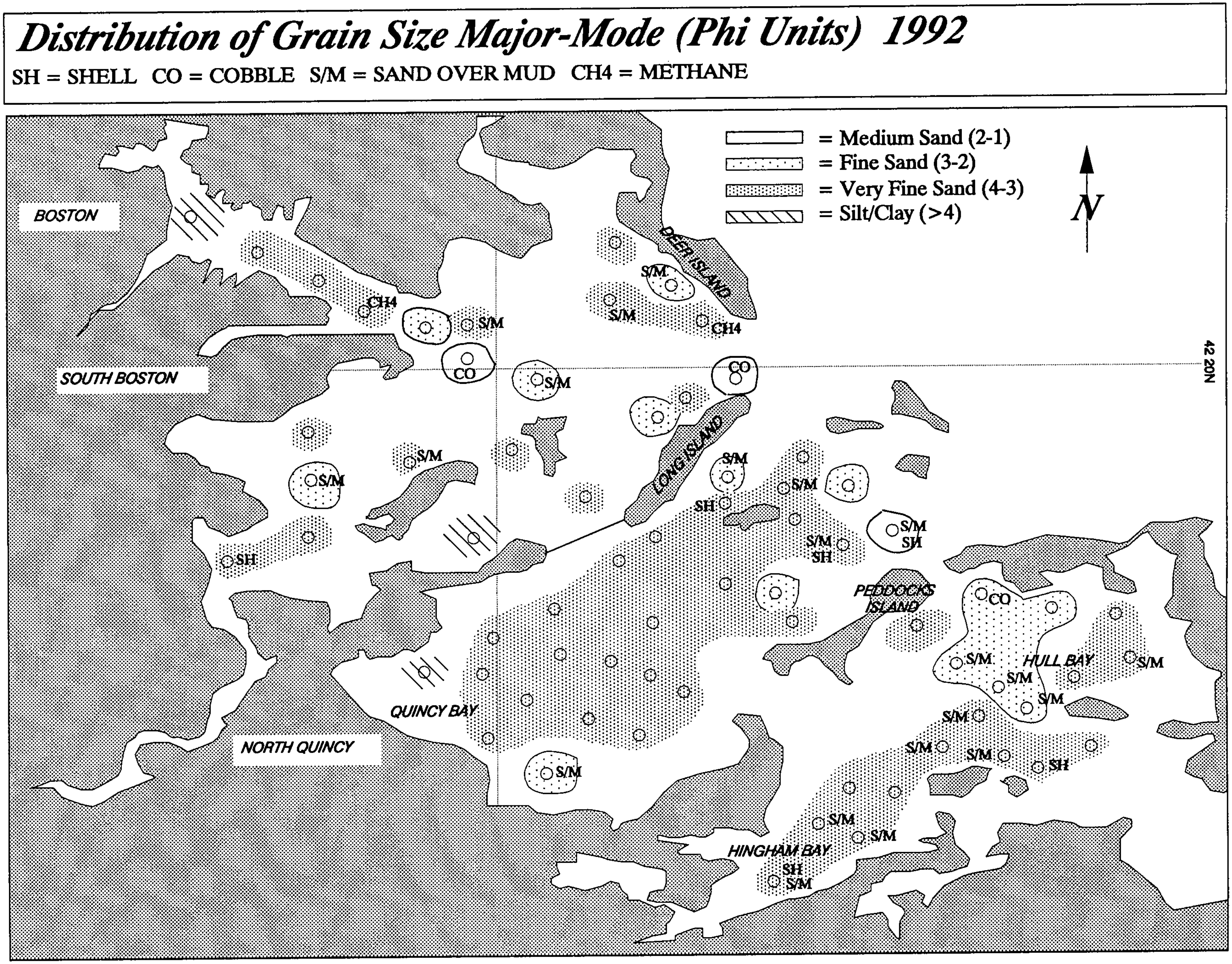
```
                         SAIC REMOTS DATASHEET

   Station . . . . mwra        Time . . . 0912        Date . . . . . 051592
   Number  . . . . T3          Frame  . . 5           Initials . . . RWW
   Replicate . . . b           Roll . . . 5           Plan view  . . NO
-------------------------------------------------------------------------
PENETRATION
   Maximum . . . . 19.92 cm    Boundary roughness . .  0.80 cm
   Minimum . . . . 19.12 cm    Roughness type . . . .  Biological
   Average . . . . 19.52 cm
-------------------------------------------------------------------------
GRAIN SIZE
   Mode . . .    3 to 4 phi    Range . . . . .  3 to > 4 phi
-------------------------------------------------------------------------
APPARENT RPD
   Minimum . . . .  1.88 cm    Width . . . 13.84 cm
   Maximum . . . .  2.60 cm    Area  . . . 31.00 cm2
   Average . . . .  2.24 cm
-------------------------------------------------------------------------
REDOX REBOUND LAYER
   Top . . . . . .  0.00 cm    Bottom  . .  0.00 cm   Width  . .  0.00 cm
-------------------------------------------------------------------------
MUD CLASTS
   Number  . . . .  2          Size  . . .  0.46 cm   Status . .  x
-------------------------------------------------------------------------
METHANE
   Minimum . . . .  0.00 cm    Number  . .  0
   Maximum . . . .  0.00 cm    Size  . . .  0.00 cm
   Average . . . .  0.00 cm
-------------------------------------------------------------------------
DREDGED MATERIAL
   Depth . . . . .  0.00 cm
-------------------------------------------------------------------------
COMMENTS
   Form comments:
   -0                  -0                  -0                  -0
   -0                  -0                  -0                  -0
   -0                  -0                  -0                  -0
   -0                  -0                  -0                  -0

   Add measure . .  0.00 cm    Comment: x

   General comment:
       extreme surf reworking,relic void,mod SOD,amphi tubes
-------------------------------------------------------------------------
BIOLOGICAL
   Successional stage . . . . . Stage I -> II
   Low DO present . . . . . . . NO
   Organism Sediment Index  . . 5
=========================================================================
```

Figure 4. Datasheet of the 1992 REMOTS® Parameters measured for Station T3, replicate "b".



Distribution of Grain Size Major-Mode (Phi Units) 1992

SH = SHELL CO = COBBLE S/M = SAND OVER MUD CH4 = METHANE

Figure 5. Grain Size Distribution Map for the 1992 REMOTS® Survey of the Boston Harbor Area.

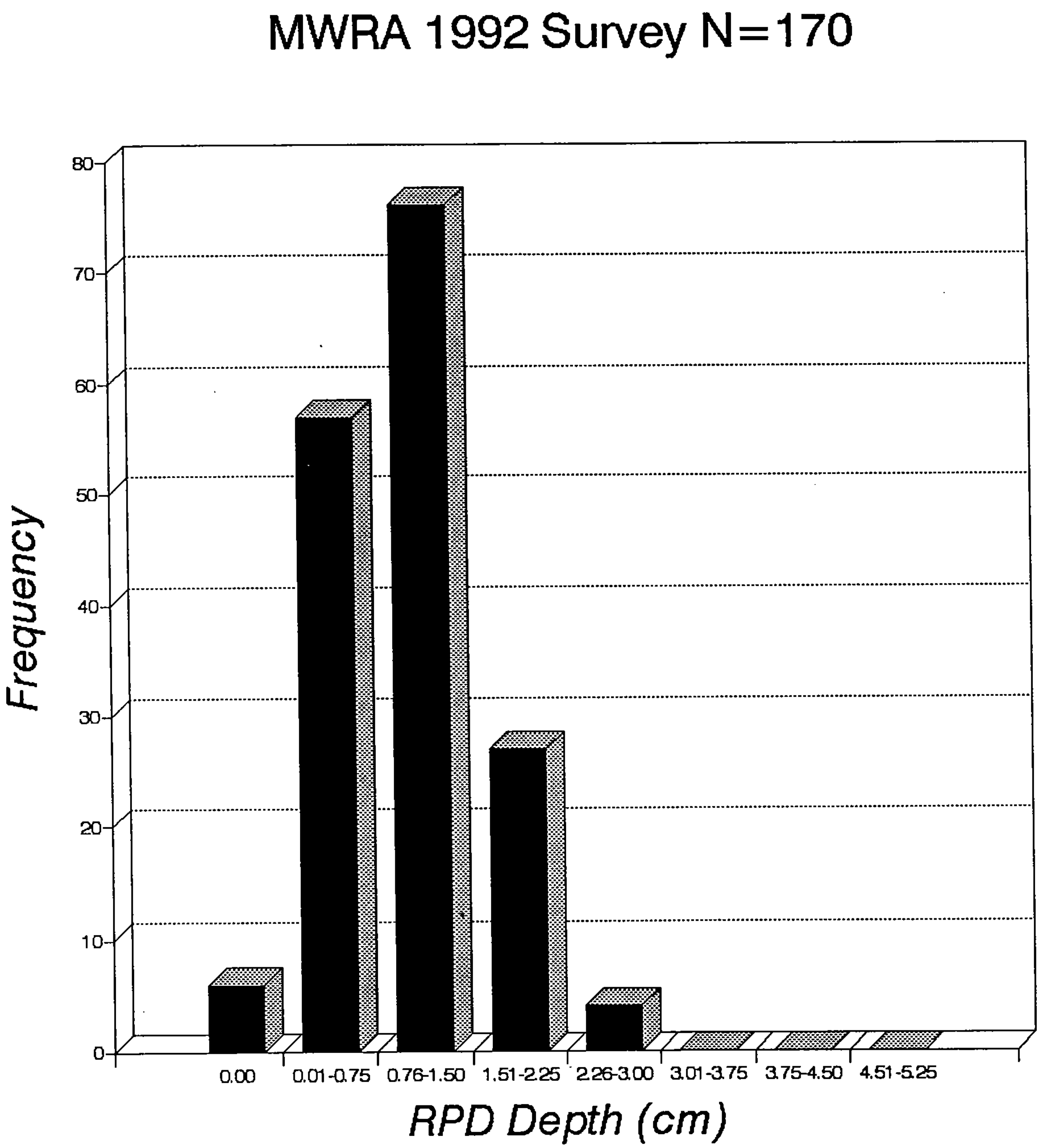


Figure 6. Frequency Distribution of Apparent RPD Depths for the 1992 REMOTS® Survey.

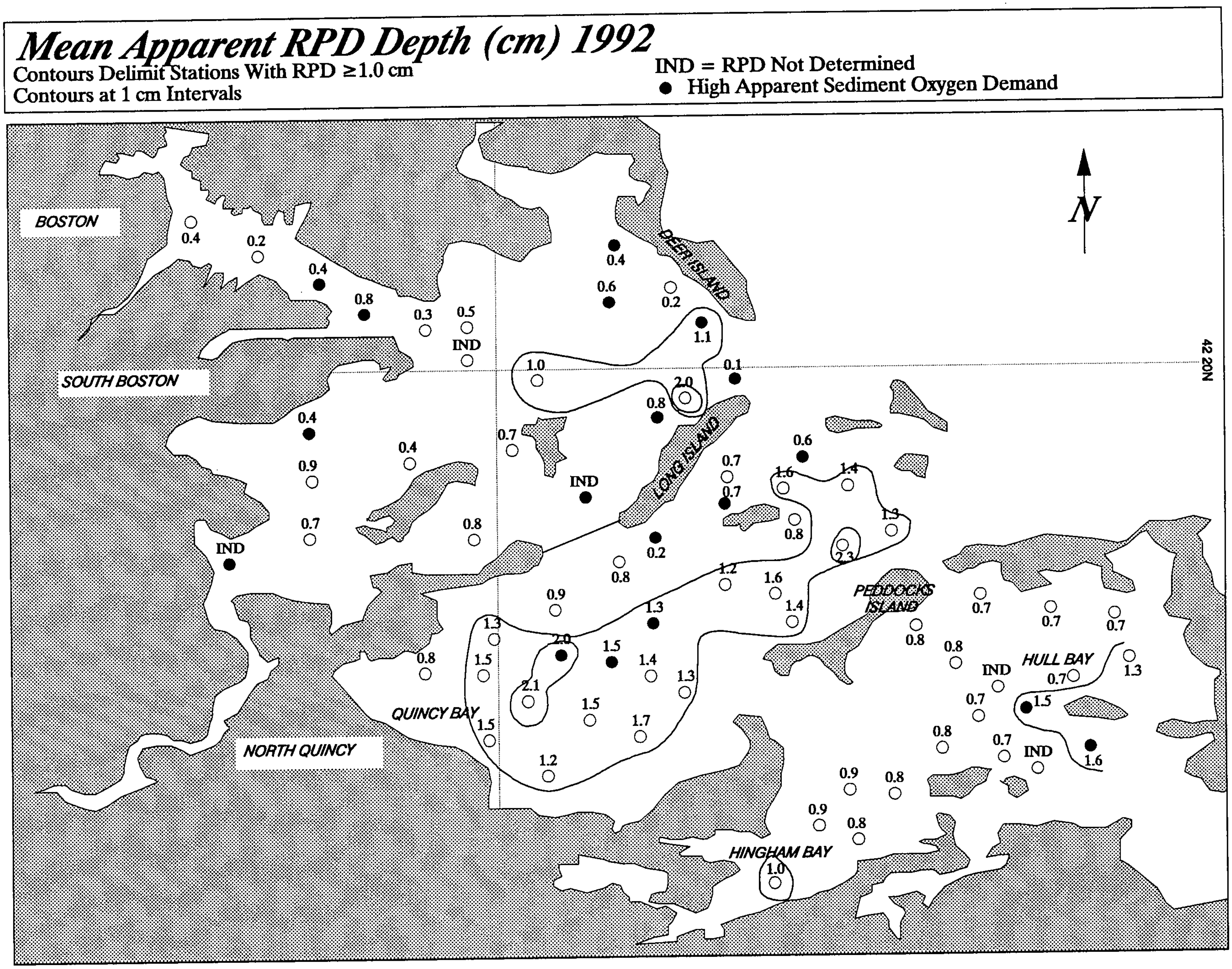


Figure 7. Mapped Distribution of Mean Apparent RPD Depths (cm) for the 1992 REMOTS® survey. Stations exhibiting very dark, low reflectance sediments (indicative of High Apparent Sediment Oxygen Demand) are also shown.

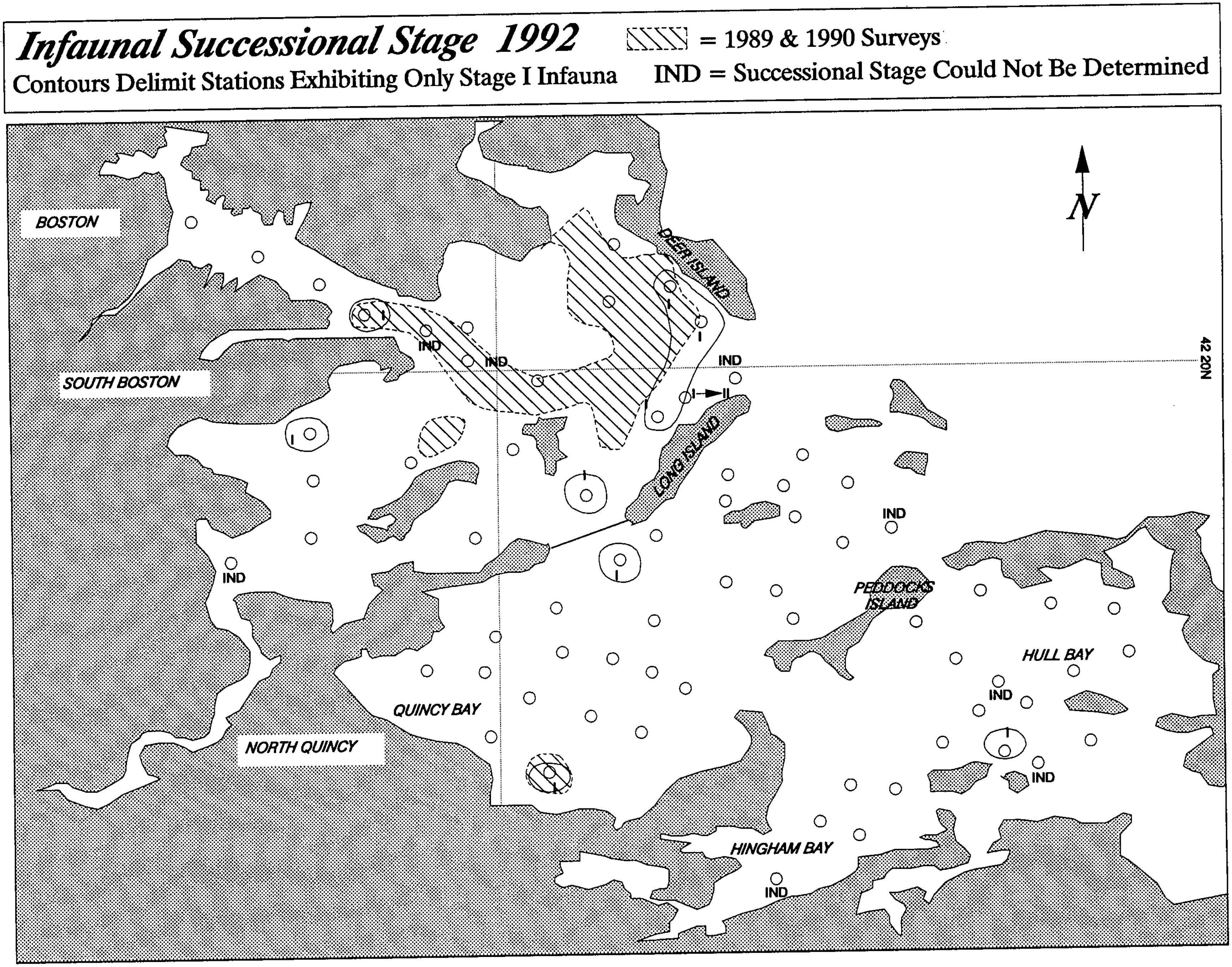


Figure 8. Mapped Distribution of Infaunal Successional Stage for the 1992 REMOTS® Survey with an overlay of the 1989/1990 Successional Stage data.

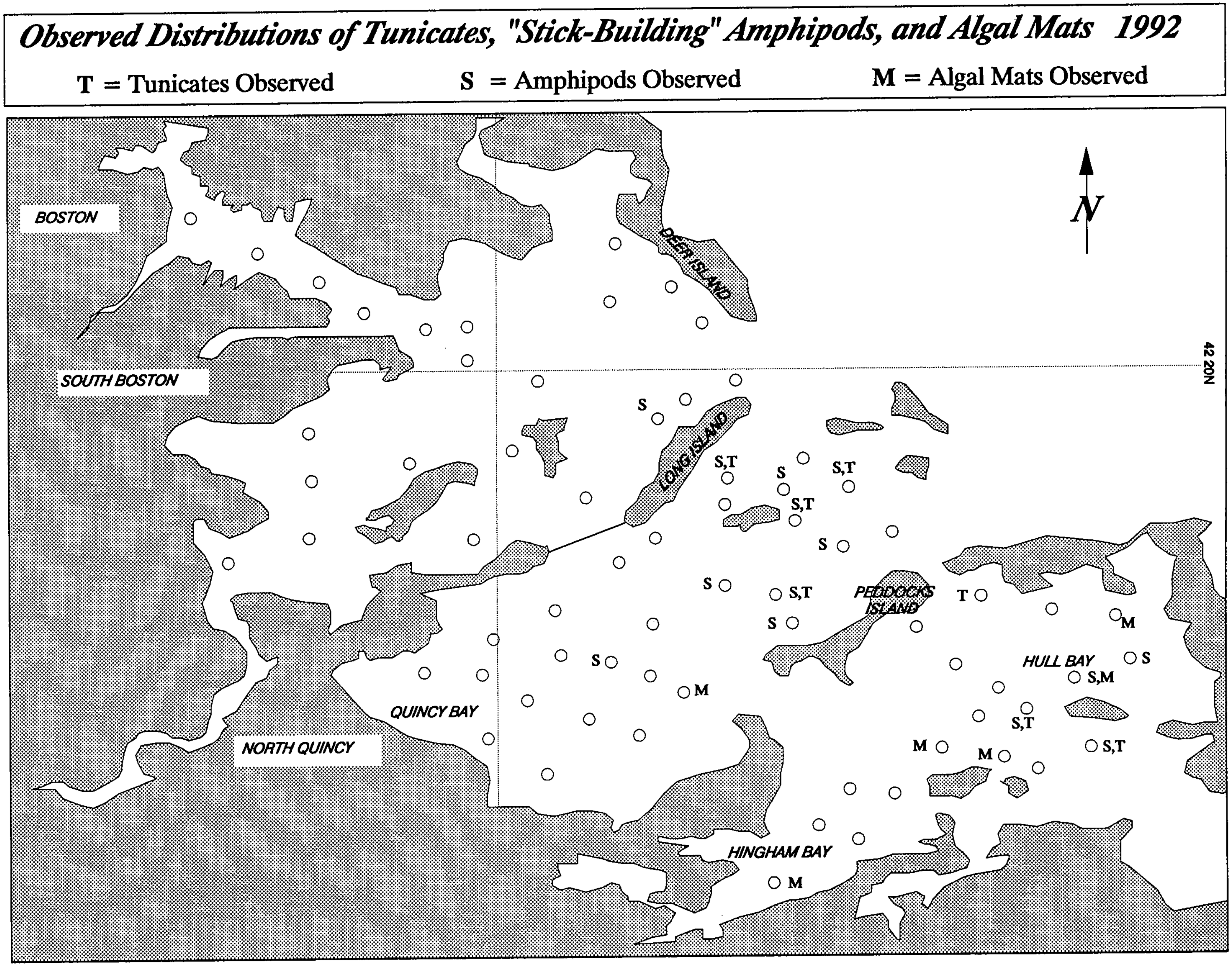


Figure 9. Observed Distribution of Tunicates, Stick-Building Amphipods, and Algal Mats for the 1992 REMOTS® Survey.

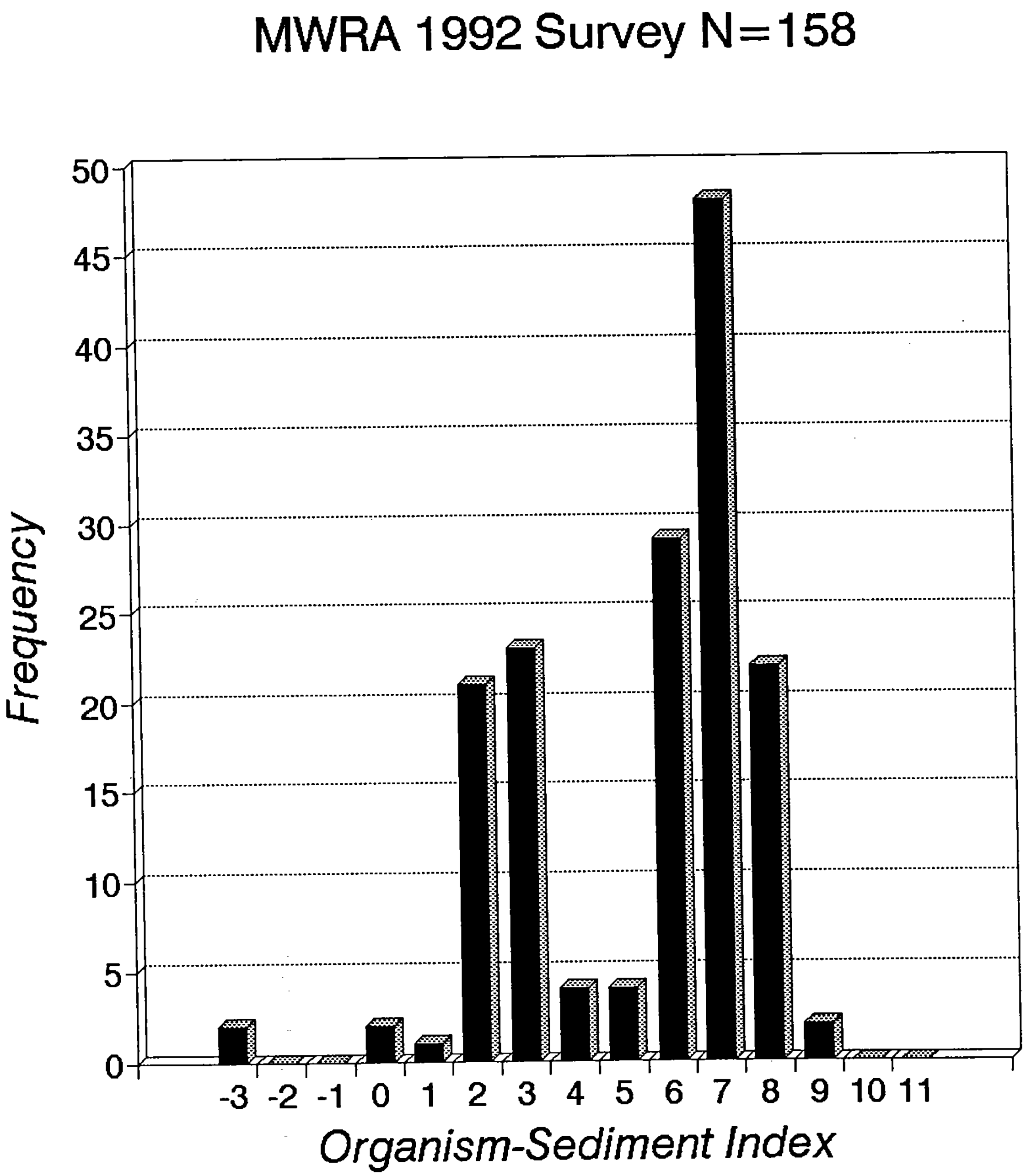


Figure 10. Frequency Distribution of Organism-Sediment Indices calculated for the 1992 REMOTS® Survey.

Median Organism-Sediment Index 1992

Contours Delimit Stations of > +6.0 OSI. IND = OSI Could Not Be Determined

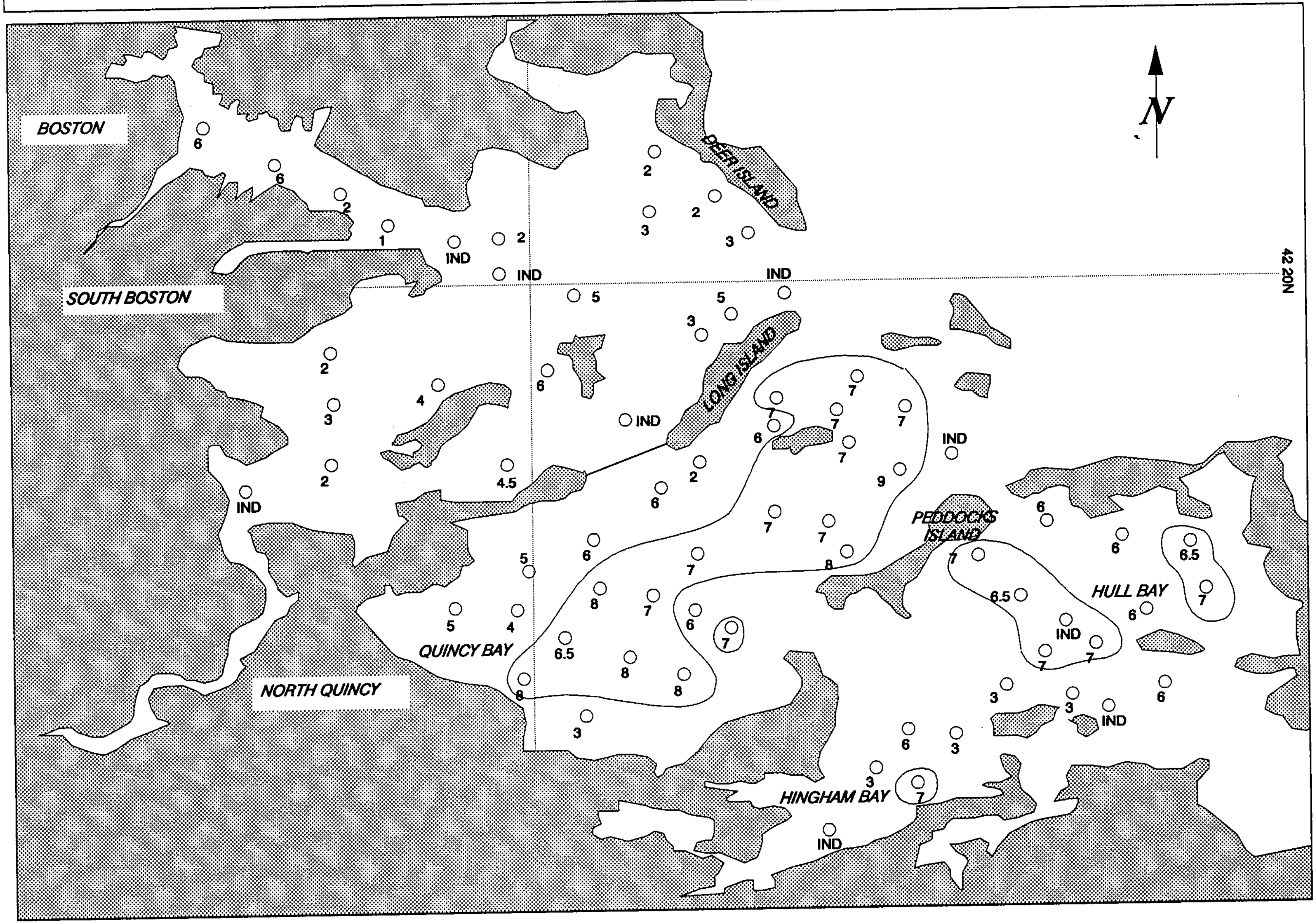


Figure 11. Mapped Distribution of Organism-Sediment Indices for the 1992 REMOTS® Survey.

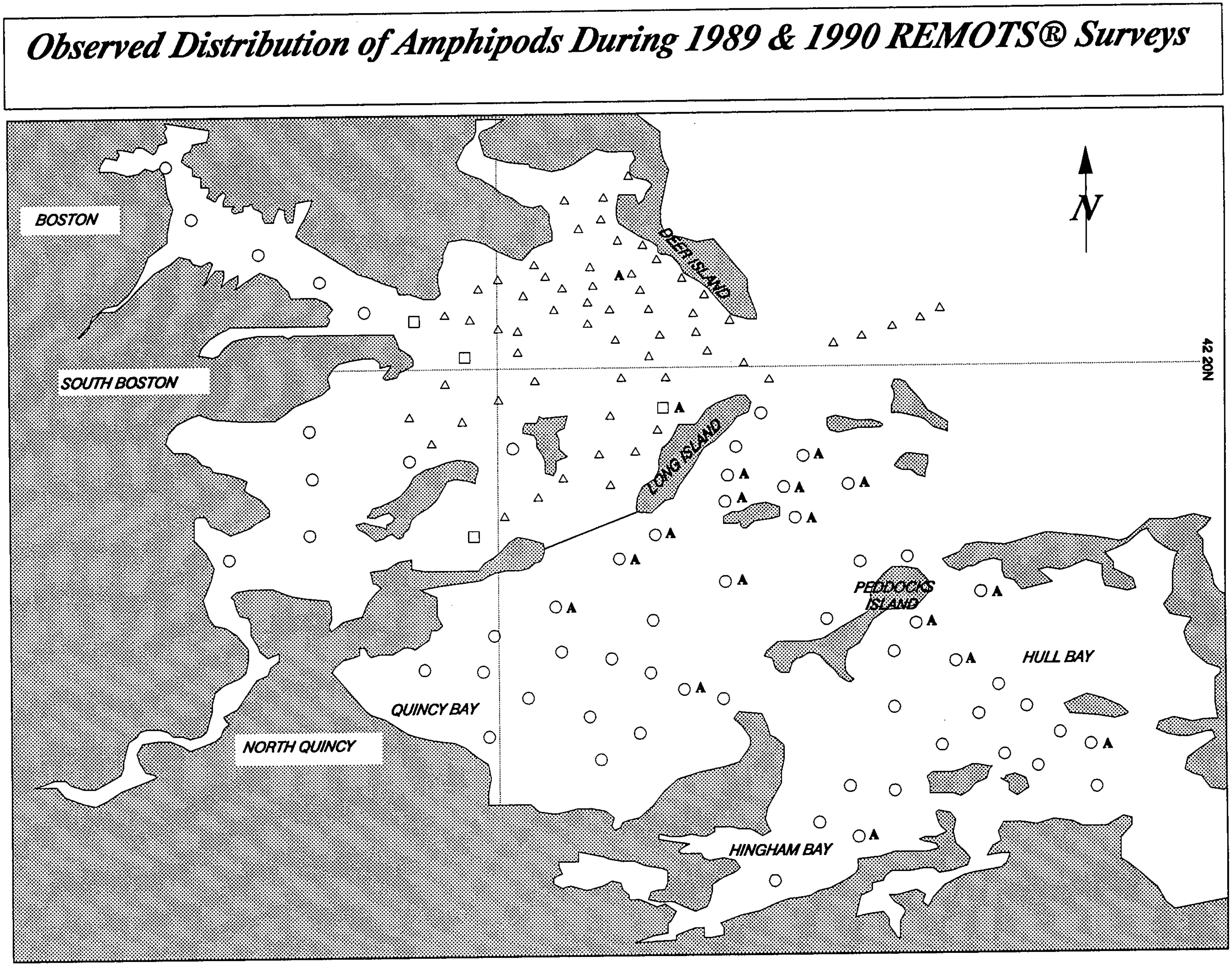


Figure 12. Observed Distribution of Tube-Building Ampeliscid Amphipods for the 1989/1990 REMOTS® Surveys.

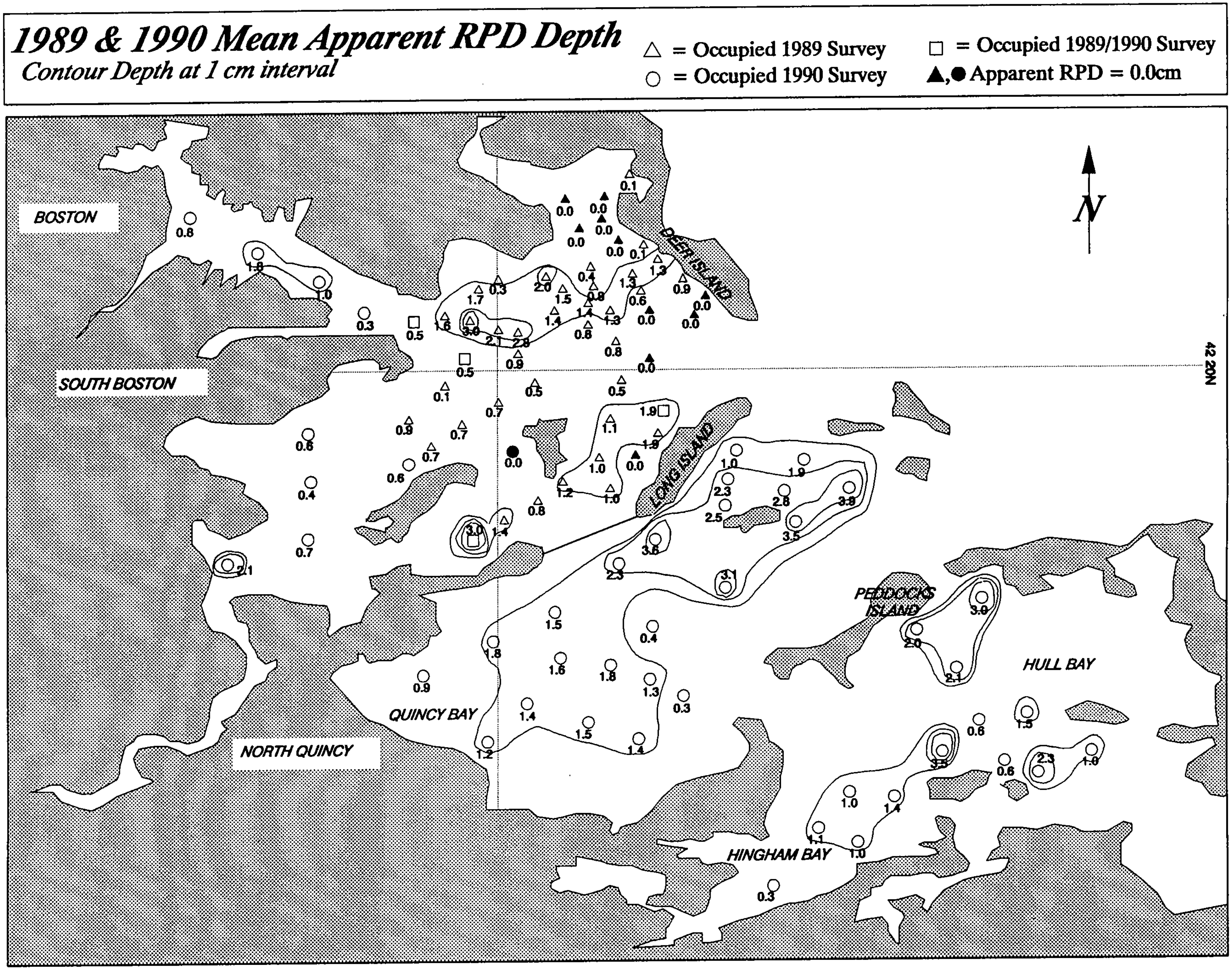


Figure 13. Mapped Distribution of Mean Apparent RPD Depths (cm) for the 1989/1990 REMOTS® survey.

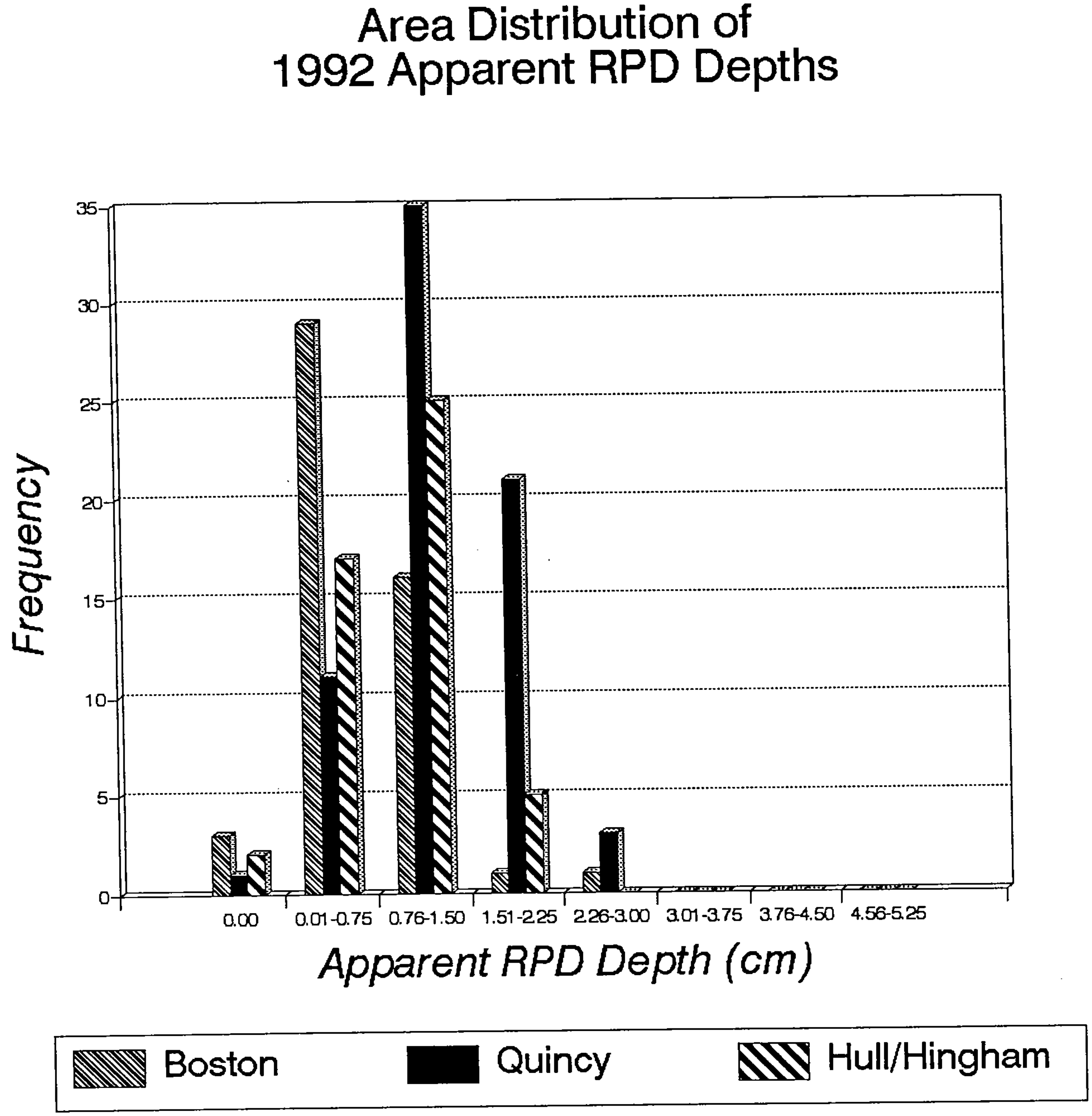


Figure 14. Frequency Distribution of Apparent RPD depths measured in Boston Harbor, Quincy, and Hull Bays during the 1992 REMOTS® Survey.

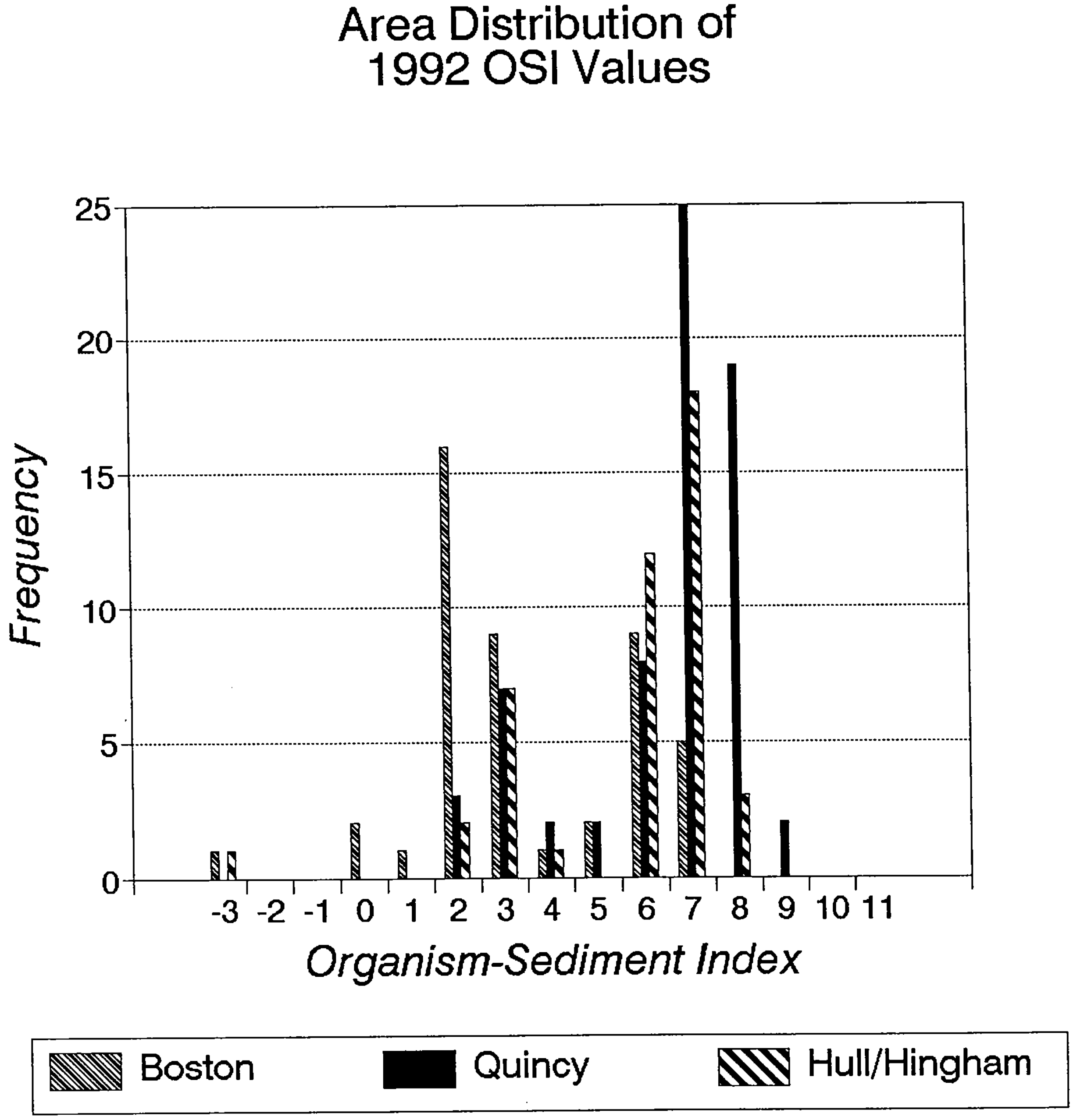


Figure 15. Frequency Distribution of Organism-Sediment Indices measured in Boston Harbor, Quincy, and Hull Bays during the 1992 REMOTS® Survey.

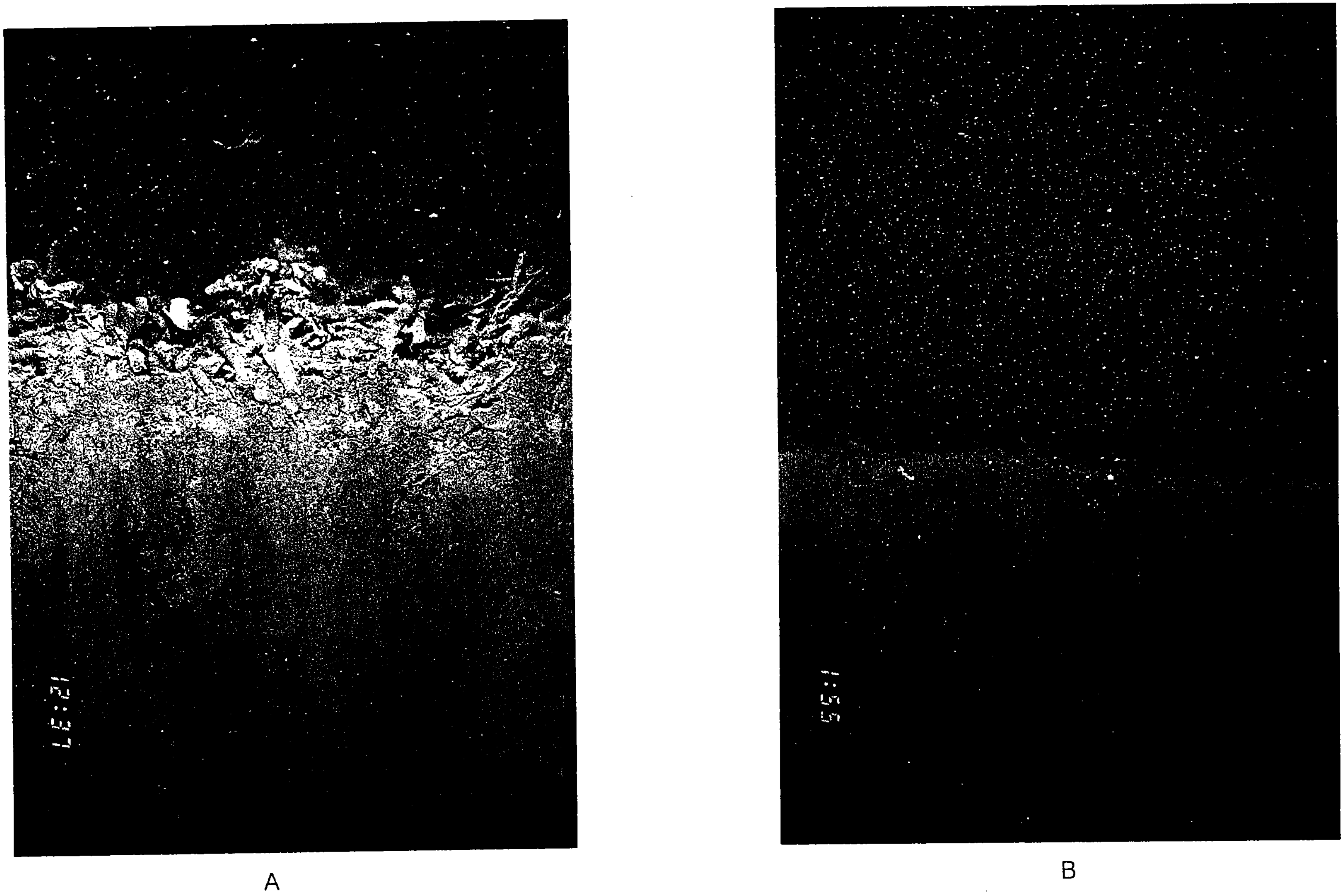
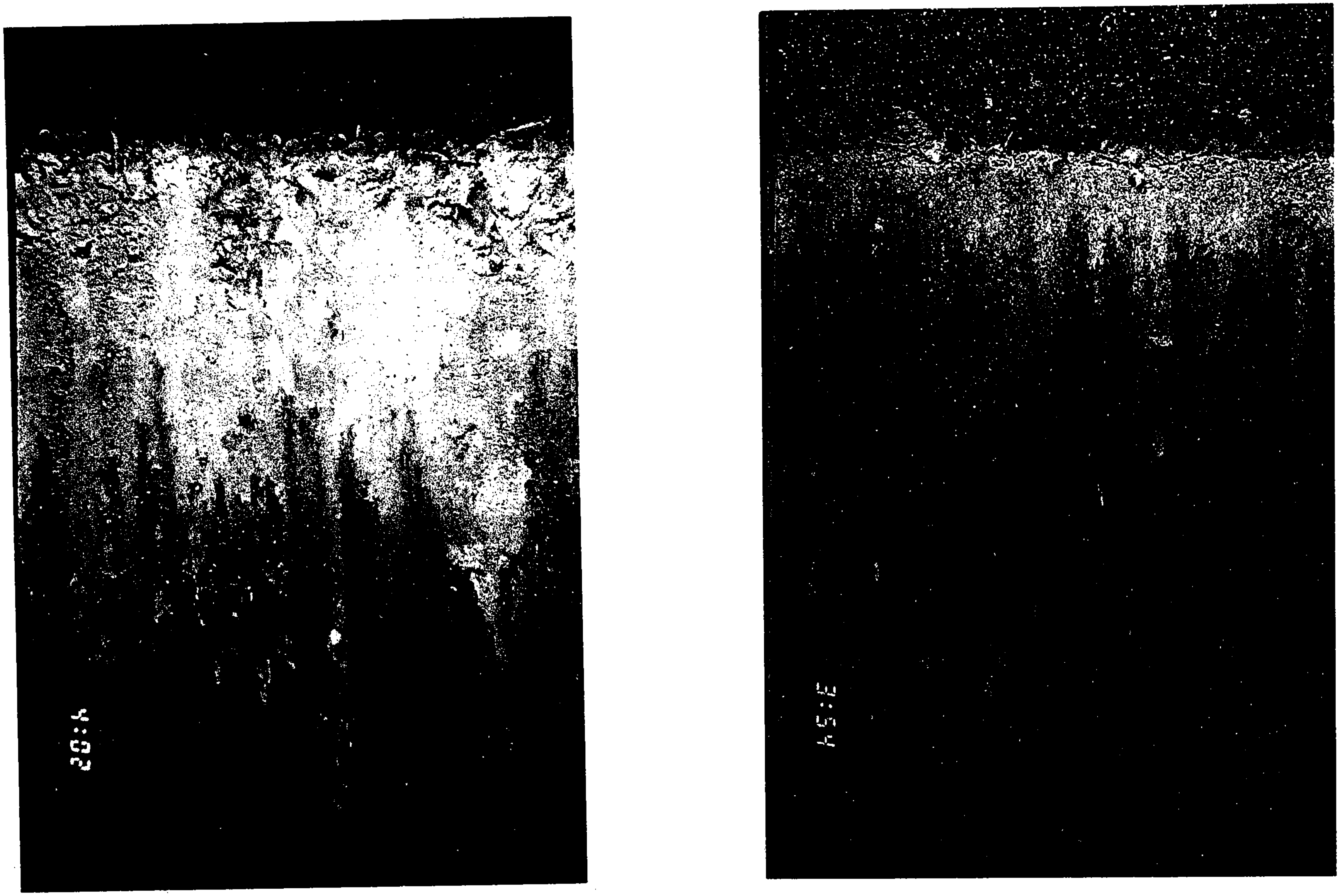


Figure 16. REMOTS® Photographs from Station 21 taken during the 1990 (A) and 1992 (B) Surveys of the Boston Harbor area. Note the apparent loss of tube-dwelling Ampeliscid amphipods during the 1992 survey.



A

B

Figure 17. REMOTS® Photographs from Station 49 taken during the 1990 (A) and 1992 (B) Surveys of the Boston Harbor area.

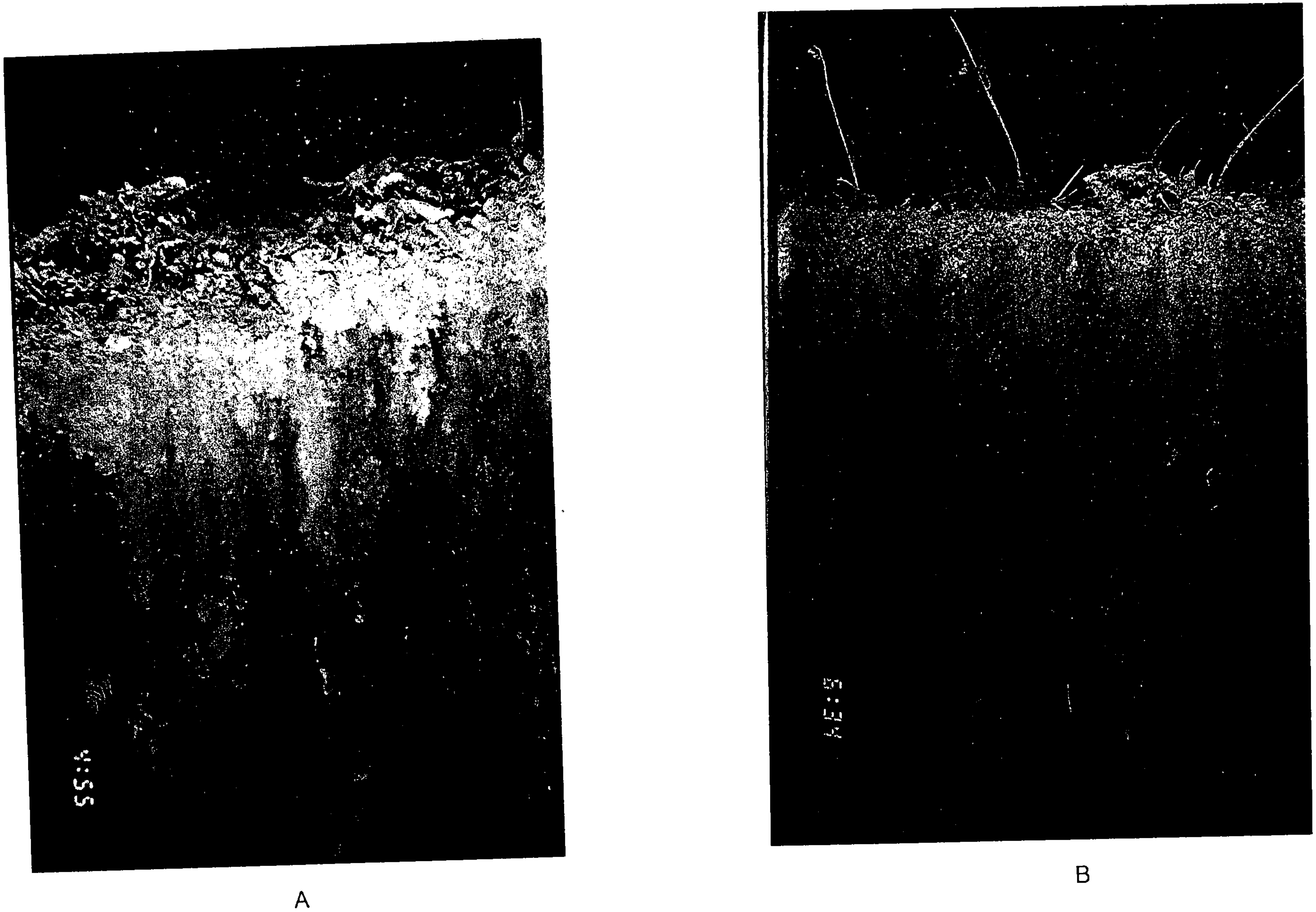


Figure 18. REMOTS® Photographs from Station 43 taken during the 1990 (A) and 1992 (B) Surveys of the Boston Harbor area. Note the apparent loss of Ampeliscid amphipods and recolonization by stick-building amphipods (Family Podoceridae) in the 1992 Survey.

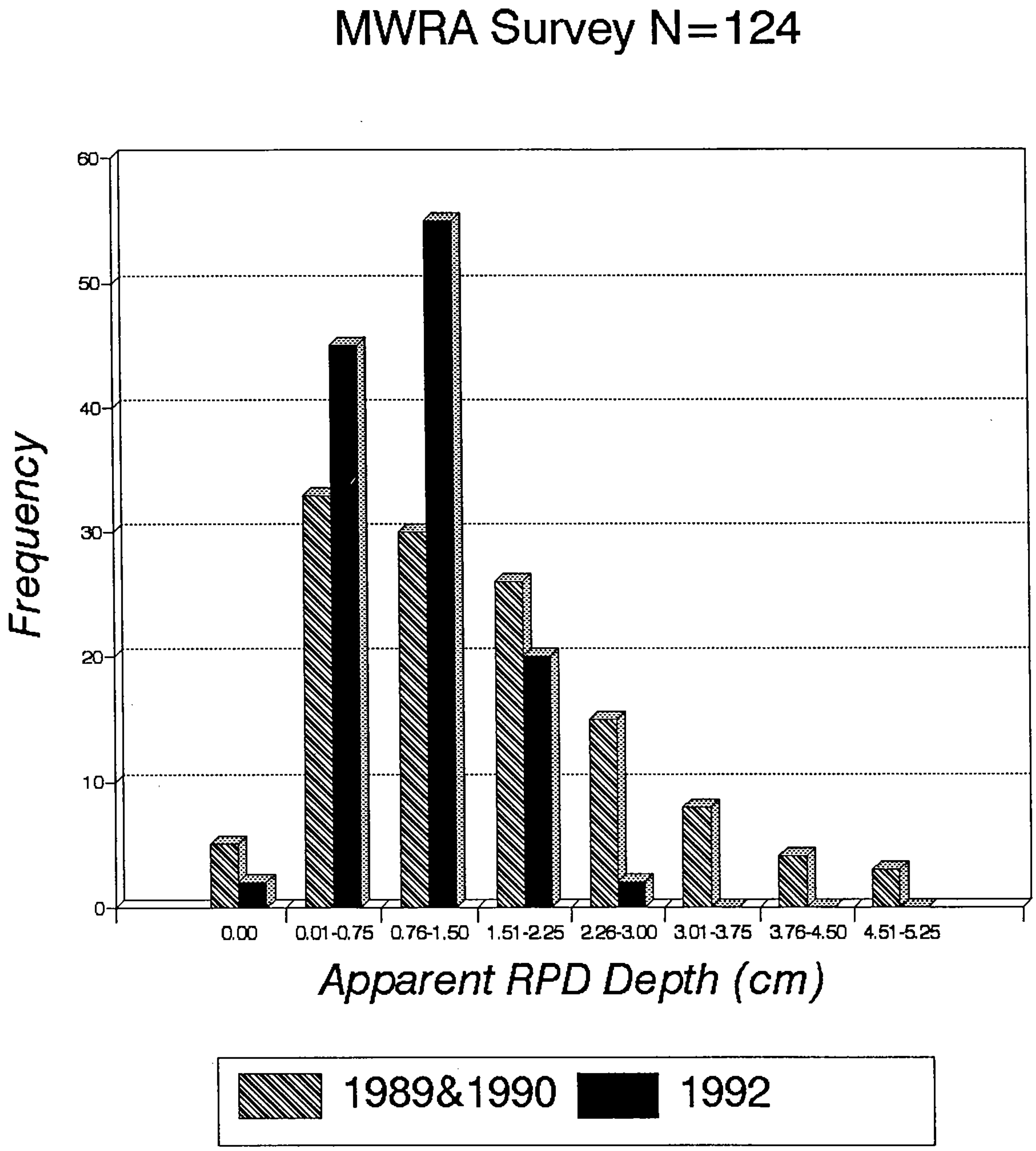


Figure 19. Comparison of Frequency Distributions of Apparent RPD Depths measured at stations occupied during the 1989/1990 and 1992 REMOTS® Surveys.

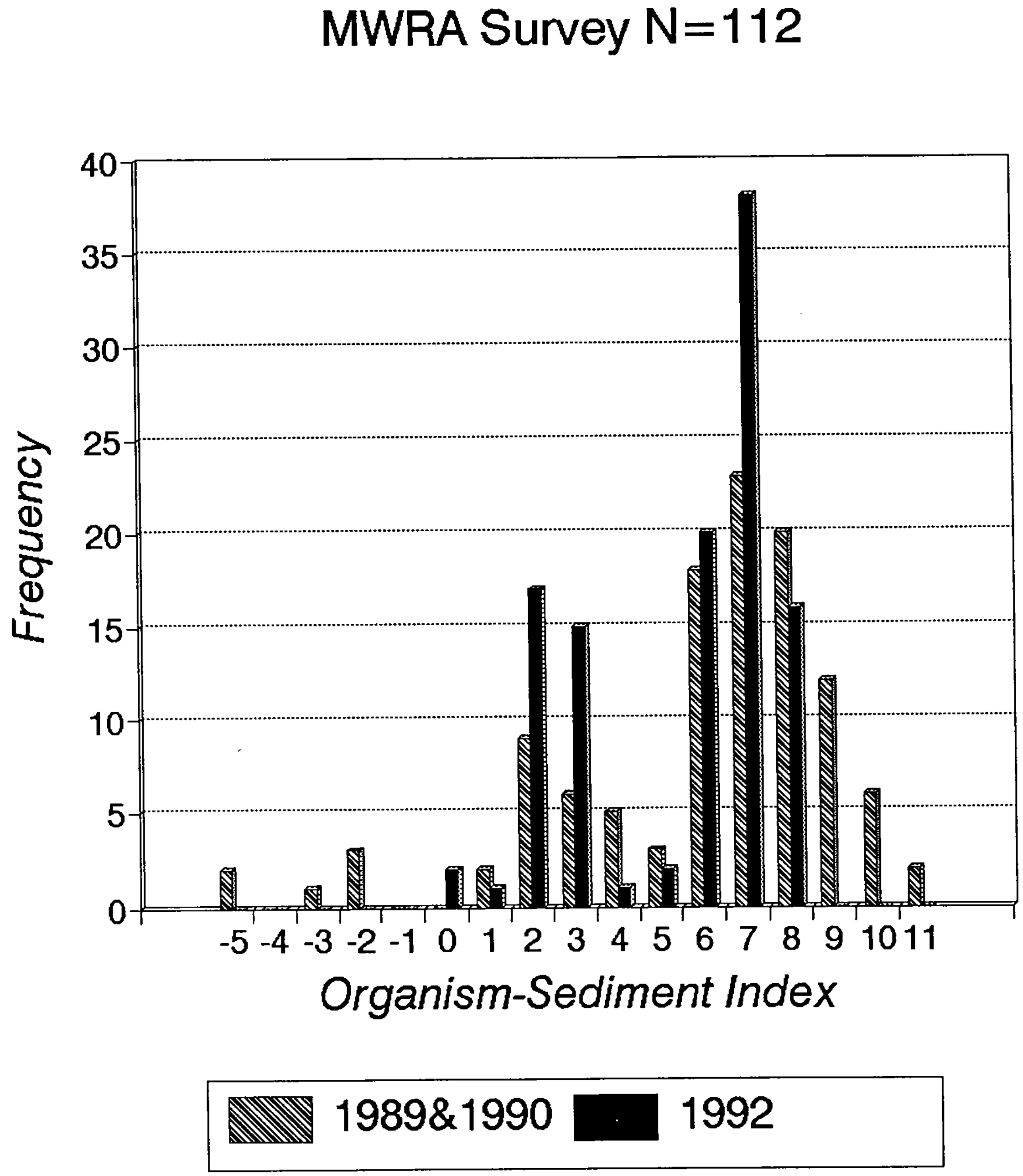


Figure 20. Comparison of Frequency Distributions of OSI Values at stations occupied during the 1989/1990 and 1992 REMOTS® Surveys.

Table 1. REMOTS® Data Summary Sheet for May, 1992.

Station	Replicate	Latitude	Longitude	GRAIN SIZE (PHI)	SURFACE BOUNDARY ROUGHNESS (CM)	ORGANISM SEDIMENT INDEX	RPD	SUCCESS. STAGE
1-90	a	42 15' 17"N	70 56' 53"W	3 to 4	1.01	INDET	1.35	INDET
	b			3 to 4	0.52	INDET	0.75	INDET
	c			2 to 3	1.65	INDET	INDET	INDET
2-90	a	42 15' 47"N	70 56' 31"W	3 to 4	2.02	7	0.77	1 ON 3
	b			3 to 4	0.56	7	0.91	1 ON 3
	c			3 to 4	1.73	-3	0.00	STAGE 1
	d			3 to 4	1.25	3	0.99	STAGE 1
	e			3 to 4	1.94	3	0.99	STAGE 1
	f			3 to 4	0.32	7	0.83	1 ON 3
3-90	a	42 15' 42"N	70 56' 05"W	3 to 4	0.60	7	0.83	1 ON 3
	b			3 to 4	0.81	6	0.75	1 ON 3
	c			3 to 4	0.77	7	0.83	1 ON 3
4-90	a	42 16' 09"N	70 56' 16"W	3 to 4	0.48	3	0.97	STAGE 1
	b			3 to 4	0.36	7	1.05	1 ON 3
	c			3 to 4	0.36	6	0.75	1 ON 3
5-90	a	42 16' 08"N	70 55' 48"W	3 to 4	INDET	INDET	INDET	INDET
	b			> 4	INDET	INDET	INDET	INDET
	c			3 to 4	2.66	3	0.81	STAGE 1
7-90	a	42 16' 34"N	70 55' 24"W	3 to 4	0.48	3	1.03	STAGE 1
	b			3 to 4	0.24	6	0.69	1 ON 3
	c			3 to 4	2.74	2	0.71	STAGE 1
8-90	a	42 16' 50"N	70 54' 59"W	3 to 4	0.12	7	0.89	1 ON 3
	b			3 to 4	0.85	7	0.81	1 ON 3
	c			3 to 4	0.36	6	0.34	1 ON 3
9-89/90	a	42 19' 38"N	70 58' 06"W	2 to 3	0.12	3	1.00	STAGE 1
	b			2 to 3	0.68	3	0.92	STAGE 1
	c			2 to 3	1.64	2	0.52	STAGE 1
10-90	a	42 16' 23"N	70 54' 29"W	3 to 4	0.65	INDET	INDET	INDET
	b			3 to 4	7.22	INDET	INDET	INDET
	c			3 to 4	1.90	INDET	INDET	INDET
11-90	a	42 16' 28"N	70 54' 50"W	3 to 4	0.69	INDET	0.60	INDET
	b			3 to 4	0.32	INDET	0.75	INDET
	c			3 to 4	0.32	3	0.83	STAGE 1
13-90	a	42 16' 30"N	70 53' 54"W	3 to 4	0.40	8	1.51	1 ON 3
	b			3 to 4	0.12	INDET	0.00	INDET
	c			3 to 4	0.65	4	1.61	1 ON 3
15-90	a	42 16' 54"N	70 54' 31"W	2 to 3	0.44	7	2.04	2 -> 3
	b			2 to 3	0.48	7	1.05	1 ON 3
	c			3 to 4	0.40	8	1.51	2 ON 3
16-89/90	a	42 18' 24"N	71 00' 08"W	> 4	0.40	7	0.92	1 ON 3
	b			> 4	0.80	2	0.62	STAGE 1
	c			3 to 4	INDET	INDET	INDET	INDET
18-90	a	42 17' 23"N	70 55' 15"W	2 to 3	1.45	7	0.93	1 ON 3
	b			2 to 3	0.44	6	0.62	1 ON 3
	c			3 to 4	3.02	INDET	INDET	1 ON 3
20-90	a	42 17' 44"N	70 55' 39"W	3 to 4	0.69	6	0.52	1 ON 3
	b			3 to 4	0.20	7	0.97	1 ON 3
	c			3 to 4	0.32	7	0.83	1 ON 3
21-90	a	42 18' 03"N	70 55' 02"W	2 to 3	0.85	7	0.81	1 ON 3
	b			2 to 3	0.97	6	0.62	1 ON 3
	c			3 to 4	0.32	2	0.67	STAGE 1
22-92	a	42 17' 46"N	70 54' 18"W	3 to 4	0.52	6	0.69	1 ON 3
	b			2 to 3	0.48	3	0.85	STAGE 1
	c			2 to 3	0.40	6	0.69	1 ON 3
23-92	a	42 17' 41"N	70 53' 49"W	3 to 4	1.37	7	0.97	1 ON 3
	b			2 to 3	1.94	6	0.46	1 ON 3
	c			> 4	INDET	INDET	INDET	INDET

Table 1. REMOTS® Data Summary Sheet for May, 1992. (Continued)

Station	Replicate	Latitude	Longitude	GRAIN SIZE (PHI)	SURFACE BOUNDARY ROUGHNESS (CM)	ORGANISM SEDIMENT INDEX	RPD	SUCCESS. STAGE
24-92	a	42 17' 13"N	70 53' 39"W	3 to 4	0.56	7	1.13	1 ON 3
	b			3 to 4	0.60	8	1.94	1 ON 3
	c			2 to 3	0.77	7	0.79	1 ON 3
25-90	a	42 16' 45"N	70 59' 45"W	3 to 4	0.44	8	1.87	1 ON 3
	b			3 to 4	0.52	8	1.65	1 ON 3
	c			3 to 4	0.60	7	1.06	1 ON 3
26-92	a	42 16' 32"N	70 59' 12"W	2 to 3	2.05	INDET	1.27	INDET
	b			3 to 4	5.46	INDET	INDET	INDET
	c			2 to 3	0.64	3	1.04	STAGE 1
27-90	a	42 17' 20"N	71 00' 25"W	> 4	0.32	INDET	INDET	INDET
	b			> 4	1.61	7	0.76	1 ON 3
	c			3 to 4	1.16	3	0.82	STAGE 1
28-90	a	42 17' 14"N	70 59' 45"W	3 to 4	2.53	3	0.90	STAGE 1
	b			3 to 4	0.84	4	1.65	STAGE 1
	c			3 to 4	0.92	8	1.97	1 ON 3
29-90	a	42 17' 03"N	70 59' 17"W	3 to 4	0.40	8	1.73	1 ON 3
	b			3 to 4	0.68	5	2.47	STAGE 1
	c			3 to 4	1.81	INDET	INDET	INDET
30-90	b	42 16' 50"N	70 58' 47"W	2 to 3	1.24	INDET	1.12	INDET
	c			3 to 4	0.36	8	1.83	1 ON 3
31-90	a	42 16' 41"N	70 58' 13"W	3 to 4	0.84	8	1.95	1 ON 3
	b			3 to 4	1.61	8	1.99	1 ON 3
	c			3 to 4	0.68	7	1.24	1 ON 3
32-89/90	c	42 20' 11"N	71 00' 06"W	< -1	0.98	INDET	INDET	INDET
33-89/90	a	42 20' 31"N	71 00' 40"W	2 to 3	0.85	INDET	0.32	INDET
34-90	a	42 17' 39"N	70 59' 40"W	3 to 4	0.64	3	1.29	STAGE 1
	b			3 to 4	0.72	7	1.29	1 ON 3
	c			> 4	2.81	INDET	INDET	INDET
35-90	a	42 17' 26"N	70 59' 03"W	3 to 4	1.24	8	2.12	1 ON 3
	b			3 to 4	1.32	8	1.96	1 ON 3
	c			3 to 4	0.84	INDET	INDET	1 ON 3
37-90	a	42 17' 12"N	70 58' 12"W	2 to 3	0.92	8	1.66	1 ON 3
	b			3 to 4	1.08	4	1.78	STAGE 1
	c			3 to 4	1.36	6	0.72	1 ON 3
38-90	a	42 17' 05"N	70 57' 50"W	3 to 4	0.48	7	0.94	1 ON 3
	b			3 to 4	0.64	7	1.34	1 ON 3
	c			3 to 4	2.08	8	1.68	1 ON 3
40-90	a	42 17' 56"N	70 59' 05"W	3 to 4	0.72	3	1.34	STAGE 1
	b			3 to 4	0.80	7	0.76	1 ON 3
	c			3 to 4	5.28	6	0.72	1 ON 3
41-90	a	42 17' 44"N	70 58' 13"W	3 to 4	0.48	7	1.30	2 ON 3
	b			> 4	1.40	INDET	INDET	1 ON 3
	c			3 to 4	INDET	INDET	INDET	INDET
42-90	a	42 18' 18"N	70 58' 25"W	3 to 4	0.36	2	0.68	STAGE 1
	b			> 4	0.32	3	0.84	STAGE 1
	c			3 to 4	0.16	3	0.80	STAGE 1
43-90	a	42 18' 13"N	70 57' 38"W	2 to 3	0.36	7	0.84	1 ON 3
	b			3 to 4	0.52	7	1.20	1 ON 3
	c			3 to 4	0.56	8	1.52	1 ON 3
44-92	a	42 18' 02"N	70 57' 07"W	2 to 3	1.08	7	1.46	1 ON 3
	b			2 to 3	1.20	7	1.42	1 ON 3
	c			2 to 3	0.88	8	1.98	2 ON 3
45-90	a	42 18' 37"N	70 58' 04"W	3 to 4	0.36	2	0.10	STAGE 1
	b			3 to 4	0.52	2	0.26	STAGE 1
	c			3 to 4	0.12	6	0.30	1 ON 3

Table 1. REMOTS® Data Summary Sheet for May, 1992. (Continued)

Station	Replicate	Latitude	Longitude	GRAIN SIZE (PHI)	SURFACE BOUNDARY ROUGHNESS (CM)	ORGANISM SEDIMENT INDEX	RPD	SUCCESS. STAGE
46-92	a	42 18' 36"N	70 56' 22"W	3 to 4	0.68	9	2.88	1 ON 3
	b			3 to 4	1.04	8	1.54	2 ON 3
	c			2 to 3	1.08	9	2.54	2 ON 3
47-92	a	42 18' 42"N	70 55' 57"W	1 to 2	1.01	INDET	INDET	INDET
	b			2 to 3	1.01	INDET	1.27	INDET
	c			1 to 2	2.14	INDET	INDET	INDET
48-90	a	42 18' 55"N	70 57' 37"W	3 to 4	1.08	7	0.78	1 ON 3
	b			3 to 4	2.08	6	0.66	1 ON 3
	c			3 to 4	1.08	6	0.72	1 ON 3
49-90	a	42 18' 45"N	70 56' 46"W	3 to 4	0.52	7	0.76	1 ON 3
	b			3 to 4	0.12	7	1.02	1 ON 3
	c			3 to 4	0.60	6	0.52	1 ON 3
50-90	a	42 19' 10"N	70 57' 20"W	3 to 4	0.48	6	0.48	1 ON 3
	b			2 to 3	0.24	7	0.78	1 ON 3
	c			2 to 3	0.88	7	0.78	1 ON 3
51-90	a	42 19' 04"N	70 56' 49"W	3 to 4	0.32	8	2.12	1 ON 3
	b			3 to 4	0.64	7	1.28	1 ON 3
	c			3 to 4	0.48	7	1.40	1 ON 3
52-90	a	42 19' 05"N	70 56' 12"W	2 to 3	0.81	7	1.01	1 ON 3
	b			2 to 3	0.36	7	1.43	1 ON 3
	c			3 to 4	0.04	8	1.87	1 ON 3
54-90	a	42 19' 20"N	70 56' 38"W	3 to 4	0.52	7	0.92	1 ON 3
	b			3 to 4	4.00	5	0.00	1 ON 3
	c			3 to 4	0.52	7	0.80	1 ON 3
57-90	a	42 18' 40"N	71 01' 30"W	3 to 4	0.28	7	0.92	1 ON 3
	b			3 to 4	0.20	2	0.56	STAGE 1
	c			3 to 4	0.48	2	0.58	STAGE 1
58-90	a	42 19' 11"N	71 01' 30"W	2 to 3	0.64	2	0.70	STAGE 1
	b			2 to 3	1.60	7	0.78	1 ON 3
	c			2 to 3	0.52	3	1.18	STAGE 1
59-90	a	42 19' 44"N	71 01' 27"W	2 to 3	0.64	2	0.42	STAGE 1
	b			3 to 4	0.60	2	0.42	STAGE 1
	c			3 to 4	0.84	2	0.30	STAGE 1
60-90	a	42 19' 13"N	71 00' 47"W	3 to 4	0.96	6	0.30	1 ON 3
	b			3 to 4	0.40	2	0.56	STAGE 1
	c			3 to 4	2.97	INDET	INDET	STAGE 1
61-90	a	42 19' 18"N	70 59' 42"W	3 to 4	1.72	6	0.30	1 ON 3
	b			3 to 4	0.16	3	1.20	STAGE 1
	c			3 to 4	0.44	6	0.68	1 ON 3
62-90	a	42 20' 48"N	71 00' 59"W	3 to 4	0.85	3	0.85	STAGE 1
	b			3 to 4	2.18	0	0.53	STAGE 1
	c			3 to 4	0.98	1	0.96	STAGE 1
63-90	a	42 21' 03"N	71 01' 28"W	3 to 4	INDET	INDET	0.00	INDET
	b			3 to 4	INDET	INDET	INDET	1 ON 3
	c			3 to 4	0.98	2	0.71	STAGE 1
64-90	a	42 21' 21"N	71 02' 02"W	3 to 4	4.70	6	0.21	1 ON 3
	b			3 to 4	0.94	6	0.36	1 ON 3
	c			2 to 3	5.04	-3	0.00	STAGE 1
65-90	a	42 21' 42"N	71 02' 41"W	> 4	INDET	INDET	INDET	INDET
	b			> 4	0.73	6	0.58	1 ON 3
	c			3 to 4	0.34	6	0.30	1 ON 3
67-92	a	42 17' 26"N	70 54' 15"W	2 to 3	0.44	7	0.87	1 ON 3
	b			3 to 4	0.48	6	0.60	1 ON 3
	c			3 to 4	0.85	6	0.71	1 ON 3
70-92	a	42 18' 55"N	70 58' 44"W	3 to 4	2.08	INDET	INDET	INDET
	b			3 to 4	1.12	INDET	INDET	STAGE 1
	c			3 to 4	3.56	INDET	INDET	STAGE 1

Table 1. REMOTS® Data Summary Sheet for May, 1992. (Continued)

Station	Replicate	Latitude	Longitude	GRAIN SIZE (PHI)	SURFACE BOUNDARY ROUGHNESS (CM)	ORGANISM SEDIMENT INDEX	RPD	SUCCESS. STAGE
71-92	a	42 20' 34"N	70 58' 00"W	3 to 4	0.12	0	0.48	STAGE 1
	b			3 to 4	0.20	3	1.33	STAGE 1
	c			2 to 3	0.16	3	1.45	STAGE 1
72-92	a	42 20' 02"N	70 59' 31"W	2 to 3	0.68	7	1.11	1 ON 3
	b			2 to 3	1.24	3	0.85	STAGE 1
	c			3 to 4	5.55	INDET	INDET	INDET
73-92	a	42 20' 39"N	70 58' 42"W	3 to 4	10.28	7	1.35	1 ON 3
	b			3 to 4	2.05	2	0.26	STAGE 1
	c			3 to 4	2.05	3	0.76	STAGE 1
74-92	a	42 21' 19"N	70 58' 35"W	3 to 4	0.96	6	0.34	1 ON 3
	b			3 to 4	2.57	2	0.34	STAGE 1
	c			3 to 4	0.44	2	0.54	STAGE 1
T1	a	42 20.95'N	70 57.81'W	2 to 3	2.13	2	0.24	STAGE 1
T2	a	42 20.57'N	71 00.12'W	3 to 4	0.43	6	0.49	1 ON 3
	b			2 to 3	2.14	2	0.66	STAGE 1
	c			3 to 4	0.30	2	0.47	STAGE 1
T3	a	42 19.81'N	70 57.72'W	3 to 4	0.84	4	1.44	1 -> 2
	b			3 to 4	0.80	5	2.24	1 -> 2
	c			3 to 4	0.88	5	2.44	STAGE 1
T4	a	42 18.60'N	71 02.49'W	3 to 4	1.56	INDET	INDET	INDET
	b			3 to 4	1.56	INDET	INDET	INDET
T5	a	42 19.91'N	70 57.21'W	0 to 1	1.16	INDET	0.24	INDET
	b			0 to 1	0.16	INDET	INDET	INDET
	c			0 to 1	1.80	INDET	0.00	INDET
T6	a	42 17.61'N	70 56.66'W	3 to 4	0.96	6	0.74	1 ON 3
	b			2 to 3	1.52	8	1.62	1 ON 3
	c			3 to 4	0.84	8	1.80	1 ON 3
T7	a	42 17.36'N	70 58.71'W	3 to 4	0.68	7	1.22	1 ON 3
	b			3 to 4	0.28	8	2.00	1 ON 3
	c			3 to 4	0.56	7	1.26	1 ON 3
T8	a	42 17.12'N	70 54.75'W	1 to 2	0.97	INDET	INDET	INDET
	b			2 to 3	0.12	INDET	INDET	INDET
	c			2 to 3	2.06	INDET	INDET	INDET

Table 2. **Calculation of the REMOTS® Organism-Sediment Index Value.**

CHOOSE ONE VALUE:

Mean RPD Depth	Index Value
0.00 cm	0
> 0 to 0.75 cm	1
0.76 to 1.50 cm	2
1.51 to 2.25 cm	3
2.26 to 3.00 cm	4
3.01 to 3.75 cm	5
> 3.75 cm	6

CHOOSE ONE VALUE:

Successional Stage	Index Value
Azoic	-4
Stage I	1
Stage I → II	2
Stage II	3
Stage II → III	4
Stage III	5
Stage I on III	5
Stage II on III	5

CHOOSE ONE OR BOTH IF APPROPRIATE:

Chemical Parameters	Index Value
Methane Gas Present	-2
No/Low Dissolved Oxygen**	-4

REMOTS® ORGANISM-SEDIMENT INDEX = Total of above subset indices

RANGE: -10 to +11

** Note: This is not based on the Winkler or polarigraphic electrode measurements. It is based on the presence of reduced, low reflectance (i.e., high oxygen demand) sediment at the sediment-water interface.

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